Fibre-reinforced polymer bridges – guidance for designers

Who we are

CIRIA members lead the industry in raising professional standards through collaboration, sharing knowledge and promoting good practice. Recognised as leaders in industry improvement, CIRIA's members represent all construction stakeholder groups including clients, contractors, consultants, public sector champions, regulators and academia.

CIRIA membership provides organisations with a unique range of business development and improvement services, focused on sharing and embedding research, knowledge and good practice. In addition to the many direct benefits, membership provides a wealth of opportunities for organisations to engage in shaping, informing and delivering industry solutions focused on innovation and improvement.

In addition to representing excellent value for money in terms of direct benefits, CIRIA membership delivers significant returns for organisational investment in business improvement and development, CPD, industry engagement, profile enhancement and collaborative research.

CIRIA membership allows your employees to access the full breadth of CIRIA resources and services, creating valuable networking, performance improvement and leadership opportunities.

In addition to CIRIA membership, there is a range of specialist community of practice memberships available:

- **CIRIA book club**
  The CIRIA book club allows you to buy CIRIA publications at half price – plus free copies of all new guidance for Gold subscribers.
- **Local Authority Contaminated Land (LACL) network**
  LACL helps local authority officers to address responsibilities and duties involving land contamination and redevelopment.
- **Brownfield Risk Management Forum (BRMF)**
  BRMF provides comprehensive support to all construction, environmental, financial and legal professionals working on brownfield projects.
- **European Marine Sand And Gravel Group (EMSAGG)**
  EMSAGG provides a forum for the marine aggregate industry across Europe to discuss sector issues and exchange ideas and learning.

Where we are

Discover how your organisation can benefit from CIRIA's authoritative and practical guidance – contact us by:

Post Griffin Court, 15 Long Lane, London, EC1A 9PN, UK
Telephone +44 (0)20 7549 3300
Fax +44 (0)20 7549 3349
Email enquiries@ciria.org
Website www.ciria.org

For details of membership, networks, events, collaborative projects and to access CIRIA publications through the bookshop.

CIRIA C779 London, 2018

Fibre-reinforced polymer bridges – guidance for designers

Edited by J Toby Mottram and James Henderson, Composites UK

ciria
Griffin Court, 15 Long Lane, London, EC1A 9PN
Tel: 020 7549 3300 Fax: 020 7549 3349
Email: enquiries@ciria.org Website: www.ciria.org

Summary

This guide is for the design, procurement, execution, monitoring and inspection of new bridges where components are made using fibre-reinforced polymeric (FRP) composite material. Over the past 25 years there has been an increasing exploitation for structural strengthening and for all-FRP or hybrid-FRP structures, including for bridges and iconic architectural pieces.

It has been a natural progression to consider FRPs in the construction of new bridges, where appropriate to do so, and on a project-by-project basis. Progress in the uptake of FRPs for bridge engineering has been partly restricted by the lack of suitable design standards and guidance for the use of these materials to enable technically efficient and economic design. The structural material of FRP was not covered by the first generation of Eurocodes that were adopted in the UK in 2010.

This first edition is intended to assist in the design of FRP bridges and has the support of all the leading consultants, suppliers, clients, contractors and universities involved in this sector of the construction industry in the UK. These groups have been recognised among the contributors of this guide by providing their time, experience, expertise, understanding and knowledge.

Fibre-reinforced polymer bridges – guidance for designers

Mottram, J. T and Henderson, J (editors)

C779 © CIRIA 2018 RP1064 ISBN: 978-0-86017-794-4

British Library Cataloguing in Publication Data

A catalogue record is available for this publication from the British Library

Keywords

Civil and ground engineering, construction materials, and products, construction process and management, infrastructure asset management

Reader interest	**Classification**	
This guide gives advice to all designers, manufacturers and contractors who wish to use FRP composites materials in the construction of new infrastructure. While it directly relates to bridges in the external environment, the guidance provided can also benefit other similar structural applications such as buildings and gantries. Several key issues relating to the use of FRP in structural applications are discussed, building on lessons learnt by industry over the past 30 years.	Availability	Unrestricted
	Content	Advice/guidance
	Status	Committee guided
	User	Bridge designers, materials engineers, specialist bridge consultants and contractors, infrastructure owners and managers

Published by CIRIA, Griffin Court, 15 Long Lane, London, EC1A 9PN, UK

Foreword

The adoption of FRP composites within the construction sector has historically been limited to lightweight non-structural elements such as sanitary items and cladding. More recently, the use of FRP composites as main structural members has seen a resurgence. Bridges made entirely of FRP composite are now being installed, with asset owners recognising the associated benefits.

Within the UK the use of FRP composites for structural applications in the construction sector suggests high levels of growth, with the UK Composites Strategy 2016 (Composite Leadership Forum, 2016) estimating significant growth. In addition to this, there are numerous technological advancements (eg nanotechnology/fibre innovations) that will make FRP composites a much more attractive solution.

At present, there are minimal resources for the bridge engineer to refer to, with no recognised design standards to follow. However, Structural Eurocodes are in development and there are a number of guides from materials manufacturers. So, the intention of this guide is to help bridge engineers to understand FRP materials and how they can use them effectively in modern bridge construction.

Within the guide, the history of FRP bridges in the UK is discussed, together with some of the key learning points relating to FRP materials, the manufacturing process and the relevant design criteria. Sustainability is also an area identified, with recommendations made. The guide is intended to be a reference document for bridge engineers and asset owners. It is not a prescriptive design text/standard, although it does aim to highlight key lessons learnt by the industry to aid future applications, so engineers should be familiar with the content, and use the guide to help inform discussions with the supply chain and bridge owners.

I am pleased to introduce this guide, which has been collated from a range of industry and academic specialists. I would like to take this opportunity to thank them all for their contributions.

James Henderson CEng MICE BEng (Hons)

Chairman of Composites UK: Construction Sector Group

Technical Authority for Composites in Construction, Atkins

Acknowledgements

This guidance document was prepared under the aegis of the Construction Sector Group of Composites UK (formerly the Network Group for Composites in Construction – NGCC) and the names and organisations for the contributors are acknowledged next.

Authors

Lee Canning	Jacobs
John Drewett	Lifespan Structures
Neil Farmer	Tony Gee and Partners
Sue Halliwell	Composites UK
John Hartley	EXEL Composites
James Henderson	Atkins & Composites UK Construction Sector Group
Mark Hobbs	Premier Composite Technologies LLC
Stella Job	Composites UK
Sarah Kaethner	Arup
David Kendall	Optima Projects Ltd.
J. Toby Mottram	University of Warwick
Wendel Sebastian	University College London
Jon Shave	WSP|Parsons Brinckerhoff
Graham D Sims	National Physical Laboratory
Geoff Turvey	University of Lancaster

Project steering group

Neil Appleton	Parton Fibreglass
Brian Bell	University of Surrey (ex Network Rail)
Lee Canning	Jacobs
Andy Cross	Network Rail
John Drewett	Lifespan Structures Ltd
Simon Eves	Pipex Ltd
Neil Farmer	Tony Gee and Partners
Sue Halliwell	Composites UK
John Hartley	Exel Composites
James Henderson (chair)	Atkins
Mark Hobbs	Premier Composites
Sarah Kaethner	Arup
David Kendall	Optima Projects
J. Toby Mottram	University of Warwick
James Quinn	J Quinn Associates
Wendel Sebastian	UniversityCollege London
Jon Shave	WSP Parson Brinckerhoff
Graham D Sims	National Physical Laboratory
Gopan Srinivasan	Arup
Liesbeth Tromp*	Royal HaskoningDHV

Geoff Turvey	University of Lancaster
Pierfrancesco Valerio	Highways England
Steve Williams	Network Rail

*corresponding members

Funders

Network Rail
Highways England

Other contributors

Christian Scholze, Fibreline, and Martin Richardson, Lifespan for providing images.

CIRIA project team

Kieran Tully	Project director
Clare Drake	Publishing manager
Paul Beverley	Copy editor

Contents

Boxes

Figures

Tables

Glossary

For a description of many terms used in the polymeric composite industry, see Lee (1989).

Accelerator Substance that accelerates the chemical reaction between the polymer resin system and the curing agent.

Acrylic Thermosetting or thermoplastic polymer or copolymer of acrylic acid, methacrylic acid, esters of these acids, or acrylonitrile, sometimes modified with non-acrylic monomers such as the acrylonitrile-butadiene-styrene group.

Additives Term used for a large number of specialist chemicals that are added to resins to impart specific matrix properties, such as removal from processing mould, flame retardancy and ultraviolet (UV) protection. Known also as modifiers.

Adherend Component in an adhesively bonded connection or joint.

Adhesion State in which two surfaces are connected together at the interface by mechanical or chemical forces or interlocking actions.

Adhesive Substance – may be a polymer-based material – which when applied on mating surfaces is capable of bonding the two adherends together. An adhesive can be in liquid, film or paste form. There are structural and non-structural types of adhesive products.

Anisotropic Material having mechanical properties being directionally dependent.

Aramid fibre High strength, long-chain, aromatic polyamide synthetic fibre.

Aspect ratio In fibre technology, the ratio of length to diameter of a fibre.

Autoclave Closed vessel with an environment of pressure, with or without heating applied to an enclosed object that is undergoing a chemical reaction or other operation.

Balanced laminate FRP where the individual layers (or plies) are stacked so that there is a balance maintained of $+\theta$ oriented layers and $-\theta$ oriented layers at the same height from the laminate's mid-plane.

Binder Agent applied to fibre mat or preforms to bond the fibres before laminating or moulding. This term is used for the matrix that holds the FRP together.

Blistering A surface bump that grows because a pocket of acidic or air fluid develops within the FRP.

Bond Adhesion of one material surface to another, using an adhesive or other bonding agent.

Bonded connection Connection between two components (adherends) where surfaces are held together by means of an adhesive or another polymer material.

Brittle material When subjected to stress the material breaks without significant deformation (strain). The material fractures.

Bundle General term for a collection of essentially parallel filaments or fibres.

Carbon fibre Fibre type with low density and high strength and/or high modulus of elasticity. High strength and/or high modulus fibres are produced from organic materials such as polyacrylonitrile (PAN).

Catalyst Chemical substance (usually an organic peroxide) whose presence, in small quantity, can initiate and increases the rate of polymerisation when curing the resin matrix. A negative catalyst (inhibitor) slows down a chemical reaction.

Chaffing Low-level surface damage caused by an FRP material rubbing against another material.

Chalking Breakdown of the gelcoat for a release of a powdery, chalk-like appearance or deposit, as a consequence of poor application, UV or weather degradation.

Chopped strand mat Non-woven mat with short strands cut (about 50 mm long) from continuous fibre (or filament) strands and fairly evenly distributed and randomly oriented in a swirled pattern within the plane of the mat. The mat is held together by a binder.

Closed mould Two-piece mould that encloses the uncured FRP component and applies pressure and heat.

Cohesive failure Failure within the adhesive bondline and not at the interface.

Colemanite Borate mineral used in the non-sodium fibreglass industry for heat resistant glass fibres.

Component	Any element or member made of one of more FRP materials, with or without a core material.
Composite	Alternative term for FRP. In this publication, composite is a material comprising a polymer resin matrix reinforced by fibres or filaments (often of glass, carbon or aramid).
Connection	For design purposes it is the assembly of the basic components required to represent the behaviour during the transfer of the relevant internal forces and moments at the connection.
Contact moulding	Manufacturing process for FRP materials and components without application of external pressure and heat.
Continuous filament	A single small-diameter reinforcement (≤ 20 μm) that is flexible and indefinite in length.
Continuous filament mat	Non-woven mat with yarns or strands (of continuous fibres or filaments) fairly evenly distributed and randomly oriented in a swirled pattern in the plane of the mat. The mat is held together by a binder.
Continuous roving	Single or multiple strands of parallel filaments coated with sizing and wound into a cylindrical package. Rovings can be used to provide continuous reinforcement in woven rovings, filament winding, pultrusion, prepregs or contact moulding components. They may be chopped to produce a chopped strand mat.
Core	In sandwich construction, the core is the central part to which top and bottom FRP face sheets or skins are attached. Foams, honeycombs, woods (balsa) and cork are core materials.
Corrosion resistance	Ability of FRP material not to have degraded mechanical properties resistance immediately, or over time, on contact with environmental conditions.
Crazing	Fine cracks at or under the surface of the matrix material in the finished FRP component. Tensile stresses causing crazing may result from shrinkage or machining, flexure, impact, temperature or swelling changes.
Creep	Time dependent part of strain resulting from stress.
Cross-linking	Applied to polymer molecules, it is the creation of chemical links between the long molecular chains. It makes, in most thermosetting resins, one infusible three-dimensional (3D) super-molecule of all the chains. The higher the cross-linking density, the higher the material's modulus of elasticity and strength.
Cure	Process of hardening of a thermosetting polymer resin (by cross-linking of the molecular structure), often under the influence of heat energy.
Cure temperature	Temperature profile that the FRP is subjected to during the curing process.
Cure time	Time needed for liquid polymer resin to reach a solid state after the catalyst/hardener has been added and thoroughly mixed and initiation has progressed.
Curing agent	Chemical substance(s) added to a polymer mix to promote or control the curing reaction of the thermoset polymer resin.
Curing cycle	Schedule of time periods at specified conditions to which a reacting thermosetting material is subjected in order to reach a specified property level.
Cyanate esters	High performance polymer resins used for synthesis of thermosetting resins.
Debonding	Failure of an adhesive layer at the interface.
Degradation	Deleterious change in physio-chemical structure of the matrix or fibre reinforcement by exposure to heat (for thermal degradation), UV (for photo-degradation), oxygen (for oxidative degradation) or weathering.
Delamination	Separation of the layers of material in a laminate. This may be local or may cover a significant area of the component. It can occur at any time in the cure or subsequent life of the laminate and has a wide variety of causes. This mode of failure is linked to a relatively low through-thickness tensile strength.
Die (tool)	Steel mould that is either on- or two-sided and is either open or closed, in or upon which FRP materials are placed, with or without a core, to make the structural component.
Dimensional stability	Ability of a polymer resin part or other substance to retain the precise shape of the component on curing.
Disbond	Separation at an adhesive bondline in an adhesively bonded connection.
Drape	Ability of a dry/wet fabric to conform to an irregular shape of the component.
E-glass	Low alkali borosilicate glass that is the most widely used in fibres for reinforcing FRPs. The designation 'E' is for electrical.

Epoxy resins	Thermoset polymer resins that can be of widely different formulations, but which are characterised by the reaction of the epoxy group to form a cross-linked hard resin.
Fabric, woven	Generic reinforcement construction consisting of interlaced yarns or fibres, usually a planar structure. The warp direction of the woven fabric is taken to be the longitudinal (0°) direction, which is the direction of the principal load action.
Fabric, non-woven	Textile structure produced by bonding or interlocking of fibres (or filaments or both), accomplished by mechanical, chemical, thermal or solvent means, and combinations thereof.
Failure criterion	Function in stress or strain space which separates the failed state from unfailed states.
Failure index	Failure criterion predicts failure when the failure index in a laminate reaches a specified value which is ≤ 1.
Ferrule	Metallic insert with an outer diameter close to the hole diameter size through which a mechanical fastener passes to strengthen an FRP bolted connection.
Fibre	General term for a material in a filamentary form. Often, 'fibre' is used synonymously with 'filament', and it is the more common of the two terms used.
Fibre architecture	Design of an FRP component where the fibre reinforcement is oriented and layered in a particular way to achieve the desired laminate mechanical properties.
Fibre content	Quantity of fibre in the FRP material, usually expressed as the percentage volume or weight fraction in the FRP.
Filament	Single element of reinforcing material having small diameter and very long length. The length can be considered as continuous.
Filament winding	An automated composite process in which continuous filaments (or tapes) are covered with resin and wound onto a mandrel in a predetermined pattern design.
Fill (filling)	In a woven fabric, the yarn running from the long, outer, finished side edges, at right angles to the warp.
Filler	Relatively inert substance added to a polymer resin to alter its physical, mechanical, thermal, electrical or other properties or to lower cost. The term is often used specifically to mean particulate additives.
Finishing	Application of a coupling agent (sizing) to fibres to improve the bond between the filament surface and the resin matrix. Finishes can contain ingredients that provide lubrication to the fibre surface, thereby preventing abrasion damage during handling, or a binder that promotes strand integrity and facilitates packing of the fibres. Finishing is also known as sizing.
Flow coat	Application of resin containing wax in styrene that produces a hard surface to be sanded for a finished product. Also known as hot coat or sand coat.
FRP	Abbreviation for any fibre-reinforced polymer material or fibre-reinforced polymer composite.
FRP designer	Experienced professional engineer with specialist knowledge of FRP materials and structural design.
FRP properties	Properties of an FRP lamina, laminate, section or component.
Gel	State of a polymer resin that has set to a jelly-like consistency.
Gelcoat	Thin layer of unreinforced quick-setting resin on the outer surface of an FRP component. Used in moulding processes to provide an improved surface to the FRP product.
Glass fibre	Reinforcing fibre made by drawing molten glass through bushings. There are different types of glass fibres. E-glass is the dominant type of glass fibre.
Glass transition temperature (T_g)	Approximate mid-point of the temperature range over which the glass transition takes place. Below T_g the polymer resin is a brittle (glassy) material and above T_g it is a flexible (rubbery) material.
Gouge	Form of wear consisting of wide-groove deformations with FRP removal.
Hand lay-up	FRP manufacturing process in which a thermoset polymer resin and the fibre reinforcement layers are applied manually, either to an open mould or to a working surface in a number of successive layers.
Hardener	A (curing agent) substance or mixture of substances added to the polymer mix that it reacts with to take part in and promote or control the curing reaction.
Honeycomb	Lightweight cellular core material made from either metallic sheets or non-metallic materials and formed into hexagonal-shaped cells.

Hybrid	Resin system or fibre reinforcement system made from two or more different polymers or fibre reinforcement types.
Hybrid connection	Connection between two components where the surfaces are held together by a combination of adhesive bonding and mechanical fastening. Hybrid connection is also known as a combined connection.
Hygroscopic	For an FRP, its tendency to absorb and/or retain moisture from the air.
Impregnation	Process of thoroughly soaking the fibre reinforcement with liquid polymer matrix which saturates the voids and interstices of the reinforcement with the matrix.
Insert	Integral part of the FRP component consisting of metal or other material that may be moulded or bonded into position or pressed into the component after completion.
Interface	Surface between two materials (eg where there's contact between fibre, sizing and matrix). Effectively has no thickness.
Interlaminar	Descriptive term pertaining to some feature (eg void), event (eg fracture) or shear stress that exists or occurs between two adjacent FRP layers.
Interlaminar shear	Shearing action between two laminae in the plane of their interface.
Interphase	Region of nanometre thickness where the sizing and matrix combine and the matrix has different physical and chemical properties from the bulk matrix.
Intralaminar	Within the laminae of a laminate.
Isophthalic polyester	Unsaturated polymer resin prepared with isophthalic acid as the starting acid constituent.
Joint	Zone where two or more members are joined using connections of mechanical fasteners, adhesive bonding or a combination of both methods.
Junction	Interface region between individual panels in a thin-walled FRP component or structure having different mechanical properties to the intersecting panels.
Kissing bond	Usually an adhesive-bonded connection that holds little bond strength.
Lamina	Single layer or ply in a laminate of a number of individual layers of fibre reinforcement.
Laminate	FRP material formed from curing and consolidating one or more laminae, layers or plies of one or more fibre-reinforced polymer materials. The structural form is a relatively thin flat or curved plate or panel component having two dimensions considerably larger than the third (thickness) dimension.
Lap-joint	Joint made by overlapping two (thin-walled) components and forming a load-carrying connection between them.
Latex	Stable dispersion (emulsion) of polymer microparticles in an aqueous medium.
Layer	Synonymous with terms 'ply' or 'lamina' with the FRP material.
Lay-up	Fabrication involving the stacking of successive laminae or layers or plies.
Mat	Fibrous material comprising randomly oriented chopped or swirled continuous fibres loosely held together with a binder.
Matrix	Polymer resin system alone or a mixture that contains additives and/or fillers.
Mould release (agent)	Lubricant applied to the mould surfaces to facilitate release of the moulded component. It can be a chemical compound or a solid material such as a cellulose or plastic film.
Moulding	Forming of an FRP material into a solid form or a prescribed shape and size within a closed or open mould can be accomplished under pressure and heat. The term can be used to denote the finished component, ie a 'moulding'.
Non-destructive evaluation	Broadly considered synonymous with non-destructive inspection.
Non-destructive inspection	A process or procedure for determining the quality or characteristics of a material, part or assembly without permanently altering the subject or its properties.
Non-destructive testing (NDT)	Broadly considered synonymous with non-destructive inspection.
Open mould	Single-piece unenclosed mould having the component shape with one smooth surface.
Orthophthalic	Unsaturated polymer resin prepared with phthalic anhydride as resin the starting constituent.
Orthotropic	Having three mutually perpendicular planes of elastic symmetry, which are coincident with the geometric planes of symmetry.

Panel	Component having two dimensions considerably larger than the third (thickness) dimension (see also plate), which can have curvature (see also *Shell*).
Peel ply	Sacrificial exterior layer that is removed to create an improved surface for bonding to another component. Acts as a proactive layer to ensure that the surface remains undamaged and uncontaminated before the adhesive bonding process.
Phenolic resin	Family of thermosetting polymer resins made by reacting epichlorohydrin with bisphenol A and sodium hydroxide in dimethyl sulphoxide. Phenolic resins are chemically similar to epoxy resins.
Physicochemical	Dependent on the combined action of both physical and chemical processes.
Plate	Component or subcomponent having two dimensions considerably larger than the third (thickness) dimension (see also *Panel*).
Polyester	Usual term for an unsaturated polyester thermoset resin, which is capable of being cured from a liquid or solid state when subject to the right processing conditions.
Polymer	High molecular weight organic compound composed – be it natural or synthetic – of molecules characterised by the repetition of one or more types of monomeric units. Also known as a plastic.
Polyurathane	Resin produced by reacting a diisocyanate with an organic compound containing two or more active hydrogen atoms to form a polymer having free isocynate groups. Under the influence of heat or specific catalysts, the groups react with each other or with a compound containing active hydrogen, such as water or a glycol, to form a thermosetting resin.
Porosity	Volume fraction of the FRP material that is of air or other gases trapped within the total volume (see also *Voids*).
Post-cure	Additional application of external heat energy, usually without additional pressure, to complete the cure or improve mechanical properties or both. With certain resins, complete cure and the highest mechanical properties can only be achieved by exposure of the cured matrix, over a period of time, to higher temperatures than in the curing process for the FRP component.
Pot life	Length of time during which a catalysed thermosetting resin matrix retains sufficiently low viscosity for FRP processing.
Preform	Pre-shaped (dry) fibre reinforcement for a moulded FRP component.
Prepolymer	Refers to a monomer or system of monomers that has been reacted to an intermediate relatively low molecular weight state. A prepolymer is capable of further polymerisation by reactive groups to a fully cured and hardened high molecular weight state.
Prepreg	Factory-made lamina (layer or ply) of a reactive polymer resin matrix and reinforcing fibres (unidirectional, fabrics or mats).
Priming	Application of a primer, which is a coating applied to improve the adhesion or durability of a subsequent surface coating.
Pultrusion	Automated, continuous closed mould manufacturing process for thin-walled open and closed FRP shapes (or profiles or sections), having constant cross-sectional area in the direction of pultrusion.
Pulwinding	Composite processing method that combines pultrusion with filament winding.
Quasi-isotropic laminate	Laminate that approaches having isotropic properties in its plane by having a number of layers with specific orientations and lay-up arrangements. As an example, unidirectional laminae are often grouped using the four orientations of 0°, 90° and ±45°.
Reinforcement	Fibres that are added to a polymer matrix to form an FRP material with the required mechanical properties. Reinforcement types range from short fibres to continuous fibres, through to complex woven fabrics and stitched fabrics.
Resin	Polymer material with indefinite and often high molecular weight and a softening or melting range that exhibits a tendency to flow when subjected to stress. It can exist in solid, semi-solid or liquid state.
Resin system	Organic polymer or pre-polymer used as the base for the matrix to contain the fibrous reinforcement in an FRP material or as an adhesive. This organic matrix may be a thermoset or a thermoplastic, and may contain a wide variety of components or additives to influence 'handleability', processing behaviour and ultimate properties. In FRP materials the resin-based matrix is used to impregnate the fibres and bind fibres and layers of fibre together.

Resin transfer moulding	FRP manufacturing process in which a catalysed polymer resin is injected into a closed mould already containing the preform for the component.
Roving	Strands or bundles of continuous fibres with little or no twist along their length.
Runner	Channel in the FRP mould to assist matrix flow for complete fibre wet-out.
Sandwich construction	FRP structural form comprising lightweight core material to which two high strength FRP faces are adhesively bonded.
Scuff marks	Surface scratches characterised as white scrape marks on the FRP.
Shell	Structural element or component having two dimensions considerably larger than the third (thickness) dimension (see also *Plate*), which can be have curvature (see also *Panel*).
Shrinkage	Relative change in dimension of a dimension of a moulded component 24 hours after it has been moulded.
Sizing	Chemical solution coating applied to fibres (or filaments) during their manufacture to improve handling and protect from water absorption and abrasion. It lubricates the filaments and reduces static electricity.
Skin	Outer laminate layers in sandwich construction.
Stacking sequence	Orientations and lay-up arrangements of the laminae (or layers or plies) in the FRP laminate.
Stitched fabric	Textile fabric that also has fibre reinforcement in the out-of-plane direction.
Stop mark	Dull glossy surface band about 12 mm to 76 mm wide extending around the periphery of a pultruded shape.
Strand	Assembly of parallel fibres (or filaments), normally an untwisted bundle or assembly of continuous filaments used as a unit.
Stress relaxation	Time-dependent decrease in stress in a solid under given constraint conditions.
Stress rupture	Failure (by rupture) of an FRP material at a sustained tensile stress level that is considerably lower than the short-term ultimate tensile strength. Can be referred to as creep rupture.
Surfacing veil	Very thin mat, usually 0.18 mm to 0.51 mm thick, of highly filamentised non-reinforcing fibre. Present in pultrusion to enhance the quality of the surface finish, to block out the fibre pattern of the underlying reinforcement and to add ultraviolet protection and a moisture diffusion barrier.
Swelling	Volumetric change due to absorption of moisture, independent of thermal expansion.
Symmetric laminate	Laminate in which each lamina type, angle and composition is exactly mirrored about the mid-plane of the FRP material.
Tape	A prepreg of finite width consisting of resin impregnated unidirectional fibre reinforcement.
Thermoplastic	Polymer resin that softens each time it is heated and hardens when cooled.
Thermoset	Class of polymer that, when cured using heat, chemical or other means, changes into a substantially infusible and insoluble material.
Tow	An untwisted bundle of continuous filaments. Commonly used in referring to man-made fibres, particularly carbon and graphite fibres, in the FRP industry. Typically designated by a number followed by K, meaning multiplication by 1000 (eg 12K tow has 12 000 filaments).
Ultraviolet stabiliser	Any chemical compound added into the resin matrix mix to selectively absorb UV rays.
Unidirectional laminate	FRP material with all the continuous fibres aligned in a single orientation.
Vacuum bag	FRP manufacturing process in which the lay-up is cured under generated by drawing a vacuum in the space between the lay-up and a flexible sheet placed over it and sealed at the edges.
Vinylester	Thermosetting resin that is chemically similar to both unsaturated polyesters and epoxy resins.
Voids	Pockets of gas or near-vacuum air trapped within an FRP laminate (also porosity).
Warp	Longitudinally-oriented yarn in a woven fabric (see *Fill* and *Weft*), ie a group of yarns in long lengths and approximately parallel.
Water absorption	Ratio of mass of water absorbed by FRP to weight of dry (cured) FRP.
Wearing surface	Top layer on a footbridge or road bridge.
Weft or fill	Transversely oriented yarn in woven fabric.
Wet lay-up	FRP manufacturing process for making an FRP laminate by applying a liquid resin system while or after the reinforcement is put in place.

Wet-out	Complete wetting or saturation of the fibre reinforcement by the resin matrix.
Working life	Length of time an adhesive remains low enough in viscosity that it can still be easily applied.
Yarn	Generic term for strands or bundles of continuous fibres (or filaments), usually twisted for producing fabric reinforcements.
0°	Orientation of fibres, laminae or components that are aligned to the principal direction of loading.
±45°	Orientation that is 45° from the 0° and 90° orientation.
90°	Orientation that is perpendicular to the 0° orientation.

Abbreviations and acronyms

1D, 2D, 3D	One, two, three dimesion(al)
ABS	Acrylonitrile-butadiene-styrene
ACI	Advanced Composites Innovation (conference)
ACIC	Advanced Composites in Construction (conference)
ACCS	Advanced composite construction system
ACMA	American Composites Manufacturers Association
ACT	Advanced composite truss system
AFP	Automated fibre placement
AIP	Approval In Principle
ANSI	America National Standards Institute
ASCE	American Society of Civil Engineers
ASTM	American Society of Testing and Materials
ATH	Alumina trihydrate (flame retardancy additive)
ATL	Automated tape laying
BCSA	British Constructional Steelwork Association
BS EN	British version of the standard issued by CEN
BS	British Standard
BSI	British Standard Institute
BVID	Barely visible impact damage
CEN	Comité Européen de Normalisation
CFM	Continuous filament mat
CFRP	Carbon fibre-reinforced polymer
CNC	Computer numerical control (applies to cutting technology)
CNR	National Research Council of Italy
COSHH	Control of Substances Hazardous to Health
CPD	Contact pressure distribution
CSM	Chopped strand mat
DIC	Digital image correlation
EC	European Commission
EQU	Equilibrium load case
ESC	Environmental stress corrosion
EU	European Union
FAT	Fatigue failure
FE	Finite element
FEA	Finite element analysis
FRP	Fibre-reinforced polymer
FS	Finite strip
FST	Fire, smoke and toxicity
FVF	Fibre volume fraction
GBT	Generalised beam theory
GEO	Stability load case
GFRP/GRP	Glass fibre-reinforced polymer
HD	High density
HDT	Heat deflection temperature
HFSG	High strength friction grip bolts
HM	High modulus (fibre)
HS	High strength (fibre)

ICE	Institute of Civil Engineers
IEC	International Electrotechnical Commission
IM	Intermediate modulus
IPA	Infrastructure and Projects Authority
ISO	International Organization for Standardization
KTN	Knowledge Transfer Network
LCA	Life cycle assessment
LM	Low modulus
LRFD	Load and resistance factor design
MSDS	Material safety data sheets
NA	National Annex
NDE	Non-destructive evaluation
NDI	Non-destructive inspection
NDT	Non-destructive testing
PAN	Polyacrylonitrile
PEEK	Polyether ether ketone
PIC	Pultrusion Industry Council
PVA	Polyvinyl alcohol
RC	Reinforced concrete
RIFT	Resin infusion under flexible tooling
RTF	Rolling tyre facilities
RTM	Resin transfer moulding
SCRIMP	Seemann Composites Resin Infusion Moulding Process
SHM	Structural health monitoring
SLS	Serviceability limit states
SME	Small and medium-sized enterprises
STR	Structural load case
TCO	Total cost of ownership
TRL	Technology readiness level
UHM	Ultra-high modulus
UHMWPE	Ultra-high-molecular-weight polyethylene
UKAS	United Kingdom Accreditation Service
ULS	Ultimate limit state
UV	Ultraviolet
VARTM	Vacuum assisted resin transfer moulding

Notation

For the purposes of this guidance document, the following symbols apply. The notation used is based on ISO 3898:2013.

Latin uppercase letters

E	Adherend tensile modulus of elasticity in direction of P, and E_1 equals E_2
E_a	Modulus of elasticity of the adhesive
E_c	Through-thickness compressive modulus of elasticity of the core material
E_f	Skin modulus of elasticity in the direction of compression
G_a	Shear modulus of the adhesive
G_c	Shear modulus of elasticity of the core material
L	Overlap length of the bonded surfaces in the lap connection
P	Relevant representative value of a prestressing action or vertical cyclic load or load per unit width of the lap bonded connection
P_d	Net design force per unit width
P_{cr}	Critical elastic buckling load for the failure mode of shear crimping
S	Cyclic stress in fatigue
T_g	Glass transition temperature
V_X	Coefficient of variation

Latin lowercase letters

c	Depth of the core
d	Equal to $c + t_s$
$f_{t,d}$	Design tensile strength of the FRP material
t	Adherend thickness with t_1 equal to t_2 and of the same laminate
t_a	Uniform adhesive bondline thickness
t_s	Skin thickness

Greek lowercase letters

ε_{wr}	Critical elastic strain for failure mode of skin wrinkling
φ	Resistance factor
γ_e	Elastic adhesive shear strain
γ_G	Partial factor for permanent actions, also accounting for model uncertainties and dimensional variations
γ_M	Partial factor for a material property, also accounting for model uncertainties and dimensional variations
γ_{M1}	Partial factor for a material property, also accounting for model uncertainties and dimensional variations, for leading variable 1
γ_{M2}	Partial factor for a material property, also accounting for model uncertainties and dimensional variations, for accompanying variable 2
γ_p	Plastic adhesive shear strain at failure
$\gamma_{Q,1}$	Partial factor for a variable action for leading variable 1
$\gamma_{Q,i}$	Partial factor for variable action i
γ_P	Partial factor for prestressing actions
η_c	Total conversion factor
η_{cf}	Conversion factor for fatigue
η_{cm}	Conversion factor for humidity
η_{ct}	Conversion factor for temperature
η_{cv}	Conversion factor for creep
ν	Poisson's ratio of the adherend

ν_a	Poisson's ratio of the adhesive
σ	Average direct stress in the adherend
σ_0	Normal (peel) stress in the adhesive layer
σ_{0max}	Maximum peel stress in the bonded connection
τ_{0max}	Maximum shear stress in the bonded connection
τ_p	Plastic adhesive shear stress
ψ_0	Factor for combination value of a variable action
ψ_1	Factor for frequent value of a variable action
ψ_2	Factor for quasi-permanent value of a variable action

1 Introduction

1.1 BACKGROUND

1.1.1 Scope for new guidance

This guide is for the design, procurement, execution, monitoring and inspection of new bridges where components, in the form of shapes or systems, are made using fibre-reinforced polymeric (known as FRP in this document) composite material. The first known FRP bridge application occurred in the early 1980s, although this material has been used extensively for over 50 years in the aerospace, automotive and marine industries as a lightweight, durable structural material.

There has been some historical use of FRPs in the construction industry for cladding panels, pipes and components subject to aggressive environments. Over the past 25 years there has been an increasing exploitation for structural strengthening and for all-FRP or hybrid-FRP structures, including for bridges and iconic architectural pieces.

Considering the continuing deterioration of the UK bridgestock, there is an ongoing need to minimise disruption and have innovative solutions that are easy to install. It has been a natural progression to consider FRPs in the construction of new bridges, where appropriate to do so, and on a project-by-project basis. Initial pilot schemes have been developed and installed in the UK since the Aberfeldy footbridge in 1992, using some of the significant advantages that FRPs can provide.

Progress in the uptake of FRPs for bridge engineering has been partly restricted by the lack of suitable design standards and guidance for the use of these materials to enable technically efficient and economic design. The structural material of FRP was not covered by the first generation of Eurocodes that were implemented in the UK in 2010. In the meantime, the construction industry requires an acceptable and credible guidance document for designers, based on the most recent technical and practical developments and on end-customer experience to facilitate the use of FRP components in FRP bridge engineering.

This first edition document is intended to facilitate the design of FRP bridges and has the support of all the leading consultants, suppliers, clients, contractors and universities involved in this sector of the industry in the UK. All of these groups have been represented among the contributors to the writing of this guidance through their time, experience, expertise, understanding and knowledge.

1.1.2 Guidance objectives

This guide is intended to provide information for all stakeholders engaged in the education, design, fabrication, maintenance, ownership and checking of FRP bridges, and it will provide useful guidance for other civil structures with FRP components. It will also be useful to other members in the supply chain, from material suppliers to bridge owners, in providing a general awareness of the main challenges and benefits in using FRPs, the market opportunities and scale, and the contrast with conventional bridge structural materials.

Chapter 2 reviews the historical development and application of FRP bridges and the reasons for their development and use. A wide range of bridge applications are briefly described, together with typical advantages and disadvantages associated with FRP bridges. The lessons learnt from executing each new project are helping to continually modify working practices, enabling the UK to have the knowledge and understanding to classify FRPs as a conventional structural material. Technical information locations for case study examples are given in **Appendix A1** where a number of UK bridges are listed.

Chapter 3 provides advice on the conceptual design of FRP bridges. The primary bridge forms, and how particular FRP types and composite manufacturing processes may suit these forms, is briefly discussed. The way that design decisions can affect the choice of FRP shape and/or system is highlighted, as these may not always be apparent due to the novelty of FRP bridges.

Chapter 4 looks at the constituent and FRP material types, their mechanical properties for design and the composite manufacturing processes currently available in the market. It is recommended that users of this document be aware of the full range of composites and manufacturing processes for economic FRP component or structure design.

Chapter 5 provides structural design guidance based on up-to-date publications, research outcomes and application feedback. It gives guidance covering the range of analysis methods and structural resistance calculation approaches that are well known within the bridge community, but includes some important aspects related to the orthotropic nature of using FRPs, such as their relatively low material stiffness in some cases, the use of sandwich construction and methods of connection. The chapter provides guidance on the determination of partial material factors for limit state design (BS EN 1990:2002+A1:2005) and design-by-testing.

Chapters 6 and 7 consider practical aspects ranging from procurement, fabrication and installation, through monitoring and inspection, to low-carbon design, demolition and recycling. It is recommended that all users familiarise themselves with these aspects, as they have a significant effect on achieving a successful FRP bridge application. This is, in part, due to the relatively untested interface between FRP suppliers/manufacturers and civil engineering clients and contractors, the need for greater design effort compared to conventional structural materials, and the primary reliance on quality workmanship in forming robust structural connections and joints.

Chapter 8 covers sustainability issues that are of particular relevance to designers because the expected low footprint associated with FRP components and the minimal maintenance requirements are important factors for choosing this structural material.

1.1.3 Design guidance flow chart

A flow chart for how to use this guidance is presented in **Figure 1.1**. The process starts with the question *"Is an FRP bridge appropriate and sustainable?"*, which requires use of the information and guidance in **Sections 2.1 to 2.3 and Chapter 8**. The process then covers decisions on structural form, to establish basic requirements and principal dimensions, choice of FRP materials and composite processing method(s).

Analysis and iterative design guidance for structural capacity and serviceability considerations of components and/or structures are given in **Sections 5.2 to 5.4**. Guidance for the design of connections and joints is given in **Section 5.5**. The preparation of technical specifications, procurement and certification is covered in **Chapter 6**. Guidance is presented in **Chapter 7** for long-term inspection, monitoring and maintenance requirements.

This guide also provides additional support to the engineering team on an FRP project by having a recommended Approval in Principle (AIP) document in **Appendix A2**. In this guide the word 'designer' is used to represent the team of engineers who are responsible for the structural engineering design works.

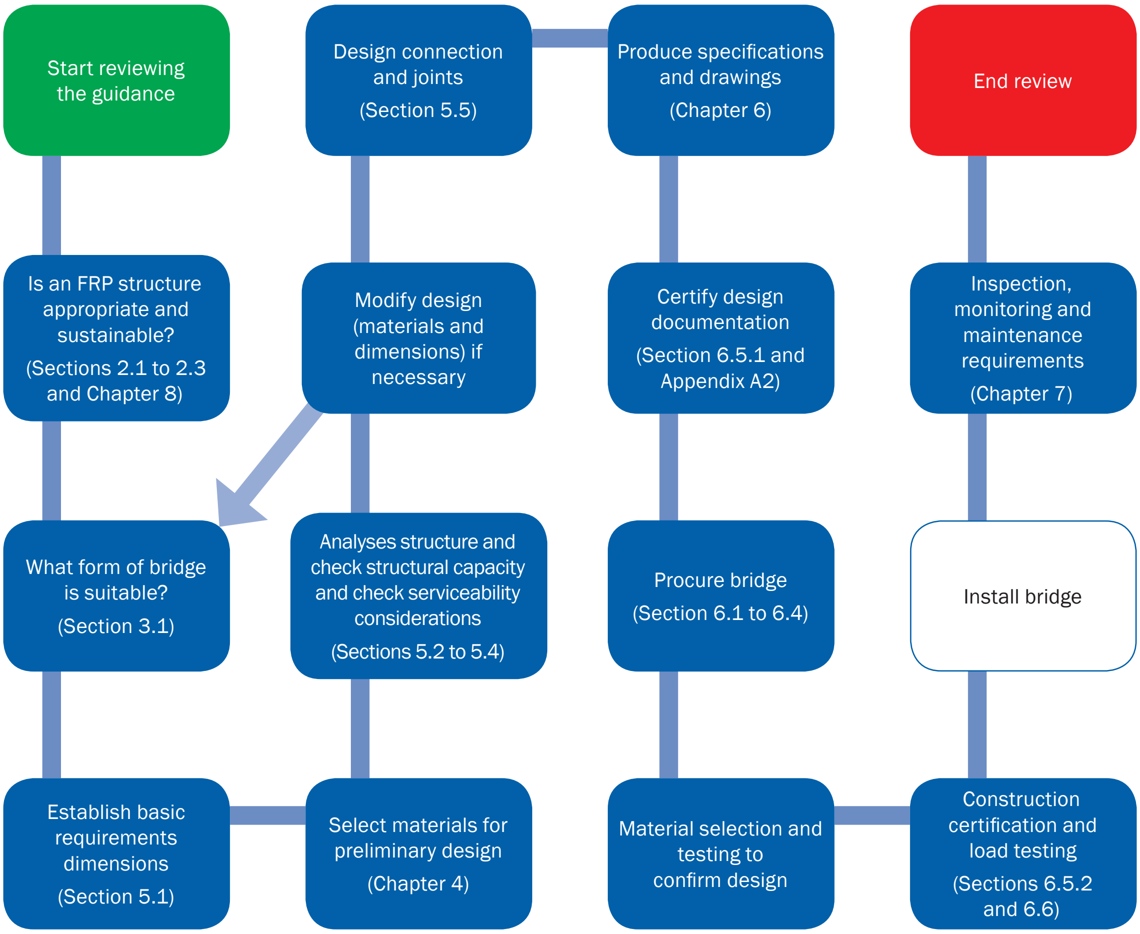


Figure 1.1 Flow chart for how to use the guidance to designers in Chapters 2 to 8

2 Background to FRP bridges

The use of FRP in infrastructure solutions and specifically bridges presents the engineer with a number of key benefits over traditional materials:

- **Durability**. FRP is corrosion resistant with exceptional resistance to acids, salts and alkalis.
- **Weight reduction**. These materials offer significant weight reduction, with a high strength to weight ratio.
- **Design flexibility**. FRP composites can be fabricated into virtually any shape.
- **Insulator.** Glass fibre is an excellent insulating material.

These unique selling points for FRP composites have resulted in an upturn in the market, where the use of advanced materials can provide significant life cycle benefits.

This chapter reviews the historical development and application of FRP bridges and explains the reasons behind this. A wide range of bridge applications are briefly described together with typical advantages and disadvantages associated with FRP bridges. Lessons learnt from executing these projects (challenges and successes) are summarised.

In the UK, the market for FRP bridges is growing significantly, with a number of key asset owners requesting FRP structures, which are now considered to reduce future maintenance burdens. Growth in this sector is envisaged, as has been illustrated in The *UK 2016 Composites Strategy* by the Composites Leadership Forum (2016) following consultation within several industry sectors, including the construction sector.

The strategy describes growth prospects and the means to achieve them, with the construction sector and FRP bridges in particular being one of the areas of focus. Among other growth-promoting factors, further development of skills and training and regulations, codes and standards are proposed to enhance the choice of FRPs for components and structures in construction, and this guide fits within this UK strategy.

2.1 BRIDGE OWNERSHIP

The development of FRP bridge technologies has been driven primarily by the pressures that infrastructure owners face in managing their bridge stock. These pressures include:

- ageing bridges reaching end of their design and/or serviceable working life
- increasing traffic load and intensity
- reductions in maintenance funding
- political resistance to lengthy disruption of transport routes caused by civil engineering works.

Simultaneously, owing to the maturity and historical track record of conventional structural materials (steel, concrete, steel and concrete composite and timber), the technical and economical limits of using steel or concrete in bridges are being reached.

In today's business landscape, the infrastructure market is finding the argument for composites, as a material of choice, more compelling than ever. Bridge owners and design engineers are looking for ways to achieve cost savings through longer product life cycles, minimise the need for maintenance and solve unique bridge challenges. With the industry's increasing stress on life cycle costing the focus is moving ever more strongly towards the use of FRP.

Furthermore, in recent years the need to move towards a low carbon economy has been high on the UK political agenda, and the positive role that new transport infrastructure can play is stated in guidance by the IPA (2016). Infrastructure owners are being challenged from both technological and political angles, and the overall portfolio of FRP components and structures for bridge engineering is helpful because it supports the aim of satisfying the HM Government (2013) action plan to achieve sustainable infrastructure.

The UK Government is building long-term partnerships with sectors that can deliver significant growth. Construction is one of those sectors and the government has been working with people across the construction industry to develop a long-term vision. The result is a joint strategy that sets out how industry and Government will work together to put Britain at the forefront of global construction over the coming years. Within this joint strategy there are some challenging objectives for the construction sector. These objectives are briefly listed below with commentary made relating to how FRP composites can help to achieve some of the goals.

Lower cost: 33 per cent reduction in initial and whole-life cost

Bridges realised in FRP composites have significantly improved long-term durability characteristics when detailed appropriately. A whole-life cost reduction significantly more than 33 per cent should be possible. Initial costs for the materials and manufacturing are generally higher (assume 5 to 10 per cent for a footbridge and possibly 20 per cent for a road bridge, but these cost increases do not factor in the potential time, labour and plant savings. For instance, most structures are built off site and can be lifted into location using an excavator as opposed to a crane. When assessing the initial cost there are associated construction savings that should also be taken into account. In many instances, these savings far outweigh the additional initial material costs.

Faster delivery: 50 per cent reduction in the programme

Almost all FRP structures are built off site and brought to site fully fabricated. So the time to install can be as small as a few hours as opposed to what could be weeks or months. FRP bridges have the potential to achieve much greater reduction in programme – more than the 50 per cent target noted in HM Government (2013).

Lower emissions: 50 per cent reduction target

The unique selling point of FRP composites is the materials durability and ability to be manufactured off site. These characteristics play a large role in the reduction of emissions, so that FRP structures can help meet the target set in HM Government (2013). Further information is included in **Chapter 8** relating to the specific sustainability aspects of FRP composites, but a simple important characteristic illustrated is the fact that a large percentage of emissions relate to traffic queuing due to temporary traffic management operations during maintenance intervals.

Improvement in exports: 50 per cent increase

At present, the FRP bridges market in the UK is slowly but steadily growing. At present, the UK is importing technology from other countries, such as the Netherlands and North America. However, one notable aspect is that the sector is seen as one with significant growth potential, and a number of steel manufacturers and other small and medium-sized enterprises (SMEs) are mobilising and investing in plant and equipment. So, the UK has the infrastructure (catapults and significant research and development centres) and the capability to actually become an exporter of technology. To aid in the development of businesses to meet this challenge a host of central government funding streams are available through bodies such as Innovate UK and the Knowledge Transfer Network (KTN). So, increasing UK exports will be possible once the local market becomes stronger.

Smart construction and digital design

The UK has a world-class science and research base, which supports the development of innovative solutions in a number of priority areas for construction. HM Government (2013) recommends that the industry should invest in smart construction and digital design while also doing more research and innovation.

FRP bridges (and other pieces of FRP infrastructure) can play a role in providing a portfolio of smart self-sensing infrastructure. The nature of composites is such that it is relatively easy to add and protect fibre optic sensing within structures such as FRP bridges. So it is possible to have smart bridges that can give the asset owner much improved operational data to allow more intelligent decisions to be made through the use of 'advanced materials'.

2.1.1 Asset management considerations

In assessing the financial viability of bridge solutions the designers should consider not only the initial fabrication cost but also the estimated life cycle costs to derive a figure to indicate the total cost of ownership (TCO) of the associated bridge asset. TCO is an estimate of the outturn construction cost combined with all other life cycle costs, assessing the 'cradle to grave' life cycle scenario.

The TCO cost model assesses the following cost categories:

1. **Acquisition cost (A)** – often includes the unit price, warranty, transportation, design and certification costs, installation and commissioning costs, project management costs and land acquisition costs.
2. **Operational and maintenance cost (B)** – typically includes all labour, preventative and corrective maintenance, refurbishment, parts replacements, materials and consumables, training, upgrading, extensions, plant and traffic management.
3. **Disposal cost (C)** – decommissioning, uninstallation, cleaning, disposal and waste management.
4. **Salvage cost (D)** – revenue from selling any recycled materials.

Box 2.1 Total cost of ownership

Indicative costs assuming 15 m footbridge 2 m wide (120 year design life)			FRP footbridge £	vs Steel footbridge £
A	Acquisition cost (£)	Design and certification	12 000	9000
		Product fee	100 000	70 000
		Transportation	3000	5000
		Install/commission	3000	6000
B	Operational cost (£)	Inspections (GI and PI)	108 000	180 000
		Inspections (SI)	24 000	80 000
		Coatings	30 000	240 000
		Joints	20 000	20 000
		Surfacing	25 000	25 000
		Major maintenance	Nil	20 000
		Traffic management	54 000	86 000
		Project management	20 000	30 000
C	Disposal (£)	Decommissioning	25 000	25 000
		Disposal	10 000	5000
D	Salvage (£)	Materials recycling	Nil	–5000
		Total cost of ownership	***434 000***	***796 000***

The TCO of an asset can be expressed by a simple formula:

TCO = (A) + present value (B) + present value (C) – present value of (D)

where A equals the acquisition cost at the present moment and B, C and D are computed as present values to reflect the current worth of future sums of money. The best opportunities for achieving significant cost reductions come at the early design concept stages (feasibility) where significant changes to the life cycle strategy can be made for the least cost to achieve maximum benefit from decisions taken.

Applying TCO in asset management is important and useful to organisations looking to measure the costs of owning an asset. It also supports one of the fundamental concepts in asset management practice, which is to have a long-term strategic approach in managing assets. A simple TCO comparison exercise is described here for reference.

From review of the cost exercise, some indicative figures are given to enable comparisons to be drawn. Each site will have varying requirements with different access needs, so variance in these figures will occur for different site topographies. However, it can be observed in general that the initial cost of the FRP footbridge is higher, but the life cycle maintenance and management costs are much less. The cost of coatings and the need for ongoing investigations and interventions are the key differentiators. FRP bridges can be shown to have significant advantages during their life cycle compared to traditional materials. However, these advantages will only be realised if the bridges are designed using the best methods and details, which have been developed over time from the lessons learnt. Note that the guidance provided here is intended to help designers make good decisions relating to the structural form and materials used to enable strong resilient structures to be put into service.

2.2 HISTORY OF FRP IN BRIDGES

The earlier and successful development of FRP applications in other industries, such as aerospace and marine, provided impetus and practical examples of what can be achieved. Significant research on FRPs in civil engineering first occurred in the 1960s in Europe, America and South-East Asia. This research focused on using FRPs for cladding (ie non-structural or lightly loaded structural elements), and then for strengthening of existing structures. In the 1970s and 1980s research and development began on the use of FRPs for primary load-bearing structural components in bridge engineering, and was promoted by large-scale state-funded programmes in America to facilitate the replacement of obsolete road bridges.

Figure 2.1 FRP edge beam strengthening (courtesy Atkins)

Although it is difficult to be sure about the first FRP bridge application, significant public FRP bridge structures were constructed in China (20 m span road bridge) and Bulgaria (10 m span road bridge with internal steel frame) in the early 1980s (Hollaway and Head, 2001). Both of these one-off applications used labour-intensive, low-technology composite manufacturing processes, such as hand lay-up (a manual method introduced in **Chapter 4**). Other FRP pedestrian and road bridges were then constructed sporadically up to the 1990s when, as Keller (2003) reports, significant and consistent growth occurred in FRP bridge applications. There were a number of important applications across the globe around this time and some of these are described as follows.

Several case studies of FRP bridge-type projects executed in the UK from 1992 to 2016 are listed in **Appendix A1**. The summary of each study (available online) has, where known, the following information:

- date of project
- span
- where FRPs are used and why
- design details
- materials
- client
- performance in service
- project partners
- key publications.

Some further pertinent information is given here.

Aberfeldy footbridge, installed in Scotland in 1992, was a major step forward in large-scale application of FRPs in bridge engineering, and with a main span of 64 m is believed to still be the longest span FRP bridge in the world. The bridge is a cable-stayed design providing access between two parts of a golf course, and makes extensive use of pultruded cellular glass FRP construction system for the bridge deck, parapets and support frames. The cables are of aramid fibre, being the first known application of this type of fibre for this type of structural element. The design, construction and in-service performance of this structure is well documented by Burgoyne and Head (1993) and Cadei and Stratford (2002), and after 20 years of service by Stratford (2012).

Figure 2.2 Aberfeldy footbridge (courtesy Dr T Stratford)

This first footbridge application in the UK was followed by the first road bridge application at Bonds Mill lift bridge, installed in 1994 in Gloucestershire (Burgoyne, 1999). The 8 m span bridge provides access across a canal to a private industrial estate and made effective use of the lightweight nature of FRPs to ease installation and the capacity of the lifting mechanism. The same pultruded cellular FRP system was employed for this bridge as was used at Aberfeldy footbridge, and showed the adaptability of this advanced composite construction system (ACCS). To provide resistance to wheel loading at the surface of the deck, two layers of the cellular FRP shape in orthogonal directions were used, and the cellular voids were filled with structural foam developed for the project. The same cellular system has been used for permanent enclosure of bridges in the UK (such as at Tees viaduct in Middlesbrough and at Belvedere bridge in London). The bridge enclosure application at Tees viaduct was the first use of ACCS installed in 1998, and is the reason for its invention and development.

The first FRP road bridge in North America was installed in 1996 over No-Name Creek in Russel Kansas (Zhou *et al*, 2007). The bridge spans 8 m and comprises a sandwich structural deck having glass FRP laminated skins and a vertical corrugated FRP core. Following this application many further FRP road bridges and deck replacement schemes were completed in North America. These applications have used a wide range of forms and composite manufacturing processes, including hand lay-up, resin infusion, filament winding and pultrusion, which are introduced in **Section 4.4**.

Figure 2.3 Halgavor footbridge (courtesy Highways England)

The Kolding bridge, installed in Denmark in 1997, was the first FRP bridge over a railway (Braestrup, 1999). The cable-stayed footbridge spans 40 m and was manufactured from off-the-shelve pultruded FRP shapes, with the cables of box section. The structure was design to carry a snow-moving vehicle.

Following the earlier applications in the UK, Halgavor footbridge was installed in 2001 and comprised a 47 m span suspension bridge over the A30 in Cornwall, using resin-infused glass FRP decking (Firth and Cooper, 2002). The main cables are of galvanised steel. This was the first use in the UK of FRP components not manufactured by the pultrusion process.

The West Mill bridge was the first FRP public highway bridge in the UK and was installed in 2002 (Luke *et al*, 2002). The 10 m span bridge crosses a river in Oxfordshire and comprises a bespoke pultruded FRP deck supported on FRP beams manufactured by a combination of pultrusion shapes and resin infused plates. For the 225 mm deep deck a new bespoke shape for road decking was pultruded (Fiberline Composites, 2016). An extensive monitoring system was built into this bridge and results from load tests have been reported widely (Canning, 2012a).

Installed in Fredrikstad, Norway, in 2003 was a 60 m span FRP lifting footbridge. This was the first major FRP lifting bridge in Europe, and essentially comprises a moulded glass FRP box beam with internal stiffeners (Anonymous, 2003).

Two multi-span road bridges, with individual spans of up to 15 m using hybrid FRP box-girders (manufactured by a hand lay-up method of wrapping fibre prepregs (around either a stay-in-place polyurethane mould or a reusable steel mould) with conventional reinforced concrete (RC) decks were installed in Spain in 2004 and 2007 (Hurtado *et al*, 2012). A similar hybrid FRP box-girder solution was used for two footbridges in the Canary Islands and Spain (at 24 m and 44 m span, respectively). When executing the second project a change was made that the two FRP structures were manufactured using the resin infusion process based on experience gained and lessons learnt from the Spanish road bridges. The first FRP road bridge owned by the Highways Agency (now Highways England) was Mount Pleasant bridge over the M6 motorway, near Garstang in Lancashire. The bridge comprises two spans each of 25 m having a deck formed of asset bridge deck shapes that are supported on two steel plate girders (Fiberline Composites, 2016). Each span, weighing in at 100 tonnes, was prefabricated on the hard shoulder and lifted into position during an overnight closure of the M6 motorway. Again, an extensive monitoring system was installed in 2006, and results from load tests have been reported by Canning (2008). A similar integral bridge of 21 m span, comprising the same FRP deck system supported on steel plate girders, was installed in Friedberg, Germany, in 2008 (Knippers and Gabler, 2008).

Following a number of FRP bridge applications in the UK, Network Rail became interested in the potential benefits of FRP bridges for minimising disruption to the operation railway (both during installation and by minimising the need for maintenance over the design working life). An early application over a railway in the UK was the St Austell footbridge, installed in 2007 (Shave *et al*, 2010), which used the same FRP cellular system (ACCS) as in the bridges at Aberfeldy and Bonds Mill, and comprised three spans totalling 26 m. Owing to the lightweight nature of the bridge, in-service monitoring provided direct measurements for dynamic train-buffeting effects. The FRP Launder aqueduct was installed in 2007 over the Chiltern railway line, south of Banbury, the structure again being fabricated from the same pultruded FRP cellular system.

Figure 2.4 St Austell footbridge (courtesy Network Rail)

Another early adoption is for the Standen Hey bridge, installed near Clitheroe in 2007 and spanning 10 m over the railway near Blackburn, providing local farm access (Dawson and Farmer, 2009). This project used FBD600 asset bridge deck shape (Fiberline Composites, 2016), but further minimised weight by using two bonded layers of the shape spanning longitudinally, effectively forming a voided deck. A similar concept was used in 2005 for a 6 m span FRP road bridge in Klipphausen, Germany, but only using a single layer of GFRP deck. The standard way to employ the FRP deck is to replace a 200 mm deep concrete slab by a single layer spanning transverse over girders spaced at two to three metre centres.

Figure 2.5 Mount Pleasant bridge (courtesy Highways England)

The Network Rail application in 2009 for a footbridge, cantilevered out from the exiting timber railway line bridge over the River Leri, near Borth in Wales, is a world-first, because the method of connection is adhesive bonding for the joints in the truss structures fabricated of standard pultruded shapes. The only mechanical fastening is the bolting to connect the 11 prefabricated modules, of up to 12 m in span, to the ground or timber bridge.

The Bradkirk footbridge was installed over a railway in 2010. The bridge is located in Lancashire and comprises two 12 m spans. This project represents a significant development because it was the first major application in the UK to use a vacuum curing manufacturing process, creating a very lightweight three-dimensional (3D) FRP structure. A similar moulding method was used for the Halgavor footbridge, although only for the FRP deck. The majority of other applications worldwide have used pultruded FRP standard shapes or bespoke FRP component systems. Similarly, to the footbridge of St Austell, monitoring at Bradkirk was undertaken to measure dynamic train-buffeting effects (Santos and Mohan, 2011).

The replacement of the Dawlish footbridge in 2012 (Kendall *et al*, 2012) is an example of the combined use of pultruded shapes and moulded FRP components. This all-FRP footbridge replaced a badly corroded Grade II listed Victorian metallic footbridge, and was chosen for maximum durability in the very severe coastal environment. The bridge form comprised U-frame girders with GFRP roof and stairs. The Grading II listing meant that the new bridge had to look as similar as practical to the old metallic bridge, and aesthetic considerations necessitated the inclusion of features such as dome-headed bolts to look like rivets.

Figure 2.6 Dawlish Station footbridge (courtesy Pipex PX)

Purfleet footbridge in 2013 replaced a timber footbridge in Kings Lynn. The original concept was a steel footbridge, but an alternative hybrid material footbridge submitted at tender stage was the most competitive. The deck is moulded FRP and the handrails are of stainless steel. The bridge was delivered to site complete with handrails and surfacing and installed within an hour.

FRP components have been used in new railway bridges. A hybrid beam system, using FRPs, concrete and high-grade steel, was tested in North America in 2008 for heavy-duty railway bridge applications. Further applications of this technology have been used in Illinois for a 17 m span road bridge (Hillman, 2012). Two railway decking schemes have also been undertaken in the UK since 2009. At the Calder viaduct, the scheme was installed during railway closures over Easters 2009 and 2010 (Canning and Speight, 2009). At the Rubha Glas viaduct the installation was over a weekend railway closure in 2011 (Canning, 2012b). In both schemes the FRP deck system was designed for full derailment loads and replaced deteriorated timber decking on metallic bridges.

The next FRP road bridge application in the UK is Moss canal bridge, installed in 2011 (Canning, 2012c, and Clapham *et al*, 2013). This bridge deck replaced an existing 9 m span portal frame RC deck and used the largest available pultruded carbon-glass FRP shape worldwide (a double web beam approximately 900 mm deep by 450 mm wide). This approach minimised the amount of fabrication work and installation cost by taking advantage of lightweight FRP materials to allow reuse of the existing substructure.

A good example of exploiting the advantages of freedom in geometry, corrosion resistance, and low weight when using both glass and carbon FRPs is Pont y Ddraig (known as Dragons Bridge) over Foryd Harbour in Rhyl, North Wales. The bridge was constructed in 2013 and comprises two bascule spans formed from resin-infused FRP decks with a central stainless steel tower and lifting cables (Hobbs, 2014). The FRP decks have a complicated geometry and are curved in both plan and elevation and split into two routes around the central mast, each deck spanning 32 m. Carbon plates are used as local stiffeners in the span direction of the two lifting structures.

Figure 2.7 Pont y Ddraig footbridge (courtesy Gurit)

Mapledurham footbridge, installed in 2015, is also an example of a resin-infused FRP deck. The 13 m span bridge was fabricated as a single unit with glass FRP skin and foam core, forming a sandwich system. The lightweight prefabricated features of the bridge allowed transportation to site by barge and installation within a single day.

Figure 2.8 Church Road bridge (courtesy Atkins)

Another FRP road bridge, which is an evolution of the form at Standen Hey bridge, is Church Road bridge in Frampton Cotterell, Gloucestershire. The bridge comprises a bonded pultruded cellular glass FRP deck system spanning longitudinally (FBD600, Fiberline Composites, 2016), with additional stiffening from glass FRP box sections and carbon FRP plates. The design was specifically developed to minimise fabrication and material cost. The entire FRP deck area of 9 m long and 13 m wide weighs only 20 tonnes without parapets and surfacing.

At the Thornaby railway station the existing footbridge (Thornaby station footbridge) was to be replaced. An FRP bridge deck was used to replace a steel deck, resulting in considerable weight savings. These savings ensured that the new structure was significantly lighter than the previous bridge. This lightweight solution ensured that the loading on the existing abutments and south pier was significantly reduced, providing assurance that the existing Victorian substructure could be retained. Being able to sustainably reuse the existing masonry supports saved the project more than £200 000 and represented excellent value for the client. The use of FRP promoted reduced maintenance benefits in providing a durable corrosion-free material solution. Heat-deflecting phenolic plates were also installed to ensure that heat emanating from diesel and steam trains would not interfere with the FRP performance.

Figure 2.9 Thornaby station footbridge (courtesy Atkins)

Also in 2015, East Sussex County Council decided to use an FRP composite footbridge to replace the existing timber bridge in the village of Sedlescombe. The decision to use FRP was made on the basis that it had a lower whole life cost, was lightweight, quick to install (minimising traffic disruption), with a design life of over 60 years and minimal maintenance. The footbridge was designed with an FRP composite deck and powder coated steel parapet. The bridge was delivered complete with parapet and non-slip surfacing and it took the contractor an hour to install. The FRP bridge was significantly lighter, weighing only one tonne, where the original bridge weighed four tonnes – reuse of the existing substructure was possible. The bridge won an Institution of Civil Engineers engineering excellence special award for Environment Engineering and Sustainability in 2015.

During severe storms on Christmas Eve 2015, the Dover seawall in Kent, UK, together with 250 metres of track, collapsed. The devastation was considerable, and this major coastal rail line and steel footbridge were subsequently condemned. As part of a £39.8M reconstruction project a replacement FRP composite pedestrian footbridge was designed and manufactured. The footbridge was a hybrid of pultruded and resin-infused components for optimum strength and aesthetics. Components consisted of two 14.5 m long sections and connecting landing and staircase, all built off site. The completed structure measured an impressive 31 m × 2.415 m wide × 3.372 m high, and was designed using advanced laminate finite element analysis (FEA) supported by hand calculations and testing. All designs had to be fully compliant with Network Rail's rigorous standards for footways situated over live railway tracks, together with Category III checking by a third party before acceptance by Network Rail.

Figure 2.10 Sedlescombe footbridge (courtesy CRL)

A number of FRP footbridges have been designed and installed in the UK. The design and installation of Bird Riding footbridge (15 m span) and East Row footbridge (16.7 m span) was completed in 2016. Both structures were manufactured using the resin infusion process. At Bird Riding, access to the remote location meant that installation methods needed to be considered, and the lightweight nature of the FRP

Figure 2.11 Dover footbridge (courtesy Pipex PX)

deck allowed the bridge to be lifted into position using tracked mechanical excavators. The solution at the East Row footbridge had to consider that the area is designated as a conservation area, and care had to be taken to match the aesthetics of the new bridge to the surrounding areas. The new FRP bridge deck was 16.7 m long and 3 m wide with an aluminium parapet attached to the outside edge to match existing hand railings used along the walls for the Beck. The use of an FRP bridge was particularly suitable due to the exposed marine environment and the rapid installation, reducing disruption in the area. More recently, in 2017, a new 7.5 m long × 2 m wide footbridge (deck replacement) for the Hilly Fields footbridge was designed. To alleviate flood conveyance concerns a thinner deck was provided which allowed the bridge to be raised 300 mm above the 100 year flood level. The existing abutments were used, with only simple modifications.

The applications introduced here are outlined in more detail in the reports referred to in Appendix A1, highlighting the range of bridge forms, spans and composite manufacturing processes for FRP bridge engineering. Two particular aspects are relevant to all of these FRP bridge applications: their light weight (sometimes only a quarter of the weight of equivalent conventional structural material solutions), and the rapid speed of installation.

Figure 2.12 East Row footbridge (courtesy Lifespan Structures)

It is generally recognised, and supported by accelerated testing, that FRP materials should be more durable than steel, concrete and timber. Achieving sustainable construction in a low carbon economy is a strong argument for having bridge components or structures of FRP. The ultimate proof of this current understanding will be the actual performance of the first and second applications over the long design working lives of civil engineering works.

2.3 ADVANTAGES AND DISADVANTAGES

All structural materials have their advantages and disadvantages, and this holds true for FRP composites. FRP bridges have technical advantages and disadvantages related to the basic material property portfolio, but also practical aspects due to the lack of experience and historical precedence in the civil engineering sector.

Technically, the fundamental advantages of FRPs are their low density (relative to material strengths and stiffness) and resistance to corrosion. Laminate density will vary depending on the fibre reinforcement and matrix constituents (see **Chapter 4**), but the density of glass fibres is 1700 to 1900 kg/m^3, or approximately a quarter that of structural steel. Reinforcing with carbon fibres will give structural laminates with lower densities. If the FRP structural form is of sandwich construction the density will be even lower, and is dependent on the design detailing.

FRPs (and the fibre and matrix constituents) are not completely inert, but they avoid the main deterioration mechanisms of corrosion with steel and RC and of rotting with timber. FRP also offers other advantages such as prefabrication, whereby large, relatively lightweight, components/assemblies/structures can be easily transported and installed with the minimum of site disruption and cost. FRPs, by their anisotropic nature, provide the engineer with the freedom to optimally vary the mechanical/structural properties to match the load paths, and this tailorability and flexibility with FRP materials is discussed in **Chapter 4**.

The relative weight of an FRP bridge compared to a steel or concrete bridge is not directly related to material density owing to the differing material properties and miscellaneous items such as parapets, fill and surfacing. Experience has shown that the weight of a glass FRP bridge can typically be 30 to 50 per cent that of an equivalent steel bridge (or 25 per cent that of an equivalent concrete bridge), depending on structural form and function. This light weight advantage is prominent in the case study applications mentioned in **Appendix A1**. Should carbon fibres replace glass fibre reinforcement, the weight reduction could reach 75 per cent. This can be particularly beneficial where ground conditions are poor or reuse of existing substructure is one of client's design requirements. To date, there have not been any all-carbon bridge structures built in the UK, but bonded unidirectional carbon FRP plates have been employed as efficient stiffeners on the West Mill road bridge (2002), the Pont y Ddraig lift bridge (2013) and Church Road bridge (2014).

Weight advantages for rail

"One of the key advantages of FRP bridges is weight reduction. For rail footbridges, spans of circa 10 m to 14 m will weigh in the region of 2 to 4 tonnes. This presents interesting possibilities in the management of the railway, where bridges can be replaced with ease. Replacement structures can be brought to site on the back of an RV and installed using simple cranage in short duration. Existing structures can be inspected and refurbished offsite and then brought back into service. So, FRP solutions provide significant operational benefits where maintenance works can be undertaken offsite reducing the potential disruption to users of the railway."

James Henderson, Technical Authority for Composites in Construction, Atkins

Benefits such as prefabrication, quick installation with reduced health and safety risks, reuse of the substructure and reduced maintenance (life cycle assessment [LCA] is introduced in **Chapter 8**) are very relevant in many situations. FRP bridges, can and should be considered objectively as a feasible option, taking account of the constraints and risks of the particular project. FRP bridge engineering will undoubtedly become more competitive with other structural materials as the number and volume of materials used within the sector increases, while still providing installation and long-term maintenance and sustainability benefits.

The sustainability aspects of FRP bridges, as introduced in **Chapter 8**, are not just those of the underlying materials, because economic, environmental and social aspects should all be taken into consideration. A standard framework for such an approach for buildings is provided in BS EN 15643-1:2010, and is found to be generally relevant for FRP bridges. BS 8905:2011 also provides important guidance on the sustainable use of materials. The importance of LCA to why FRP components are to be chosen is presented in Chapter 8. For the environmental metrics that are often used for materials, embodied energy and CO2, FRPs will vary significantly owing to the wide range of material types and composite manufacturing processing/fabrication methods.

For automated production of glass fibre-reinforced polyester or vinylester FRPs (common for bridge applications), the embodied energy and CO_2 metrics can be as low as 30 MJ/kg and 5 $kgCO_2/kg$, but can be as high as 100 MJ/kg and 15 $kgCO_2/kg$ for other material types/production methods. The same metrics for biocomposites (composite materials manufactured from biological materials such as plant fibres and oils) would generally be lower than that of synthetic FRPs. As summarised in **Chapter 8**, it is found that the overall impact of FRP bridge technologies (or any other material) in terms of social benefits (eg minimising road closures and diversions), environmental benefits (eg material sourcing and transportation and habitat loss) and economic benefits (eg installed and life costings) are of greatest importance when considering sustainability through the life of a project.

A good example of this is that the economic, environmental and social impacts of bridge replacement have typically been found to heavily favour reduction in disruption (Mara and Haghani, 2012, Zhang *et al*, 2011). This is because the energy, pollution and indirect cost associated with traffic using a typical road diversion is far greater than that of the bridge itself. On this basis, FRP bridges can be shown to have positive sustainability credentials by enabling quick installation and minimising disruption to the public.

Practical advantages include the benefits of minimising *in situ* construction and transportation (which has the potential to generally improve safety within the industry). Disadvantages include the lack of experience of FRP suppliers/fabricators when working with civil contractors and contracts (particularly for FRP moulders) and the generally greater level of detailed design effort without standardised design guidance – and also the design cost. Indeed, such disadvantages are part of the reason for the production of this guidance for designers, and it is expected that adoption of the recommendations will allow knowledge of previous experience and more effective and efficient design to be objectively disseminated to the industry.

2.4 LESSONS LEARNT

A host of lessons have been learnt in the development of FRP bridges to date. This section provides some of the key learning points to help guide the industry in the development of FRP bridge solutions using good practice guidance honed from the experience gained to date.

2.4.1 Case study 1: Aberfeldy bridge

The Aberfeldy footbridge was built in 1992 and was the world's first major advanced composite footbridge manufactured entirely using FRP composites materials. The cable stay structure, 113 m long used 14.5 tonnes of composite materials, and it is understood that this is longest span composite bridge in the world. The main span of 63 m and 2.2 m wide is supported by 40 cable-stays from two 17.5 m high towers.

The need for cranage was removed and a unique method of erection of towers, cables and deck was adopted. This was made possible by the lightweight components which permitted minimal foundations and rapid site assembly, resulting in a solution that was very cost effective for the client.

Unfortunately, the bridge design did not take into account the loading of a golf cart or a small tractor transporting sand. The bridge was then overloaded on several occasions and cracks formed in the top surface of the GFRP deck parallel to the webs of the cellular sections. GFRP strengthening was installed in 1997, which involved bonding pultruded plates to the topside of the deck and carbon fibre-reinforced polymer (CFRP) sheets to the deck edge beams near the stay connections.

Impact damage also occurred to the hand railing after following a collision with a golf cart. Having not been designed for vehicle impact loading, this has caused delimitation of the posts, but protective kickboards or additional rails may have mitigated this risk.

Mould and moss is a considerable problem for the footbridge, there being a growth of mould, lichen moss and algae on both the primary structure and parapets. It was suggested that improved detailing and the addition of mould-inhibiting additives in the resin would have combated the problem.

As a highly innovative prototype this structure pushed forward the boundaries of bridge design at any early stage in the use of composites for the bridge sector. While repairs have been needed the performance of the structure has been good over the past 25 years. Lessons learnt from Aberfeldy were applied to the Wilcott suspension footbridge (Votsis *et al*, 2017), which combines a GFRP deck with steel cables and stainless steel parapets and connection details.

2.4.2 Case study 2: Kolding bridge

The footbridge in Kolding, Denmark was Scandinavia's first advanced-composite bridge and was the first in Europe to be built over a railway. When it was built, it was innovative and boundary-pushing, and two decades on it continues to push the limits in terms of its performance to date.

Measuring 40 m long by 3.2 m wide, the Kolding bridge is a cable-stayed design supported by eight stays. The load-bearing structures, bridge deck and handrails are all made of GFRP profiles. The bridge was assembled in the factory in three modules, which were then transported to the site and lifted into place. The bridge weighed less than 12 tonnes and was erected in just 18 hours with only minimal impact on rail services.

Kolding Bridge

"Twenty years ago it was the state of the art in pedestrian bridges. By demonstrating that it was possible to build a bridge entirely of composites we generated tremendous interest, and this has paved the way for many subsequent composite bridges. Today the bridge is continued proof that composite materials not only produce durable bridges but is a competitive alternative to traditional construction materials."

Henrik Thorning
Fiberline Composites founder

Figure 2.13 Kolding footbridge (courtesy Fiberline Composites)

The bridge still fulfils its primary purpose of carrying cyclists and pedestrians across one of Denmark's busiest railways and has so far required only cosmetic maintenance. The only attention received to date is removal of graffiti.

A detailed report on the condition of the bridge, including the durability of the fibreglass, was published four years ago, by engineering consultant Ramboll. The report found that after 15 years' service and exposure to sun, frost and salt the characteristics of the fibreglass were unchanged: *"We can find no form of significant deviation in the material properties, and it is Ramboll's opinion based on the tests performed that the material properties are unchanged after 15 years of bridge service"*.

Fiberline's expectation is that no structural maintenance will be needed for the next 20 years either. This is a notable economic benefit for the Municipality of Kolding as the running costs associated with the bridge will be far lower than for bridges built out of conventional materials, thereby making fibreglass a competitive alternative.

2.4.3 Case study 3: Mount Pleasant bridge

In April 2006, Highways England replaced a defective 40-year-old farm accommodation bridge over the M6 motorway in Lancashire with its first FRP vehicle bridge. The £2M Mount Pleasant bridge was erected between junctions 32 and 33 of the M6 in Lancashire. The bridge is considered a hybrid, using longitudinal steel beams with a transverse spanning FRP deck.

The bridge elements were fabricated off site, brought together on site, and the assembled structure was lifted into position. The bridge uses FBD600 (Fiberline Composites, 2016) asset pultruded profiles and has built-in structural health monitoring sensors. One of the key successes of this structure was the off-site build allowing the occupancy of the network to be significantly reduced. The lightweight nature also made lifting into position a much simpler task. Some challenges were encountered during the site works and these are listed below.

Bonding of the FRP transverse sections to steel beams proved problematic. The weather assumed during design was quite different from the weather encountered on site. So the selection of adhesives should consider worst case scenarios.

Material interaction knowledge was limited. Interaction of Steel and FRP was one area, the other was the interaction of the parapet with the deck. From the perspective of the client (asset owner) the inspection and maintenance needs were not clear, this concerned Highways England as the speed to react to site issues during construction and operational phases would be slow. This was also not helped by the lack of competent inspectors. Reference to The Concrete Society (2003) was recommended.

Figure 2.14 Challenging site conditions (courtesy Highways England)

2.4.4 Case study 4: West Mill bridge

The West Mill bridge was built in 2002 and was a demonstrator project as part of ASSET EU research project (Canning, 2008). The bridge was Europe's first 'all' FRP road bridge. The structure spans 10 m with a width of 6.8 m and there are four cellular GFRP box section beams stiffened with CFRP plates. A transverse spanning deck is located above the stiffened box beams comprising 34 FBD600 planks (Fiberline Composites, 2016). The surfacing installed was polymer concrete with a thickness varying from 30 mm to 90 mm.

Figure 2.15 West Mill bridge (courtesy Skanska)

In 2009, the structures were observed to be free of defects, although cracking was seen in the polymer concrete surfacing in 2010. In the following years, localised potholes developed in the polymer concrete surfacing. These potholes were patched, and further investigations were undertaken, which concluded that the surfacing bond was poor and in many locations the surfacing could be removed by hand. Temporary surfacing was then installed and a weight restriction introduced while further investigations were made.

As a result of the surfacing defects, wear to the top surface of the GFRP sections was evident (potentially from abrasion). In localised areas, two of the box sections had suffered mechanical damage. During November and December 2017 the bridge was successfully repaired within a tented enclosure (**Figure 2.16**). All pre-existing surfacing was carefully removed with vibrating hammers and the deck surface was cleaned via a sanding machine followed by solvent. Then, for the damaged lengths of box section a high density structural foam was used to fill the voids and the damaged zones of top flange were reconstructed using bonded GFRP plates. A double layer of GFRP plating was then bonded onto the entire bridge deck and surfaced with asphalt.

Figure 2.16 Repair of West Mill GFRP deck bridge in November to December 2017 (courtesy Wendel Sebastian)

2.4.5 Case study 5: River Chor aqueduct

The River Chor aqueduct was originally a three-span masonry arch supporting an existing cast iron aqueduct over the railway. The existing structure was replaced with a load-bearing FRP aqueduct allowing the removal of the existing central masonry arch span, to aid future electrification clearance requirements. The arch side spans were infilled with lightweight concrete and masonry cladding.

The replacement aqueduct is 38 m long, 2 m wide and 1.3 m high with a clear span over the railway of 10 m and a design life of 120 years. The aqueduct was fabricated in three sections manufactured using a resin infusion process, and vacuum infused site joints were used to join the three individual sections into a seamless water retaining structure.

FRP was used mainly due to its light weight, low maintenance and ease of installation in a difficult access location. On this project the initial cost and the whole life cost of the FRP solution were the most favourable of all the materials considered.

The aqueduct was fabricated by vacuum resin infusion using an epoxy vinyl ester resin and a gelcoat with structural foam core and glass fibre reinforcement.

Figure 2.17 River Chor aqueduct (courtesy Delft Infra Composites)

Figure 2.18 Site infusion (courtesy Delft Infra Composites)

Good practice learning points

- **Site joints.** This structure highlighted that site joints can be undertaken if appropriate controls are in place. Challenges will always remain (environmental) and avoidance of joints where possible should be the goal, but in specific bespoke instances it is possible to undertake this type of connection.
- **Design.** Experienced designers were employed, and Highways Agency (2005) was used, supplemented by Dutch standards (CUR, 2006) where required. Where there were areas of uncertainty in design, a series of tests were undertaken to help inform the design process. Coupon tests were undertaken to provide material characteristics, and deflection and creep test were undertaken on a full-size sample for a period of 42 days under full loading.
- **Site conditions.** Consider reducing the need for tented operations with heated tents by using materials with specific low temperatures tolerances, and consider the need for on-site manufacturing and question whether the entire bridge deck could be fabricated off site?
- **Sensors.** Structural health monitoring (SHM) has been installed but as the decks used preformed members (pultrusion), all sensors and cable runs are bonded to the deck. These will only have a finite lifespan and so their effectiveness will be a future concern. Understanding the data, and screening out the background noise is also a big data challenge for the SHM industry. Informed decisions relating to this data need to be quickly made.
- **Design.** When considering the use of structural health monitoring (as noted above), it would be useful to publish the design stress envelopes for the associated structure (maintenance manuals) to allow trigger points to be understood and used for future management operations. So there is a need to consider the interfaces between members, ie steel beam to FRP deck and parapet to FRP deck, and give further consideration to producing an effective detail – test accordingly if needed.
- **Water management.** Water absorption into the composites has occurred. Although this has not affected the overall integrity, the external elements have become covered in moss, so additional measures such as inhibitors are now included with modern pultrusions, plus the inclusion of a surface veil for added protection. The use of modified resins and appropriate coatings is advised, together with good detailing and water management. Future material developments will include the use of nano coatings and fillers that will improve the resin characteristics to mitigate these effects.
- **Impact.** Composites have the potential to vary the constituent materials and tailor properties accordingly, and this approach should be used in areas where the risk of impact is higher. Alternatively the use of risk avoidance measures such as kerbs or bollards should be considered where appropriate. Where higher risks exist, consider replacement, noting that the use of traditional restraints should not be discounted (ie use aluminium post and rail fencing).
- **Design.** Consider resilience and risk of unplanned events, building in damage tolerance in high risk areas. Composites can provide a freedom of form, so use this if needed (ie for a 14 m footbridge, an extra one tonne of composite can add a lot of additional strength for little additional cost). Also consider sacrificial thicknesses/coatings or build tolerance in design to allow for water absorption or loss of strength in external layers.
- **Surfacing requirements.** The stiffness of surfacing system, when compared to the flexibility of deck and the lack of bond, may have resulted in some of the observed problems with the material. Although the defects in the surfacing were identified at an early stage, remedial works were not undertaken in a timely fashion which increased the issue.
  - On the Church Road bridge (**Section 2.2**) flat transverse plates were installed above the longitudinal spanning pultrusion to provide better load distribution, and the topside of the plate had a gritted finish to help promote bond between the surfacing and the FRP deck.
  - The addition of a secondary or rather 'sacrificial' plate will also provide additional protection to the underlying structural members if resurfacing is required, where possible damage to the GRP could occur due to the mechanical removal processes adopted by the industry (planeing). Historically, red sand asphalt has been used to indicate the presence of waterproofing layers, and similar solutions will help in the deployment of FRP bridges.
  - Recent structures have used conventional bitumen surfacing with a bitumen emulsion acting as a bond promoter between the GRP and the surfacing.
- **Road profile/alignment.** In addition to the material challenge (surfacing) it is also thought that the road profile was increasing the induced wheel impact forces and that the pressure under these wheel loads may have been different from that assumed in the original design. Also:
  - the addition of a flat plate bonded to the top of pultruded FBD600 (Fiberline Composites, 2016) sections has been proved by the University of Bristol to provide enhanced wheel load distribution characteristics
  - the flat plate, when spanning in the opposite direction to the main beams, provides additional transverse distribution connecting the individual beams, creating a more monocoque structure, thereby helping to distribute localised wheels loads.
- **Rail application.** GRP provides an inert material suitable for rail applications, especially where electrification of the railway is required due to its light weight and insulating characteristics.
- **Parapet.** The main maintenance required has been graffiti removal and the only visible defect observed in a visit to site was minor blistering to the parapet face sheets with areas of the face sheet observed as being subject to impact damage with minimal damage visible. The impact of the solvents used in process of graffiti removal should be considered, as well as the appropriate selection of resin and coatings to mitigate this risk. Alternative solutions would be to have removable cladding panels in GRP or other materials (eg timber).
- **Design.** Modular build using pultrusions and connections has proved effective in this structure, and the pultrusion process has provided a material with known properties derived from a controlled repeatable manufacturing process with a time-served quality control process adopted. This form of construction is a good introduction to the use of FRP composites, allowing engineers to use transferable design skills, similar to steel design. It is, however, noted that the section sizes differ and connections present more of a challenge. Further guidance on the use of bonded and bolted connections is included in this guidance document.

3 Conceptual design

3.1 GENERAL

The first stage in the design of any bridge project is to consider the opportunities and constraints, including aesthetic, economic, practical and technical aspects. This is the situation regardless of the structural material type. Owing to the relative lack of awareness of or education about FRPs among bridge engineers, the consequences for the solution that early decisions can have are presented next.

The most important aspect is for the designer to have, or have access to, general knowledge of the full range of FRP material types and composite manufacturing processes. This guide provides useful, consensus and unbiased information on this subject in **Chapter 4**. Readers can find guidance in the Further reading section at the end of this guide. Two particular aspects are often critical to the design process for any type of FRP bridge, and these are structural rigidity/dynamics (due to relatively low modulus) and resistance of connections and joints (which may require design assisted by testing, as given in **Section 5.1.12**).

For relatively longer span structures (circa 100 m or longer) there has been little or no accumulation of knowledge for FRP bridges, and the engineer should consider in detail the full range of FRP/manufacturing processes and structural forms, including suspension structures.

Similarly for pedestrian bridges, which experience lighter loads than road or rail bridges, the engineer should consider the full range of structural forms. The truss, shallow arched box beams (internally stiffened) and U-deck structural forms are found in conceptual designs and in the applications to date to be particularly viable (technically and economically) owing to their ability to maximise structural rigidity (critical for FRP pedestrian bridges where deflections and dynamics govern).

Creating the numerous connections and joints in truss structures requires careful consideration in design. Bolted joints (**Section 5.5.5**) might be technically inefficient and may require design assisted by testing, while conversely bonded truss joints (**Section 5.5.4**) currently have a limited track record (see Appendix A1 for the River Leri footbridge, 2009), and require a high degree of workmanship for long-term structural integrity (see **Chapter 5** regarding connection choices).

Research and development has been undertaken to develop the framework for an efficient FRP truss system having a monolithic 3D joint component that accommodates hollow box shape with adhesive bonding as the method of connection (Farmer and Smith, 2011). None of the 23 case studies in **Appendix A1** have employed this innovation.

A significant number of FRP road bridge applications have now been undertaken, and certain structural forms have been shown to be the most cost-effective for spans of less than 50 m. In this situation, all-FRP voided slab decks (as used at Klipphausen, Standen Hey and Moss canal bridges) are economic for spans of up to about 10 m, and possibly longer if multiple deck layers or carbon FRP is used for stiffening (see **Appendix A1** for the West Mill footbridge, 2002, Pont y Ddraig lift bridge, 2013 and Church Road bridge, 2014). Beyond spans of 10 m the beam-and-slab form tends to be more favourable (comprising an FRP deck with steel or FRP girders, such as used at the Mount Pleasant bridge, 2006). In either case, making structural use of other components (eg parapet beams, verges) to improve global stiffness should be considered. Where spans exceed about 50 m, composite action between the FRP deck and beams becomes less useful – due to the limited depth (over 200 mm) for available pultruded FRP road decking systems – and other structural forms may be equally viable.

All-FRP or hybrid-FRP railway bridges are currently novel – there was only a few applications worldwide using hybrid-FRP beams. Case study information for deflections and dynamic performance are showing that these serviceability limit states (SLS) (BS EN 1990:2002+A1:2005) are governing the design of railway bridges, which is even more relevant because FRP material has high strength-to-stiffness ratios. Other issues associated with derailment (concentrated deck load and 'robust kerb' to resist transverse impact) will be critical in the design process. There are other structural options that still use the advantages of FRPs available to the designer, such as FRP primary beams with concrete decking as used for the Cantabrico bridge (Hurtado *et al*, 2012).

Where design cost or duration is limited (often the case for short-to-medium span bridges), the designer should consider the benefits and disadvantages of moulded FRP components – which can provide greater design and aesthetic freedom in conjunction with greater design input – and pultruded FRP components, which limit size/shape, but generally require less design effort. In particular, the design of moulded FRP structures generally requires a greater degree of liaison between designer, finite element analyst, composite processing engineer, fabricator and material supplier(s), and may require additional materials characterisation testing, although this gives the designer the opportunity to maximise the technical efficiency of the structure and minimise weight.

It is recommended that the above aspects are objectively considered in a formal feasibility study for all FRP bridge applications, taking account of constraints from the client brief. It should be recognised that new developments occur rapidly in the field of FRP bridges due to its infancy, and bridge engineers can keep abreast of these developments through industry publications (from Composites UK, which is the trade body for the UK composites industry) and from contact with FRP suppliers and manufacturers.

3.2 FUTURE INNOVATIONS

A great deal of research is ongoing within the FRP composites industry covering developments in constituent materials, material strength theory and analysis methods, composite processing and fabrication methods. There are also national and international projects transforming knowledge and understanding into design and testing guidance, which will ultimately become recognised design standards. A number of observations are made in what follows on particular current developments that relate to FRP bridge engineering and other infrastructure works.

Material innovations

There have been innovations in constituent materials, the composite processing methods that manufacture the FRP components from them, and in structural design, construction and asset management through structural health monitoring in parallel with the field applications, starting with the Aberfeldy footbridge in 1992. Similar advances in materials science, material processing etc will continue to influence the development of FRP bridge engineering. Also, there will be a transfer of know-how and technologies from other industries using composite materials, including those producing wind turbines and automotive and aerospace vehicles. Another source of innovation for a potential step-change in exploitation will be when an official design standard for FRP bridges is published.

In general, the common matrix materials in current use (2017) for FRP bridges are predominantly thermoset epoxies, vinylesters and higher grade polyester resins (Bradkirk footbridge, Church Road bridge Frampton Cotterell). This palette of materials is well established and has seen year-on-year processing improvements. Such improvements relate to ease of use, performance, environmental and Control of Substances Haardous to Health Regulations 2002 (COSHH) aspects. This incremental improvement is expected to continue as suppliers strive to improve their products to increase market share.

Recently though, there have been major developments around resin formulations for low fire, smoke and toxicity (FST) applications. Phenolic resins are becoming available with substantially reduced COSHH implications and capable of moulding parts with far less steam liberation and associated quality issues. In parallel with this, urethane acrylate resins have evolved into readily usable formulations that can be easily infused with high alumina-trihydrate (ATH) filler loadings to enable better FST performance. There is also a trend towards resins that have increasing levels of bio-based material that perform similarly to their entirely hydrocarbon-based predecessors.

Gelcoat technology has also incrementally improved, to provide products that are also easier to use, reliable and provide improved performance without the need for heavy-metal pigments.

While E-glass fibres will undoubtedly dominate for the foreseeable future, higher performance S-2 glass is likely to become more prevalent, as are natural fibres such as flax, but also reprocessed cellulose fibres. It should be appreciated that natural fibres are biodegradable and their use in outdoor environments must be considered with care. The availability of reliable quality basalt fibres is increasing, offering superior properties to E-glass, although uptake as a reinforcing fibre in composite structures has been limited to date with most uptake being in rebar applications. Aramid fibres deliver superior structural properties to E-glass but they are costly, primarily due to processing costs, and it seems unlikely that there will be an increased use.

Carbon fibre is used in various grades within bridges, typically in limited areas for maximum impact due to the relative cost of the materials versus E-glass, such as on Foryd bridge. However, the process of creating fibres by carbonising lignum from timber waste is proven and gaining momentum (patented process Oakridge National Laboratory). Such carbon fibre is expected to have a very competitive price point owing to the negligible cost of the precursor and it has properties similar to low grade polyacrylonitrile-based (PAN) carbon fibres. The availability of a cheaper low-grade carbon fibre is likely to affect both bridges and the wider composites industry.

It is likely that short-fibre recycled carbon fibre will also have the potential for use in the future, although a lot will depend upon processing capability and performance versus cost, recycled carbon fibre is currently being developed for use in compression-moulded parts.

The traditional rule that composites have entirely matrix-dominated properties in the Z axis has been changed by Z-stitching techniques which are being more widely used as understanding increases. This is coupled with the development of 3D knitting techniques to introduce fibres in the Z axis. Such reinforcement is likely to see increased use around bridge structures in areas of high through thickness stress.

Thermoplastic matrix composites and thermoplastic reinforcements currently see little use for bridge structures because of the difficulty of processing for larger structures and because of cost. The extreme toughness and damage tolerance of thermoplastic matrix materials makes their use attractive for bridges, and it is likely that a thermoplastic matrix bridge will exist at some future stage, once processing can be solved. The precedent for this is the tail assembly on current Fokker G650 aircraft which exploit the benefits of thermoplastic composites and are fabricated by an automatedc tape laying type technology (ATL). Also, certain thermoplastic fibres such as ultra-high-molecular-weight polyethylene (UHMWPE) have excellent stiffness and strength at a relatively low cost, although they also have very low surface energy and are difficult to bind into a matrix. So, equally, once this material develops it could see uptake. More established materials with high performance such as polyether ether ketone (PEEK) are thought less likely to see adoption due to price.

There is substantial research on graphene, including its use within FRP composite structures, particularly in the aerospace sector. Indications are that addition of graphene, and for that matter other nanoscale materials, can enhance the performance of the composite. It is likely that nano-modifiers will see more use around bridges, but it is less likely that graphene will be used as a structural material on its own for a bridge due to cost.

Processes innovations

Major development effort is going into the efficient manufacture of large high-performance composite structures, driven by the needs of the aerospace sector. Automation is a key element in this, as established processes are labour- and skills-intensive. For large structures, work is underway (at the National Composites Centre) to optimise the infusion process through automation at all stages, ie preparation, infusion and cure. The use of preforms is key to this, as they can be constructed by automated placement of fabric plies or increasingly by robot deposition of tapes or fibres (ATL and AFP processes). For many structures, the viability of large braids is increasing which can also accelerate production rates.

The use of automated fibre or tape placement is thought to be an enabler for steered tows, in which the tows or rovings are aligned to the max/min principle stresses for optimal effect. Such technology is already in use by sailmakers and is under development for more complex shaped structural composites.

Robotics

With the increasing introduction of robots in the workplace, processes such as trimming can be readily automated, saving on time, improving quality and removing personel from hazardous environments. Robots or automated systems with digital feedback and control are increasingly prevalent and effective for composites production areas of activity including prepreg lay down, ply nesting and cutting, ply placement, drilling and bonding. For high volume components there are no real barriers to full intelligent automation.

Although composites manufacture is an additive process by default, it does not immediately lend to free-form deposition via techniques typified by 3D printing – at least where fibres are required in the vertical axis. Structures with fibres exclusively in the lateral plane can already be manufactured by AFP and ATL processes. Work is progressing but on more open, large and complex structures built upon temporary armatures or a frame. It is conceivable that such automated techniques will evolve to produce shell type structures and find their place in the mainstream for which bridge type structures could be eminently suitable.

In recent years there has been a small boom in multi-axis computer numerical control (CNC) capability which is an enabler for large tooling, and in turn this has led to reduced dependency on skilled labour to produce tooling and an increased capability for constructing precise complex forms. The emergent technology of adaptive tooling enables the moulding of one-off or batch runs of parts without the need for a pattern/tool by using a mechanically adjustable reusable tooling device. Although currently limited in size and geometry, this technology is expected to develop and drive down cost of one-off and short-run components. Competition to this technique comes 3D printing of polymers in which a short-run tool can be 3D printed economically. Currently the definition from 3D printed surface finishes precludes larger parts.

Pultruded profiles see widespread use in and around bridge structures as they can be highly cost-effective in the right situation. The pultrusion process is evolving and it is now feasible to pultrude profiles that are curved in two planes, enabling the construction of cambered members, arches and tubular frameworks.

SMART structures

A selection of sensors can be incorporated in composite structures to generate data on structural performance that can be used to inform usage data for fatigue limited structures, for instance, or for structural health monitoring. Storage and critically, interpretation of data is developing year-on-year.

Near-nano-sized materials are also developing to imbue useful properties to composites such as anti-microbial, hydrophobic or self-cleansing. Further ahead though, it is likely that self-healing materials will find their place and enable structures to respond against damage. On a longer timeline, it is expected that materials currently in early technology readiness level (TRL) development will become available that can accurately pinpoint any damage and even respond to conditions.

Failure criteria

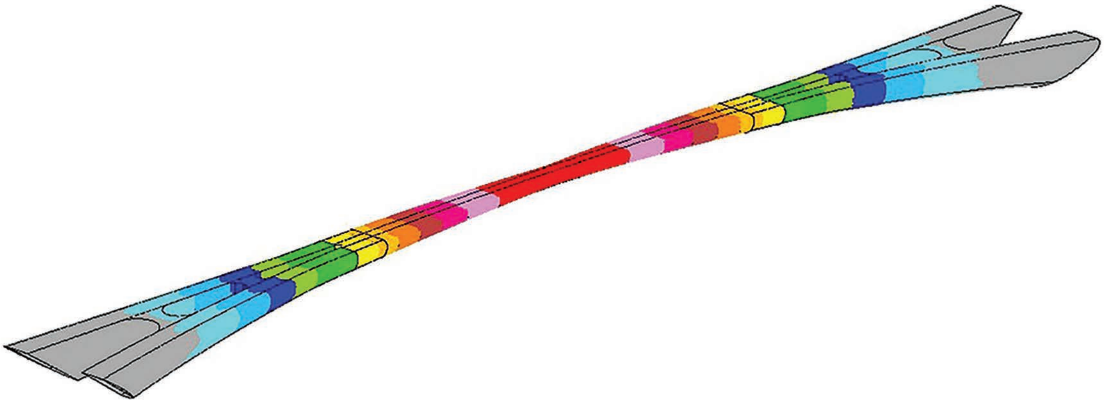
A global effort to critically review existing failure criteria, and develop improved failure criteria, for FRP laminates (Christensen, 2018) has been ongoing since the late 1990s. Failure criteria are directly relevant to FRP bridge design (in particular for moulded monolithic structures), and improved failure theories will no doubt allow more efficient design methods for the application of FRP materials.

Slip-resistant hybrid connections

The design of economically and technically efficient connections and joints is a challenge for FRP bridges and load-bearing structures in general. In particular, it is currently difficult to design slip-resistant connections (as required by design standards for all public bridges in the UK) due to relatively poor through-thickness creep and stiffness characteristics of FRP materials. Research and development work is ongoing in this area (Zafari *et al*, 2016) and efficient connection methods based on mechanical fasteners and/or adhesive bonding and/or mechanical interlocking will be crucial to the growth in use of FRP components in future bridge projects.

Box 3.1 Long-span CFRP footbridges

Long-span CFRP footbridges have been investigated in detail and over several years of research a number of conceptual designs have been produced with clear spans of 200 m to 300 m. The philosophy has been to omit intermediate supports and create a single long-span monocoque CFRP structure. Using geometric and material optimisation, the resulting structure is only a fraction of the mass of a conventional alternative, reducing dead loading and increasing frequencies of vibration to improve dynamic response. By avoiding masts and cables and using a durable FRP structure the through-life costs are significantly reduced, without any premium on initial costs, due to savings in foundations and installation.



This will be particularly beneficial for river crossings or over major infrastructure such as railways or roads where intermediate piers are expensive and time-consuming to construct and can cause significant disruption. Modular, off-site construction will also bring advantages in time and construction costs.

4 FRP materials

To design bridge structures having FRP components requires knowledge of the mechanical properties to be used in the calculations to check the design limit states, as introduced in **Chapter 5**.

An FRP material consists of fibre reinforcement embedded in a cured matrix of a polymer resin (Bank, 2006, Hull, 1996). The resin chosen is usually a thermoset, is often from the epoxy, polyester or vinyl ester families and there are preferred matrix compositions for different composite processing methods. The matrix can primarily consist of the polymer resin constituent, and can have additives (or modifiers) and fillers, depending on the manufacturing process or required FRP functionality (such as colouring and fire resistance). Furthermore, the type(s) of fibre reinforcement in a laminate stack will vary with the processing method and the required directional structural/mechanical properties. If the bridge component is of sandwich construction there is a relatively very lightweight and flexible core material (Gurit, 2011) involved in the processing for the FRP component.

An important consideration for the designer to understand and to take account of is that, until the matrix in the FRP material is fully cured, for an FRP material (with or without sandwich construction), an FRP component or an FRP structure, the actual mechanical/structural properties and their inherent variations are unknown. Historical precedence for a component or structure engineered with the same FRP material(s) or sandwich construction(s) means that mechanical property data may be available for the purpose of performing a new design solution.

Because of the enormous choice in constituent material combinations and processing methods to manufacture FRP components (Barbero, 2011, Bank, 2006, Gurit, 2011) this chapter can only provide, at best, an overview of the types of product and their properties. In **Sections 4.1 to 4.3** the constituent materials will be introduced, with technical information relevant to how FRPs perform as a structural material. **Section 4.4** provides a summary for the key features of the main composite processing methods found in bridge engineering. **Section 4.5** introduces some adhesives used to form bonded connections (see also **Section 5.5.4**) between FRP and FRP or FRP and a sandwich core or another construction material. **Section 4.6** then gives guidelines for determining mechanical properties, but the illustrative values reported are not to be taken as specific design data. Relevant and reliable properties can be obtained either by testing (**Section 5.1.12**) or directly from the FRP material manufacturer. Important design guidance is given in **Section 4.6.5** concerning the long-term durability of FRP materials and their structures.

It cannot be over-emphasised that the short-term mechanical properties of FRPs are affected by a range of factors, including the resin matrix and reinforcement fibre types, orientation and lay-up, as well as the processing method and the conditions used to manufacture components.

4.1 RESIN MATRIX

The matrix in an FRP mainly comprises an isotropic polymer resin and can have other chemical substances for additives and fillers. In the pultrusion processing method (**Section 4.4**) the number of individual substances – filler (kaolin clay or calcium carbonate) and additives – in the matrix design can exceed 10 in number. Bank *et al* (2003) summarises 12 substances for an additive (with no limit, unless stated otherwise):

- coupling agents
- release agents
- initiators

- hardeners
- dilutents (styrene added to the base polymer at the time of production not exceeding 10 per cent by weight of the base polymer resin)
- promoters
- catalysts
- UV agents
- fire retardants
- low-profile (shrink) additives (not exceeding 20 per cent by weight of the base polymer resin)
- foaming agents
- pigments

The resins that are used are sometimes referred to as 'polymers'. Man-made polymers are generally called 'synthetic resins' or simply 'resins'. Polymers can be classified under two types, 'thermoplastic' and 'thermosetting', according to the effect of heat on their mechanical properties.

Thermoplastics soften with heating and eventually melt, hardening again with cooling. This process of crossing the softening or melting point on the temperature scale can be repeated as often as desired without any appreciable effect on the properties in either state. Typical thermoplastics include nylon, polypropylene and acrylonitrile-butadiene-styrene (ABS), and these can be reinforced, although usually only with short, chopped fibres such as glass. This category of FRP material does not generally find applications in load-bearing structures such as bridges.

Thermosetting polymers, or 'thermosets', are formed from a chemical reaction *in situ*, where the resin and additive(s) are mixed and then undergo a non-reversible chemical reaction to form a hard, infusible product. Once cured, thermosets will not become liquid again if heated, although above a certain temperature their mechanical properties will change significantly. This temperature is known as the glass transition temperature (T_g), and will be found to vary widely according to which standard test method is used for its determination, and also to the particular resin system, its degree of cure and whether it was mixed correctly. The T_g is found to vary with time if the FRP material takes up water, and this durability effect is introduced in **Section 4.6.5**. Above the T_g, the molecular structure of the thermoset changes from that of a 'glassy' crystalline polymer to a flexible, 'rubbery' amorphous polymer. This change is reversible on cooling below T_g. For temperatures above T_g, properties such as modulus of elasticity (resin stiffness), drop sharply, and so do the compressive and shear strengths of an FRP laminate. Other material properties, such as water resistance and colour stability, are found to reduce markedly for temperatures above T_g.

Although there are many different types of resin in use in the polymeric composite industry, the majority of structural parts are manufactured with three main types: polyester, vinylester and epoxy. An introduction to these types is given in **Sections 4.1.1 to 4.1.3**. For the overall property portfolio there is a general advantage in choosing an epoxy over a vinylester over a polyester resin. The penalty for an improvement is that the cost can be higher. Mayer (1993) offers a pragmatic approach to choosing the best combination of constituents for an FRP material.

4.1.1 Polyester resins

The principal types of polyester resin for laminates in FRP bridge engineering are orthophthalic (saturated) or isophthalic (unsaturated) polyester resins. The latter polyesters are capable of being cured from a liquid or solid state when subject to the right processing conditions. It is usual to refer to unsaturated polyester resins as 'polyester resins', or simply 'polyesters'. An orthophthalic resin matrix is an option if the component is to be painted. Isophthalic types are preferred where the superior water resistance is desirable.

Fillers are used extensively with polyester resins to reduce the cost of the FRP, facilitate the laminating process and impart specific properties to the material. Fillers are often added in quantities up to 50 per cent of the resin weight, although such addition levels will adversely affect strength and an FRP's durability. In their model specification for FRPs, Bank *et al* (2003) limited the quantity of filler to 20 per cent by weight of the base resin. Fillers can be beneficial in the laminating of thick components where otherwise considerable exothermic heating during curing can occur. There are specific fillers, such as ATH, which contribute to increasing fire resistance. Because of their proven durability performance vinylester or epoxy resin matrices should be considered when the site environment is known to be aggressive.

4.1.2 Vinylester resins

This resin type is similar in its molecular structure to polyesters, but it differs primarily in the location of the reactive sites, these being positioned only at the ends of the molecular chains. As the whole length of the molecular chain is available to absorb shock loadings this makes vinylester resins tougher and more resilient. The vinylester molecule features fewer ester groups, which are susceptible to moisture uptake degradation by hydrolysis. This chemical difference means that vinylesters are found to exhibit better resistance to water and many other chemicals than their polyester counterparts.

4.1.3 Epoxy resins

This type represents some of the highest performance resins in the catalogue available from resin suppliers. Epoxies generally outperform other resin families in terms of mechanical properties at elevated temperatures and of resistance to environmental degradation. Their superior adhesive properties and resistance to degradation due to water make an epoxy appropriate for use in high performance applications, such as in FRP bridge engineering. But this advantage is mitigated by their relatively higher material and processing costs.

4.1.4 Speciality resin systems used in bridge FRPs

Besides the three main types summarised in the previous sections, there are several other resin systems that can be use when a specific property is required. These systems are described as follows.

4.1.4.1 Phenolic

Phenolics are primarily used where highest practical fire resistance is required. This is because this resin family retains mechanical properties well at elevated temperatures. For room-temperature curing phenolics, corrosive acids are needed, which demand extra control when being handled. Another disadvantage is that the condensation nature in the curing process tends to create many voids and surface defects, and a phenolic matrix might be relatively brittle and have inferior mechanical properties.

4.1.4.2 Acrylic

Acrylic (urethane methacrylate) resin is primarily employed where fire resistance is required. Having a low viscosity, this type can accommodate the highest levels of ATH (eg at 200 parts per 100 parts of acrylic polymer). This produces an FRP material with enhanced fire resistance, while retaining acceptable mechanical performance that cannot be achieved with other fire-retardant matrix systems.

4.1.5 Comparison of resin properties

As already alluded to, because of the enormous range available, the choice of the resin matrix for any component will depend on a number of its characteristics. The most important characteristics (in no particular order) are adhesive properties, mechanical properties and long-term degradation from moisture/water uptake.

The adhesive properties are important in realising the full mechanical properties in the FRP material. Adhesion of the matrix to the fibre reinforcement or of the adhesive to a core material in sandwich construction (**Section 5.3.2**) is essential for strength and durability. Polyester resins generally have the lowest adhesive properties. A vinylester shows improved adhesion with an epoxy offering the best performance of the three main resin types. It is for this technical advantage that epoxies are commonly the polymer in high-strength structural adhesives (Lees, 1984). The adhesive properties of epoxy are especially beneficial in the fabrication of honeycomb-cored sandwiched laminates, where the small bonding surface area means a maximum adhesion performance is required.

Bond strength between matrix and fibre is not solely dependent on the adhesive properties of the polymer resin. Performance is acutely affected by the surface finish of the fibres. The importance of the coupling agent and sizing is explained in **Section 4.2.1**.

Two important mechanical properties of any cured polymer resin are tensile strength and modulus of elasticity. The bar charts in **Figure 4.1** show illustrative test results for neat resin casts of commercially available polyester, vinylester and epoxy resins cured at 20°C for seven days and after an additional post-cure at 80°C for five hours. After the cure conditioning, the epoxy resin will have higher mechanical properties than the polyester or vinylester resins. The beneficial effect of the post-cure conditioning is seen from the indicative results in **Figure 4.1**.

The direct stress–strain relationship under tensile deformation of the matrix will have an initial linear elastic range and for strains exceeding the strain limit of the reinforcing fibres, the relationship will become non-linear. The matrix will experience viscoelastic behaviour (McCormick, 1984), which is the main reason that, at working temperatures, FRP structures will creep when subjected to permanent actions and will relax (creep recovery) when permanent load is removed.

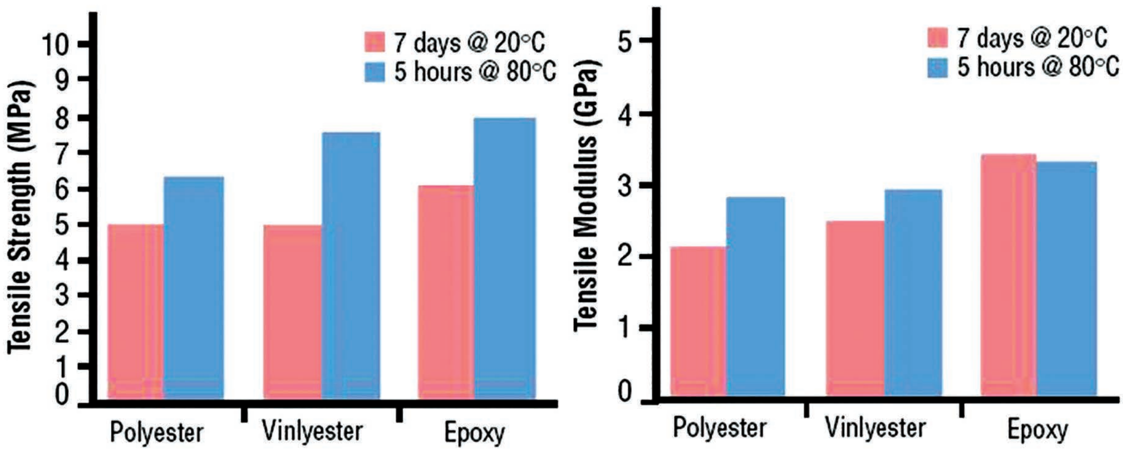


Figure 4.1 Relative mean tensile strengths and moduli for the three main resin types (courtesy Gurit)

A bridge with FRP components will be exposed, over its design working life, to the local weather environment. A key matrix property for durability is the resin's ability to withstand material degradation from moisture diffusion (Karbhari, 2007). All polymer resins absorb moisture due to a diffusion process, many orders of magnitude slower than heat flow in thermal diffusion, changing an FRP material's weight over time. What is most significant to engineering design is how the absorbed water affects the matrix and the fibre interphase region, which may lead to permanent long-term losses in mechanical properties. Both polyesters and vinylesters are prone to degradation due to the presence of hydrolysable ester groups in their molecular structures. Epoxies do not contain these susceptible ester groups and show improved resistance to the effects of moisture uptake, which are temperature and time dependent. When selecting a resin matrix, linked to the composite processing method, the choice will depend upon the site environment. This can minimise the risk that the long-term mechanical/structural performance be found to be unacceptable. Further background information and guidance on design for durability (BS EN 1990:2002+A1:2005) for FRP materials is given in **Section 4.6.5**.

4.1.6 Matrix property guidance

The minimum information to be declared for resins, curing systems, additives and modifiers to be used for the manufacturing of FRP components may be specified in accordance with BS EN 16245-2:2013. Note that BS EN 16245-1:2013 is for general requirements.

Matrix composition needs to be appropriate for the finishing on the fibre reinforcement. Choice of polymer resin will depend on required design properties, which can include T_g, chemical resistance, fire reaction properties or transport (thermal or electrical) properties. Additives (or modifiers) and fillers can be added to the resin to provide the cured matrix with specific properties. The effect of additives and/or fillers on mechanical properties of the FRP should be accounted for. The cured neat resin should satisfy having a tensile strain of at least 1.8 per cent when tested by BS EN ISO 527-4:1997 (Ascione *et al*, 2016) with test specimens prepared to BS EN ISO 20753:2014.

4.2 FIBRES AND FIBRE REINFORCEMENTS

The function of the cured matrix is to hold the reinforcing fibres in their positions and transfer forces through the fibre–resin bond. To have an FRP material for bridge components the mechanical properties of the fibres have to be considerably higher than are the equivalent properties of the resin matrix. Unless otherwise stated, it may be assumed that the fibres have a length that is for continuous reinforcement. Mechanical properties of an FRP for engineering design calculations are established by the contribution of the fibre reinforcement (Hull, 1996). There are four factors to this contribution:

1. strength and stiffness of the fibre type
2. interface/interphase bond strength between the fibres and the matrix
3. volume fraction of fibres in the FRP material and in the individual reinforcement layers, if the laminate comprises more than a single type of lamina reinforcement
4. orientation of the fibre in the laminae and of the individual reinforcement layers.

Table 4.1 lists illustrative mechanical properties of commonly used reinforcing fibre types of glass, aramid and carbon. Column 1 lists the fibre types, and columns 2 and 3 give their longitudinal tensile strengths and stiffnesses. Column 4 presents the densities having the Eurocode action units of kN/m^3. The fifth column in the table gives the specific moduli for the fibre types obtained by dividing column 3 by column 4. The higher the specific modulus is greater can be the FRPs 0° stiffness per unit weight. The last row in the table is for S355 grade structural grade steel (included for comparison). Note that this specific modulus is with different definition than is commonly found in the composite industry (Hull, 1996).

Surface interaction at the fibre–resin interface is controlled by the degree of bonding that exists between the two through the interphase where the finishing has reacted with the curing matrix to form a graded layer around the fibre. This is heavily influenced by the matrix system and finishing treatment given to the fibre surface.

The amount of fibre in a laminate is governed by the composite processing method, which is introduced in **Section 4.4**. Reinforcing fabrics with closely packed aligned fibres will give higher fibre volume fractions (FVF) than will fabrics made with coarser fibres, or which have gaps between the fibre bundles. Fibre diameter is an important factor, with the more expensive smaller diameter fibres ($< 10\ \mu m$) providing higher fibre surface areas, spreading the interfacial forces. As a general rule, the in-plane tensile stiffness and strength of an FRP will increase in proportion to the volume fraction of fibre present. Although tensile stiffness continues to increase, for FVFs above 55 to 70 per cent (depending on the processing method and the way fibres pack together) the laminate's strength will reach a peak and then begin to decrease due to the lack of sufficient matrix to fully wet out the fibres.

Since aligned fibres are efficient when loaded in their length direction, the orientation of fibres in the FRP laminate creates highly 'direction-specific' mechanical properties. This 'anisotropic' feature can be used to good advantage in structural engineering designs (Bank, 2006), with the majority of fibres being placed with orientations parallel to the main load paths. The designer may use this tailorability to minimise the amount of parasitic reinforcement that has an orientation where there is little or no force being transmitted.

Table 4.1 Reinforcing fibre types and typical mechanical properties

Fibre type[1]	Tensile strength1 (MPa)[2]	Tensile modulus of elasticity (GPa)[3]	Typical density (kN/m³)[4]	Specific modulus (m) (5) = (3)/(4)
E-glass[2]	2400	69	25	28
S2-glass[3]	3450	86	25	34
CR-glass[4]	3400	80	27.2	29
Low modulus (LM) aramid	3600	60	14.5	40
High modulus (HM) aramid	3100	120	14.5	80
Ultra-high modulus (UHM) aramid	3400	180	14.7	120
High strength (HS) carbon	3500	160–270	18	90–150
Intermediate modulus (IM) carbon	5300	270–325	18	150–180
High modulus (HM) carbon	3500	325–440	18	180–240
Ultra-high modulus (UHM) carbon	2000	440+	20	200+
S355 steel	355[5]	210	77–78.5	27

Notes

1 Single fibre strength before handling and processing.
2 Alkali free, highly electrically resistive glass made with alumina-calcium borosilicates.
3 High strength glass made with magnesium aluminosilicates.
4 An E-glass with higher acid corrosion resistance made with calcium aluminosilicates.
5 Characteristic yield strength (BS EN 1993-1-1:2005+A1:2014).

4.2.1 Fibre types

As introduced by the illustrative (or indicative) fibre properties presented in **Table 4.1**, the main fibre types are of glass, aramid and carbon. In each type, there are a number of fibres to choose from. It is essential to liaise with the fibre or fibre reinforcement (eg fabric) supplier to obtain the appropriate fibre mechanical properties, and to verify that the surface finish is compatible with the matrix. In terms of what the designer needs to know, the following sections introduce the main fibre types.

4.2.1.1 Glass

By blending quarry products (sand, kaolin, limestone, colemanite) at 1600°C, liquid glass is formed. The liquid is passed through micro-fine bushings and then simultaneously cooled and drawn down to produce glass fibre filaments from 5 to 24 μm in diameter. The filaments are combined into a strand (closely associated) or roving (loosely associated), and coated with a finish to provide filament cohesion and protect fibres from abrasion (for surface crack creation) when handled.

By variation of the 'recipe', different types of glass can be produced. The commonest type used as reinforcement is E-glass. The corrosion resistance type is labelled CR-glass. The first three rows of **Table 4.1** report the mechanical properties for three types of glass fibre. The S2 type has a recipe for a glass fibre with higher strength than the other two types. It is worthy of repetition, so that the designer is clear, that the single filament strengths in the second column of the table are before fibre handling. Crack generation on fibre surfaces will occur with handling and processing, and so the fibre strength inside the FRP material is an unknown – it may be 50 per cent of the strength in **Table 4.1**.

Glass fibres are supplied in the following forms:

1 Strands are compactly associated bundles of filaments, which are rarely found commercially because the fibres are then usually twisted together to give yarns.

2 Yarns are closely associated bundles of twisted filaments or strands. Each filament diameter is constant and usually in the range 5 to 13 μm. Yarns have varying weights described by their 'tex' (the weight in grams in one kilometre length) or denier (the weight in lbs of 10 000 yards), with the typical tex range usually being between 5 and 400.

3 Rovings are loosely associated bundles of untwisted filaments or strands. Each filament diameter is constant and is usually in the range 13 to 24 μm. Rovings are supplied in varying weights, and the tex range can be between 300 and 9600. When the filaments are gathered together directly after the melting process, the fibre bundle is known as a direct roving. Several strands can be brought together separately after fibre manufacture to give an assembled roving. Assembled rovings usually have smaller filament diameters than direct rovings, giving better wet-out and FRP mechanical properties. Their disadvantages are that they can suffer from a catenary problem of unequal strand tension and are higher in cost because of the more involved manufacturing processes.

It is practical to make continuous fibres from short glass fibres by spinning them. These spun yarn fibres can have higher surface areas and have better wetting-out with the matrix. Their disadvantage is that they have lower structural properties than the equivalent continuously drawn glass fibres.

4.2.1.2 Aramid

Aramid fibre is a man-made organic polymer (an aromatic polyamide) produced by spinning a solid fibre from a liquid chemical blend (**Box 4.1**). The bright golden yellow filaments of about 10 to 12 μm diameter can have a range of mechanical properties, as seen by the data in rows 4 to 6 of **Table 4.1**. All have relatively high tensile strength and with a density of 1.45 g/cm^3 have relatively very high specific tensile strengths of more than 2000 N/mm^2. All grades have good resistance to impact, and lower modulus grades are used extensively in ballistic energy-absorbing applications. A disadvantage of aramid fibre is that its compressive strength is substantially lower than its tensile strength. Their use as a compression or flexural reinforcement should be treated with caution.

Box 4.1 Aramid cable stays

The Aberfeldy footbridge in Scotland was the first application of the advanced composite construction system in bridge engineering (Burgoyne and Head, 1993). The material used for the cable stays was aramid fibre. For the Aberfeldy project metallic connectors were developed to grip the unreinforced fibres and to efficiently transfer the cable forces.

There are several grades of aramid fibre (see **Table 4.1**) having various combinations of tensile modulus of elasticity and surface finish to suit various applications. This type of reinforcement offers good resistance to abrasion, and chemical and thermal degradation. It is known that aramid polymer can degrade slowly when exposed to ultraviolet light. Aramid fibres are supplied in the form of rovings, with texes of 20 to 800.

4.2.1.3 Carbon

Carbon fibres are produced by the controlled oxidation, carbonisation and graphitisation of carbon-rich organic precursors, which are already in fibre form. The most common precursor is polyacrylonitrile (PAN), because it gives the best fibre properties. There are other forms of carbon fibres made from precursors of pitch or cellulose. Variation in the graphitisation process produces groups of either high strength fibres (at 2600°C) or high modulus fibres (at 3000°C), with other types (eg intermediate modulus) in between. Indicative bands of tensile properties for these fibre grades are reported in rows 7 to 9 of **Table 4.1**. As seen from the data in row 10, there is a fourth grouping, known as ultra-high modulus, having a modulus of elasticity in excess of 440 GPa. Note that, by increasing the fibre modulus the fibre strength reduces, and so will the longitudinal strain for tensile failure, making it more brittle. Once formed, a carbon fibre has a surface coupling agent applied to allow matrix bonding, and a sizing to protect each filament during handling.

The filament diameter of most types is about 5 to 7 μm. Carbon fibres have the highest specific modulus (**Table 4.1** shows it can be over 200) of any commercial fibre reinforcement, relatively very high strength in both tension and compression and a high resistance to corrosion, creep and fatigue (Mayer, 1993). The impact strength of HM and UHM carbon FRPs is known to be lower than for laminated reinforced similarly with grades of glass or aramid fibres.

4.2.1.4 Fibre property guidance

The minimum information to be declared for the fibre(s) used to manufacture FRP components may be specified in accordance with BS EN 16245-3:2013. Note that BS EN 16245-1:2013 is for general requirements.

When designing with property data taken from technical literature allowance should be made for the probable change in mechanical properties when different suppliers use a different fibre finish and processing for the fibre type. It is the designer's responsibility to verify that the constituents for the FRP material provides the FRP mechanical properties required in the design calculations.

4.2.2 Fibre reinforcements

The reinforcing laminae in an FRP consist of laminae, typically having thickness of 0.125 mm to 2.0 mm of one or more fibre types (if there are two types of fibre the reinforcement layer is hybrid). Layers in a fabric construction are held together either by mechanical interlocking of the fibre bundles or by having a secondary (polyester) fibre (FVF at one to two per cent) to bind the bundles together and hold them in position. For mat reinforcement with randomly distributed fibres the bundles are held together by a binder material. Both fabric and mat assemblies possess adequate structural integrity on their own to be handled during the composite processing method.

Tables 4.2 gives a summary to the main forms of fabric, and shows that there are four main categories based on fibre orientation. The four categories are unidirectional, biaxial 0°/90°, multi-axial and other/random. The designation for fibre orientation angle is that the 0° direction of the laminate is aligned to the principal direction of loading.

As introduced in **Table 4.2** there are various methods of maintaining the fibre positioning in a unidirectional fabric, including weaving, stitching and bonding. As with other reinforcing fabrics, the surface quality of a unidirectional fabric is established by two main factors – the combination of tex and thread count (a measure of the coarseness or fineness of fabric) of the primary fibre, and the amount and type of the secondary fibre. The drape, surface smoothness and stability of a fabric are controlled primarily by the fabric's construction pattern, while the area weight (g/m^2), porosity and (to a lesser degree) wet-out are determined by selecting the appropriate combination of fibre tex and numbers of fibres per cm width.

The efficiency or effectiveness of continuous fibres (having properties such as those listed in **Table 4.1**) will be reduced in a woven fabric because the fibres are no longer lying in a single plane. The designer needs to know and understand how the fibre reinforcement(s) in an FRP material will affect the laminate properties. The most reliable method to obtain the data is by coupon testing with the FRP material, as introduced in **Section 4.6.1**.

Table 4.2 Fabric forms and descriptions of construction

Forms	Description
Unidirectional	Fibres are predominantly in one direction and held together by weaving, stitching or bonding. The secondary fibres in the transverse direction (90°) amount to no more than 1% of the unit mass.
0°/90° fabrics	These are for applications where more than one fibre orientation is required. Note that the proportion of fibres in the orthogonal directions can be balanced or different.
Woven fabrics	Woven fabrics are produced by the interlacing of warp (0°) fibres and weft (90°) fibres in a regular pattern or weave style. The fabric's integrity is maintained by the mechanical interlocking of the fibre bundles. There are several possible construction patterns.
Stitched multi-axial fabrics	Multi-axial fabrics can be made by a stitching process, which effectively combines two or more layers of unidirectional reinforcement into a single fabric. Compared to a woven fabric, a stitched 0°/90° fabric can provide mechanical properties with up to 20% increase that are more consistent. These benefits over woven fabrics are because stitched multi-axial fabrics will drape over irregular shapes and offer improved resin infusion. A wide range of combinations of fibre orientations and variations in reinforcement weights in the multi-axial layers are commercially practical.
Chopped strand mat (CSM)	CSM is a non-woven material which, as the name implies, consists of randomly orientated chopped strands of glass fibres (20 mm to 50 mm in length), held together by an polyvinyl alcohol (PVA) emulsion or a powder-based binder.
Continuous filament mat (CFM)	CFM is a non-woven material which, as the name implies, consists of randomly orientated continuous strands of glass fibres, held together by an PVA emulsion or a powder-based binder. This material is commonly used in the pultrusion composite processing method (**Section 4.4**). In North America abbreviation CSM is used instead of CFM.
Tissues	Tissues are made with uniform continuous filaments randomly distributed over a flat surface. These are then chemically bound together using organic based binding agents (PVA, polyester etc). Having relatively low strength, tissues are not primarily for reinforcement. They can be used to form a surfacing layer having a smooth finish.
Polyester surfacing veils	Not a reinforcing lamina, a veil (30 g/m^2) can be incorporated into the surface layer of, for example, a pultruded shape. A veil is used as a surface layer in order to have a resin rich surface to improve the component's appearance. This is achieved by reducing the print-through of the underlying fibre reinforcement. For structural engineering performance the veil serves to protect the underlying fibre reinforcement from hostile environments, such as UV. The permeability for moisture/water diffusion is lowered (Grammatikos *et al*, 2015) and this resistance to water uptake is beneficial for material durability (**Section 4.6.5**).

4.3 CORE MATERIALS

Foams are a common form of core material used in sandwich construction (Davies, 2001). They can be manufactured from a variety of synthetic polymers including polyvinyl chloride, polystyrene, polyurethane, polymethyl methacrylamide, polyetherimide, polyethylene terephthalate and styrene acrylonitrile. They can be supplied in densities of 30 to 300 kg/m^3, although the common densities with FRP skins are in the range 40 to 200 kg/m^3. They are supplied in a variety of thicknesses, typically from 5 mm to 50 mm, and a range of cut patterns to allow forming with surface curvature out of the plane (Gurit, 2011). Bradkirk footbridge is a case study in Appendix A1 that has a superstructure of sandwich construction and a foam core.

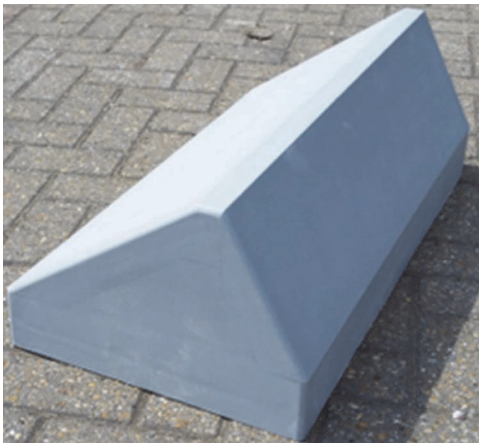
Another type of core material used in FRP bridge components is balsa wood (Osei-Antwi *et al*, 2013). The mechanical properties of foams and balsa wood are generally taken to be proportional to their densities. Honeycomb core manufactured from paper, aluminium or polypropylene is an alternative core material, which was developed for the aerospace industry (Davies, 2001) and is likely to be less common for sandwich construction in FRP bridge engineering. There has been no UK bridge fabricated with these two core materials to date.

The minimum information to be declared for core materials to be used for the manufacturing of FRP components may be specified in accordance with BS EN 16245-5:2013. As with all constituent materials used to make an FRP component it is the designer's responsibility to confirm and verify the required mechanical properties and other technical information. Detail information for design will be available from core manufacturers and composite processors/fabricators who are experienced in free-form sandwich constructions.

Box 4.2 *Core innovations – FRP coping units*

The replacement of masonry coping stones to a bridge parapet with new FRP copings was undertaken following the strengthening and raising of the parapet walls on a 75 m long farm accommodation bridge over the railway.

200 FRP coping units 390 mm wide × 255 mm high were manufactured. The copings used 3D structural foam core and were fabricated in 750 mm lengths with a weight of 9 kg (compared to PCC copings that weigh 80 kg). The copings were fabricated by vacuum resin infusion using polyester resin and glass fibre reinforcement affording excellent impact resistance at a significantly lower weight.



4.4 COMPOSITE MATERIAL PROCESSING

Sections 4.1 to 4.3 have highlighted the many different constituent options to choose from for the resin matrix, fibre reinforcement layers and core in sandwich construction. Mechanical properties of an FRP component produced from combining these different materials are not only a function of the constituent properties but, equally importantly, are highly dependent on the ways in which the materials themselves are designed and processed to produce the component. Every FRP option will offer a unique portfolio of material properties, including mechanical, production rate and size and cost. Also, depending on the composite processing method the reinforcing fibre layers being laid up for FRP manufacture will either be dry (without matrix) or 'wetted out' – a prepreg reinforcing layer has a partially cured resin matrix.

This section briefly introduces a number of composite processing methods that may be used in FRP bridge engineering. Fuller descriptions with main advantages, main disadvantages and typical applications are to be found in a number of publications such as Gurit (2011) and various manufacturer internet sites. The process has to ensure that the matrix has fully wetted out the reinforcement layers and provides curing conditions of temperature and pressure for a consolidated laminate (to thereby have a minimum void content).

Before listing methods for how an FRP component can be manufactured, it is worthwhile mentioning some facts about processing that the designer should understand when communicating with the fabricator and ensuring quality control in fabrication (see **Sections 6.2 to 6.4**). Processing conditions need to be controlled, and often the composite manufacturer will treat their company's processing specifications as intellectual property and so not be willing to divulge specific information on the constituents and/or processing specifications.

To ensure that the as-received FRP is of quality, great care is needed in the preparation of the resin mix for the matrix before processing. Mixing should be done in accordance with the resin manufacturer's recommended procedure. The polymer resin and any additives and fillers should be thoroughly stirred to disperse all the matrix components uniformly before the catalyst (and/or hardener) is added. All parts in the matrix's recipe should be at the proper temperature and thoroughly mixed in the correct ratios. Parts in a matrix are often of contrasting colours, so full mixing is achieved when colour streaks are eliminated. Matric systems are to be mixed for the prescribed mixing time and visually inspected for uniformity of colour. The resin manufacturer is responsible in supplying the recommended batch sizes, mixture ratios, mixing methods and mixing times.

Mixing equipment can include small electrically powered mixing blades or specialty units, or resins can be mixed by hand stirring, if needed. Matrix batching should be in quantities sufficient to ensure that all of the mixture will be used within the pot life. Mixed matrix that exceeds the resin's pot life should not be used because the viscosity will continue to increase and will adversely affect the resin's ability to fully saturate (wet out) all the fibre reinforcement.

Stirring should be carefully controlled, because air introduced into the mix will generate voiding (or porosity) that adversely affects the quality and mechanical properties of the FRP component. This is especially so when laminating with layers of fabric/mat reinforcement as air bubbles can be formed, which will weaken the laminate. Judd and Wright (1978) reviewed 47 papers for an appraisal of the effects of voids on mechanical properties. Regardless of resin matrix type, fibre type or fibre surface treatment, *"the interlaminar shear strength of a composite decreases by about seven per cent for each one per cent of voids up to a total void content of about four per cent"*. The decrease in other properties for the first one per cent of voids is reported as high as 30 per cent (flexural strength), nine per cent (torsional shear), eight per cent (impact strength) and three per cent (tensile properties).

It is important to add the catalyst (and/or hardener) in controlled measured amounts to control the polymerisation reaction for the optimum mechanical properties. Too much catalyst will cause too rapid a gelation time, whereas too little catalyst will result in under-cure or maybe regions of no cure. Both can adversely affect the performance of the final FRP material.

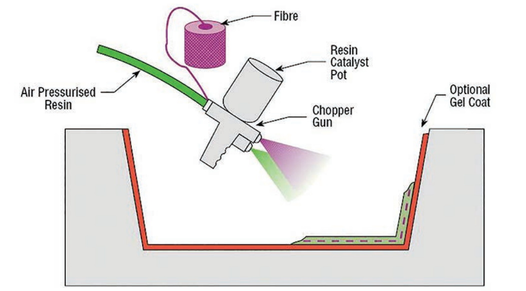
Colouring of the matrix mix can be carried out with pigments. The choice of a pigment, even though only added at about three per cent resin weight, should be carefully considered. It is very easy to affect the curing reaction and degrade the final laminate by having an unsuitable pigment. Colouring of pultruded shapes can be used to identify the matrix type and/or level of fire retardancy.

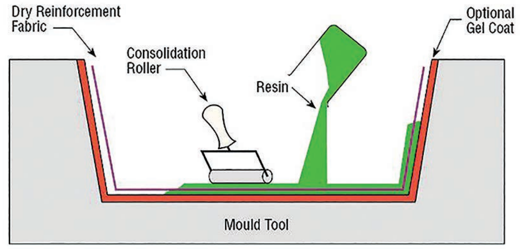
Companies that specialise in composite processing have expert knowledge and experience that the designer will need to consult at all stages of an FRP bridge project. The choice of processing method can dictate the structural form (see **Section 3.1** and the case studies in **Appendix A1**), and the specification of the basic mechanical properties for preliminary and final designs.

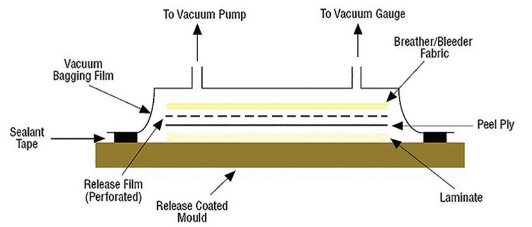
Table 4.3 gives a labelled schematic drawing for possible processing methods that can be used to produce FRP bridge components. Background information on the size and form of component for each method, and the mechanical properties achieved, is available on the internet and in several publications such as Barbero (2011), Bank (2006) and Hartley (2010). The processes of pultrusion, pulwinding – and to a lesser extent filament winding and resin transfer moulding (RTM) – produce standard components that can be many in number. The other processes in **Table 4.3** are for moulding and free-form components that are usually few in number. Sandwich constructions are not fabricated using the three processes of pultrusion, pulwinding and filament winding. Other methods that could be used for bridge components are hot press compression moulding and injection moulding (Quinn, 1999). Note that because there are always going to be advances in processing technology, knowhow and constituent materials the designer should ask questions to discover what can be achieved before deciding on a particular process.

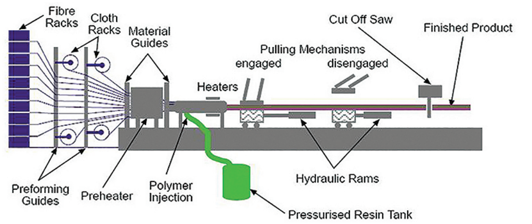
BS EN 13706-2:2002 specifies the general requirements to the specification of all types of structural FRP components produced by the pultrusion processing method. Within the range of shapes produced standard ones mimic the shapes of standard steelwork sections. The other processing methods in **Table 4.3** do not have a similar specification standard. All matrices should be cured as per the manufacturer's recommendation. Field modification of resin chemistry should not be permitted.

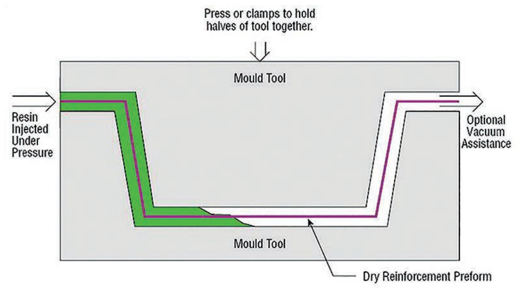
Table 4.3 Summary of composite processing methods used for bridge engineering (courtesy Gurit)

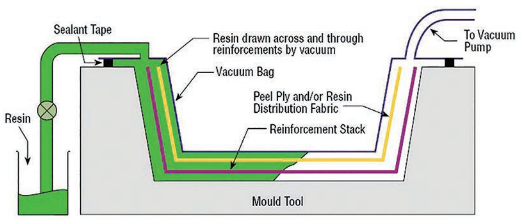
<table>
<tr><th>Process</th><th>Schematic representation</th></tr>
<tr><td>Spray lay-up (contact moulding)</td><td>


</td></tr>
<tr><td>Wet lay-up or hand lay-up (contact moulding)</td><td>


</td></tr>
<tr><td>Vacuum bagging (moulded)</td><td>


</td></tr>
<tr><td>Pultrusion</td><td>


</td></tr>
<tr><td>Resin transfer moulding (moulded)</td><td>


</td></tr>
<tr><td>SCRIMP, RIFT, VARTM, resin film infusion etc (moulded)</td><td>


</td></tr>
</table>

Key

SCRIMP = Seemann Composites Resin Infusion Moulding Process

RIFT = Resin Infusion under Flexible Tooling

VARTM = Vacuum Assisted Resin Transfer Moulding

4.5 ADHESIVES FOR BONDED CONNECTIONS

This section summarises what the designer ought to know to be able to choose the adhesive product for the fabrication of sandwich construction with the bonded core or bonded connections (and joints) when one of the joined materials is FRP. For structural joints where the method of connection is adhesive bonding there is the design guidance given in **Section 5.5.4**. A useful text on bonding specific to civil engineering is Mays and Hutchinson (1992). Other sources for background information are Lees (1984), Clarke (1996), Hutchinson (1997) and The Concrete Society (2012). Guidance by Clarke (1996) is solely for the joining of FRP to FRP, whereas information provided by The Concrete Society (2012) is for strengthening concrete structures using fibre composite materials.

4.5.1 Selection

The adhesive should be selected to be compatible with both adherends (one may not be of FRP) and meet the specified performance and design requirements. To do this there should be a check made either in co-operation with the adhesive manufacturer or by testing, as a possible material incompatibility may significantly reduce the adhesion. When the adherend materials have dissimilar stiffnesses or coefficients of linear thermal expansion, a ductile adhesive is recommended. Where practical, a ductile adhesive is to be selected in preference to a brittle adhesive. The shear stress–shear strain response at room temperature, for ductility, will have considerable non-linearity, and a shear strain at failure that could be an order of magnitude higher than when the adhesive's mechanical properties is for a brittle mode of failure (at 1.5 to 3 per cent).

The starting point for any successful adhesive selection procedure is a comprehensive and clear specification. The following guidance is given in Clause 5.3.4.3 in Clarke (1996):

- Adhesive selection should be based on previous experience or on a specific selection process.
- Preliminary adhesive selection should be performed using any unbiased method, which includes all the factors required for a reliable selection procedure.
- Any selection process can do no more than suggest one or more generic types of adhesive that are worthy of more detailed examination (Lees, 1984).
- A detailed selection within the most promising groups of adhesives can be based on information provided in publications or by the adhesive manufacturer.
- Whenever necessary, tests in accordance to appropriate ISO or American Society of Testing and Materials (ASTM) standards are to be performed to verify the adhesive material property data.
- Factors to be considered in adhesive selection are:
  - adherend materials and compatibility
  - environmental factors, including maximum service temperature
  - design actions for creep/peel/fatigue/impact resistance
  - joint geometry restrictions
  - bonding, gap filling and curing processes and working life
  - adhesive/preparation/application/curing cost
  - manufacturing aspects
  - special requirements, including health and safety
  - availability and size of post-cure heating facilities.

The term working life for an adhesive is the length of time a product remains low enough in viscosity such that the adhesive can still be easily applied to a substrate in a particular application. Lees (1984) provides an alternative adhesive selection procedure that can be recommended. His method is based on the elimination of adhesives using a questionnaire form to indicate the most suitable – or least objectionable – adhesive for any particular application.

The range of adhesive products is vast and for structural engineering applications they can be broken down by chemistry group. **Table 4.4** presents the three main groups and gives a summary of important characteristics for selection. It is recommended that the designer seeks advice from experts when selecting an adhesive for structural engineering applications. These experts can include material suppliers, fabricators, and consultants known to have experience of working with this method of connection.

Table 4.4 Adhesive types with their characteristics

Adhesive type	Characteristics
Epoxies and toughened epoxies	■ Relatively high mechanical strength having shear strength of 25 to 40 MPa. ■ Excellent adhesion to most metals, FRPs, many polymers, concrete, glass and wood ■ High chemical resistance ■ Known long-term durability (airplane structures bonded with an epoxy adhesive 40 years ago are still fit for purpose). ■ Wide range of working lives is possible ■ Relatively high rigidity (except for toughened epoxies that are often rubber modified), so a poorer resistance to peel or cleavage actions ■ Typical service temperatures: −55° to +120°C ■ (Examples in **Appendix A1** of joints using epoxy adhesive with mechanical interlocking are for the ACCS bridges of Aberfeldy, Bond Mill, Parsons and Wilcott.)
Polyurathanes	■ These semi-structural adhesives have shear strengths of 6 to 20 MPa. ■ Excellent adhesion to FRPs, metals, polymers, glass and wood ■ Regarded as durable, having adequate water resistance and high tolerance to oil and fluid ■ Working life times are limited ■ More flexible than most epoxies ■ Typical service temperatures: −75 to +80°C
Urethane methacrylates (acrylics) structural adhesives	■ Relatively high shear strengths: 10–30 MPa ■ Excellent adhesion to almost all polymers and FRPs ■ Two-component thermoplastic (one is for the hardener), with various mixing ratios, possessing, at room temperature, fast curing (from 10 to 120 minutes) ■ Higher impact and fatigue resistance, with good resistance to water and chemicals ■ Higher working service temperature range that exceeds 150 to 175°C

4.6 MECHANICAL PROPERTIES

One advantage of lamination is that the fibre reinforcement can be arranged to tailor the directional mechanical properties, with the laminate's 0° in direction of the principal loading. It is recommended that the stacking sequence of the laminae be balanced and symmetrical (Barbero, 2011). This design restriction prevents the existence of interactions between in-plane and out-of-plane deformations that can be difficult to design for.

Issues related to the determination of mechanical properties for design are introduced in Section 5.1.12. Characteristic values for any FRP material should be determined by testing the laminate using the appropriate standard test method and suitable statistical analysis, such as found in Annex D of BS EN 1990:2002+A1:2005.

4.6.1 FRP materials

Mechanical properties of an FRP laminate will derive from those of the reinforcing fibres and lamination arrangement and from the way the reinforcement interacts with the matrix in the individual laminae. Variations for the as-received laminate will be realised from changes in the matrix properties, the fibre volume fraction (FVF) and the fibre orientation(s) throughout the laminate. **Figure 4.2** gives the linear elastic tension plots to ultimate failure for five fibre types, when the unidirectional laminate is of epoxy resin and has an FVF of ≅ 60 per cent. The comparison shows the range in tensile or compressive strengths and tensile or compressive longitudinal moduli of elasticities. A brittle type of response is found for both loading actions. The plots show how fibres, such as aramid have very different properties when loaded in compression. When a unidirectional FRP material is subjected to load either in the transverse (90°) direction or for pure in-plane shearing the stress–strain curve shows non-linearity before ultimate failure. Note that to fully characterise the in-plane properties of a single unidirectional laminate requires up to five independent measurements combining elastic constants and a strength. If the structural material can be assumed homogeneous and isotropic (eg structural steel, which for one grade has an entry in row 11 of **Table 4.1**) only a single standard coupon test is needed to characterise the design properties (yield strength, modulus of elasticity and Poisson's ratio).

If no characteristic value is known, an allowable design may be taken as the minimum value for that property that is expected to exist in the structure at the time of execution. Characteristic values are material properties that have been obtained by statistical methods from coupon test data and are expected values based on a defined probability and confidence level. In limit state design (BS EN 1990:2002+A1:2005) characteristic values are factored down using partial factors to, effectively, give what is referred to as material design allowables. In North America, characteristic values can be determined using ASTM D7290-06 (2017), because this standard is specific to FRPs intended for use in civil engineering structural applications. By using a different statistical distribution and analysis method to BS EN 1990:2002+A1:2005 there will, with the same data, be a difference in the characteristic value determined by the two standards. Another important difference is that the minimum batch size of coupons for the ASTM approach is 10. A batch with fewer coupons (say a minimum of three) can be used in the Eurocode approach. In **Section 5.1.12** on design by testing there is a discussion of the number of nominally identical test specimens per batch when characteristic values for resistance formulae are to be established. The authors recommend that for a reliable determination of the mechanical properties for strength and stiffness the minimum batch size should be 10.

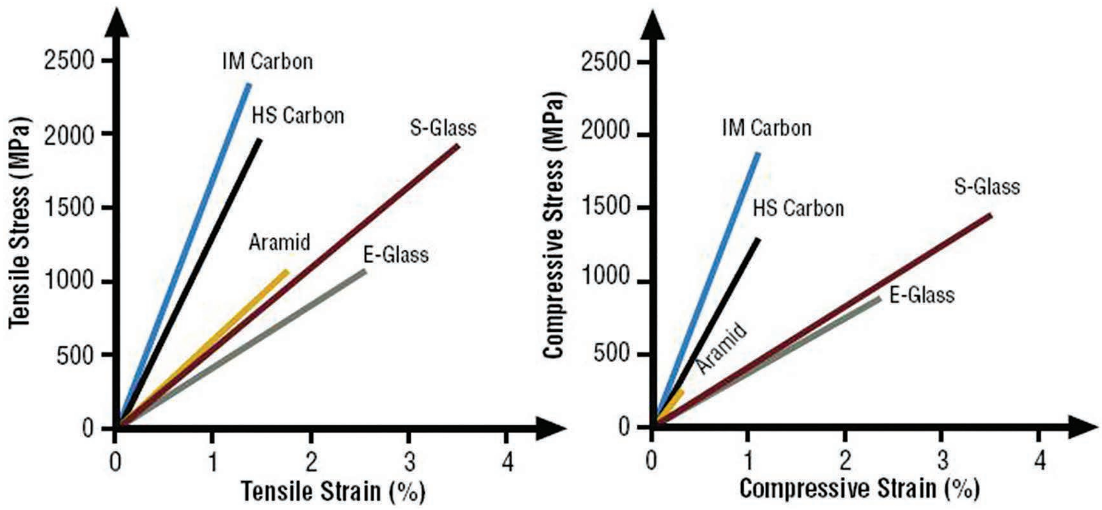


Figure 4.2 Direct stress against direct strain relationships for unidirectional FRPs, tension (a) and compression (b) (courtesy Gurit)

In the design part to Clarke (1996) strengths and stiffness of FRPs can be determined at three levels:

1 Properties of constituent fibre and matrix materials are determined by standard test. Properties of individual laminae, laminates and panels are derived from theory, ie micromechanical modelling using constituent properties for lamina properties and (classical) lamination theory for laminate and panel properties (Barbero, 2011).

2 Properties of individual laminae are determined by standard test. Properties of laminates and panels are derived from theory, ie by applying lamination theory (Barbero, 2011).

3 Properties of laminates and panels are determined by testing – there is no theory.

As the level number increases the partial factor for resistance can be reliably reduced. This approach, taken from Ascione *et al* (2016), following Clarke (1996), is presented in **Section 5.1.9** for partial factors for FRP materials, which are expected to be valid only at Level 3.

There are standard test methods from ISO and ASTM catalogues that are employed. Many of the standards for testing composite materials were not written for the types of (thick) laminates that are needed in bridge engineering and so it may be necessary to do the testing in accordance with the clauses and not exactly to them.

Table 4.5 is reproduced from Ascione *et al* (2016) to give recommended ISO test methods. For balanced symmetrical laminates the short-term properties in this table should be determined (using the ISO standards) with respect to the two principal directions (ie 0 and 90° orientations). For comparison, the ASTM standards that are required in design guidance for pultruded structural are listed in the third column of **Table 4.5**. The qualification 'short-term' is required to indicate that the mechanical properties are being determined shortly after composite processing and thereby do not account for changes due to long-term durability effects. These effects are introduced in **Section 4.6.5**.

Neither of the guidance sources presented in **Table 4.5** recommends a through-thickness tensile strength standard. ASTM D7291/D7291M-15 is for a new test method designed to produce through-thickness failure data for structural design and analysis, quality assurance and research and development. There is no ISO equivalent standard.

Stiffness properties (elastic constants) for deflection and global stability checks should be defined using average values obtained from testing. Stiffness properties for checking of local buckling resistance (such as skin wrinkling or shear crimping in sandwich construction – see **Section 5.3.2**) should be based on characteristic values. ASTM D7290-06 (2017) and BS EN 1990:2002+A1:2005 scopes both strength and stiffness and a characteristic value representing the 80 or 75 per cent lower confidence bound on the fifth-percentile value of a specified population.

Table 4.5 Mechanical properties for design

Property	ISO test method (Ascione *et al*, 2016)	ASTM test method (ASCE, 2010)[1]
0° tensile modulus 90° tensile modulus	BS EN ISO 527-4:1997	ASTM D638-14
0° tensile strength 90° tensile strength	BS EN ISO 527-4:1997	ASTM D638-14
0° compressive modulus 90° compressive modulus	BS EN ISO 14126:1999	ASTM D6641/D6641M-16e1
0° compressive strength 90° compressive strength	BS EN ISO 14126:1999	ASTM D6641/D6641M-16e1
0° pin-bearing strength 90° pin-bearing strength	BS EN 13706-2:2002	ASTM D953-10
0° interlaminar shear strength 90° interlaminar shear strength	BS EN ISO 14130:1998	ASTM D2344/D2344M-16
Major Poisson's ratio Minor Poisson's ratio	BS EN ISO 527-4:1997	ASTM D638-14

Note

1 This standard is to be published following approval through the standard's committee. The draft version (ASCE, 2010) may be obtained on request from the Pultrusion Industry Council (PIC) of the American Composites Manufacturers Association (ACMA).

A word of caution is necessary concerning the reliability of the pin-bearing strength test method in ISO 12815:2013. The test results in Mottram and Zafari (2011) show that pin-bearing strength (laterally unrestrained because there is no bolt tightening torque) reduces, for a constant thickness of pultruded FRP, with increase of bolt diameter and increase of hole clearance. To determine the pin-bearing strength by testing it is essential to duplicate the actual bolted connection details, and to not account for the considerable beneficial effect on strength if there is lateral restraint.

Because FRPs absorb and desorb moisture and there are durability changes in mechanical properties over time, as explained in Section 4.6.1, it is of relevance to know what the moisture uptake is. ASTM D5229/D5229M-14 is for a test method that has a procedure for the determination of moisture absorption or desorption properties in the through-the-thickness direction for single-phase Fickian solid materials of FRP in flat or curved panel form. There is no BS equivalent standard.

Annex B (Ascione *et al*, 2016) reported indicative values for fibre, lamina and laminate properties that can be used in preliminary design.

Table C1 in (informative) Annex C in BS EN 1991-1-5:2003 presents coefficients of linear expansion for conventional structural materials, but it does not have data for any FRP material. The directional coefficients of thermal expansion for an FRP material can be assumed linear and they should be determined by physical testing. There is no ASTM or ISO standard test method for coefficient of linear thermal expansion for an FRP material, only for plastics. For their pultruded shapes Fiberline Composites report typical values of 8 to 14 × 10^{-6} K^{-1} and 12 to 22 × 10^{-6} K^{-1} in, and transverse to, the direction of pultrusion. For preliminary design, an estimate for a coefficient for other FRP laminates can be established using micromechanical modelling (Barbero, 2011), as long as the constituent properties for the closed form equation are available. Alternatively, indicative coefficients can be taken from the mechanical property data presented in Hancox and Mayer (1994) and Quinn (1999).

4.6.2 Core materials

Properties for core materials can be obtained from manufacturers' minimum stated values or via the Approval Finder with DNV GL (2016). Core properties typically vary with material density, and these minimums are normally defined based on a regression analysis of test data to determine core properties at the minimum supplied density. Another source for core properties is Annex D (normative) on sandwich mechanical core properties and sandwich calculation in BS EN 12215-5:2008+A1:2014. Where the mechanical properties of sandwich cores have not been verified by testing, the respective properties for small craft hull construction and scantlings have to be taken from Table D.1 in this standard.

4.6.3 Factory components

For composite processing methods, such as pultrusion, where the FRP is produced in the factory in a continuous and repeatable way, design properties of the finished component may be taken from the manufacturer's minimum data. However, the data need to meet the requirements of being characteristic values, in accordance with BS EN 1990:2002+A1:2005.

In Part 3 of BS 13706-3:2002 Table 1 (presented in **Table 4.6**) gives minimum properties that are required for two grades of pultruded shapes. The two grades of E17 and E23 are defined by their properties with 'E' for the longitudinal modulus of elasticity which, in Table 1 of BS 13706-3:2002, is 'tension modulus-axial'. For the purpose of material specification the standard requires that a pultruder has to meet all the requirements for all the minimum properties included in Table 1 (**Table 4.6**).

Because commercially available pultruded shapes supplied in the European Community have to meet these requirements the minimum values of the as-received material can be used at the preliminary design stage. The moduli and strengths presented in **Table 4.6** are not characteristic values and can be significantly lower than the actual mechanical properties for a pultruded shape. Actually, values for material stiffnesses and strengths will be dependent on the size of shape, fibre architecture, matrix composition, and pultrusion processing conditions.

Table 4.6 Minimum properties that are required for each grade (from BS EN 13706-3:2002)

Property	Unit	Test standard	Minimum properties	
			E23 grade	*E17 grade*
Full section test	GPa	Annex D, BS EN 13706-2:2002	23	17
Longitudinal tension modulus of elasticity	GPa	BS EN ISO 527-4	23	17
Transverse tension modulus of elasticity	GPa	BS EN ISO 527-4	7	5
Longitudinal tension strength	MPa	BS EN ISO 527-4	240	170
Transverse tension strength	MPa	BS EN ISO 527-4	50	30
Longitudinal pin-bearing strength	MPa	Annex E, BS EN 13706-2:2002	150	90
Transverse pin-bearing strength	MPa	Annex E, BS EN 13706-2:2002	70	50
Longitudinal flexural strength	MPa	BS EN ISO 14125	240	170
Transverse flexural strength	MPa	BS EN ISO 14125	100	70
Longitudinal interlaminar shear strength	MPa	BS EN ISO 14310	25	15

4.6.4 Moulded components

Mechanical properties of moulded free-form components are not commonly publicised and will vary depending on the method of processing (see **Table 4.3**), and the skill of the laminator(s), especially for spray, hand and wet lay-ups. A design approach of taking mechanical properties from technical literature to design should also note the partial factors given in **Table 5.3** (**Section 5.1.9**).

Testing of laminates for a project in accordance with this section of **Chapter 4 and Section 5.1.12** will provide more confidence in the design properties. Properties determined by coupon testing should be carried out in accordance with recognised test standards, such as presented in **Table 4.6**. Characteristic values for the fibre dominated properties should be normalised with respect to the design FVF to have reliable design properties.

4.6.5 Durability of FRP materials

FRP has been used successfully over the past 60 years in a wide range of applications in the marine and civil engineering sectors. These include pipes, tanks, slabs, walkways, bridge decks, gratings, column reinforcing wraps and reinforcing bars for concrete. In many of these applications FRPs are exposed to one or more environmental influences. FRPs can be formulated to meet the durability requirements of even the harshest environment, and they are durable because they are water resistant, thermally stable and cannot rust. Durability means that all the basic requirements in BS EN 1990:2002+A1:2005 are satisfied over the structure's design working life, which is a design requirement in itself.

Characteristics of the FRP material having an impact on durability are: constituent material combination, composite processing method, surface protection, void (porosity) content, cure process (with post-curing contributing to a longer service life), chemical resistance of the fibres, matrix, fibre–matrix interphase and fibre–matrix interface bond. It is advisable to consult with the resin/matrix supplier to evaluate a material's suitability against the design criteria and project site requirements.

Durability of FRPs is generally good when compared to the performance of conventional structural materials. Durability performance will ultimately depend on the quality of the laminate (see **Section 6.4.3**). The structural form of the designed component or structure is also going to be important, such as having curved or flat surfaces where water does not run off. FRPs generally exhibit exceptional resistance to corrosion (they do not rust) in the aggressive environments in which bridges are located, including in marine salt environments. The durability of polymeric composites is a complex and wide-ranging subject and more information for civil engineering applications can be found in the book edited by Karbhari (2007).

Box 4.3 Dover footbridge – materials characterisation (courtesy Pipex PX)

For the Dover footbridge (**Figure 2.11**), the FRP structure was processed using a combination of pultruded and moulded shapes. The main compression and tension cords were resin infused shapes, while the truss members consisted of back-to-back pultruded shapes with additional infused connection plates. The tension cords are incorporated into a single deck design, by way of thickening at the edges and upstands.

The flooring and deck sections of the footbridge comprise moulded sections 5 mm to 29 mm thick. Matrices are of two-component epoxy systems, specially formulated for resin transfer processing methods such as injection or infusion.

The fibre reinforcement lay-up varied by having different weight fabrics (typically 1150 g/m^2 and 1200 g/m^2) and a variety of fabric types (unidirectional, 0/90° and 0/90/45/−45°, arranged in the laminate with several different orientations).

An adhesive is used for bonded connections. Glass spheres are added to ensure constant bond-line thicknesses of 0.5 mm to 1 mm.

The post-curing process involved 24 hours cure at ambient room temperature and 16 hours at 60°C. Coupon tests were undertaken to:

- avoid the use of theoretically determined mechanical properties that would require the application to be designed with more conservative material factors and would thereby increase overall product cost
- determine the required design mechanical properties for the individual laminate
- be able to use these lamina properties to model the structure's laminates in 2D shell finite element modelling and simulations (see **Section 5.2.3**)
- support the reliability of the laminates and composite processing methods for FRP components
- permit the development of the most realistic finite element model to compare computational predictions against test results from physical testing of the assembled footbridge structure.

The effects of outdoor use on structural FRPs such as glass/polyester or carbon/epoxy laminates are confined to the surface and do not often involve a serious threat to their structural integrity. The effects are mainly cosmetic including the following.

- Fading and darkening. Colour fading or darkening without loss of gloss can be due to the use of unstable pigments or pigment combinations that change colour after exposure. This can be mitigated by the appropriate choice of pigment.
- Yellowing is usually due to the darkening of the base gelcoat resin, especially in whites. This can be overcome by using a more UV-resistant resin and better UV additives, and by ensuring good cure of the resin. Surface coatings also provide protection.
- Blooming is caused by migration of an incompatible pigment or additive to the surface of a gelcoat to give a mat, faded appearance.
- Loss of gloss and chalking is normally brought about by erosion of the surface layer of the gelcoat due to chemical and/or physical damage.

The chemical resistance of FRP is predominately attributed to the matrix because it protects the reinforcing fibres. The fibres themselves (introduced in **Section 4.2.1**) may have different corrosion resistance properties. For example, CR-glass has a greater resistance than does E-glass. The influence of additives, modifiers or fillers on durability performance should be taken into account. Consideration needs to be given to the presence of fire-retardant additives and to the amount of filler (specified as a percentage mass of polymer resin).

What is known is that, over time, an FRP material will absorb and de-absorb water, either by direct contact or via moisture in a humid environment. The diffusion process can be reversible or irreversible and is temperature driven. When the water uptake increases to a maximum (one to three per cent of FRP mass) there can be physicochemical changes within the matrix, within the interphase, at the fibre-matrix interface bond and on the fibre surfaces (Grammatikos *et al*, 2015). These changes in microstructure are slow, and can either reduce or increase (eg because of post-curing) the mechanical properties established by coupon testing on as-received material from the supplier. An important reason why the changes cannot be easily quantified is that the mechanisms, promoted by thermal energy, can occur at different times and with different (unknown) rates. It is feasible that a new mechanism is activated after an existing mechanism or more so when it reaches a critical point in its lifetime, either independently or via an interaction. Because different FRP materials might not respond over time in the same way to different environments it is important for the designer to known and to take account of the degree and type of exposures to chemicals, including water.

The rate of diffusion of moisture into and out of an FRP material will depend on the FRP's surface condition. The presence of a surface veil (in pultrusions) reduces the diffusion coefficient (Grammatikos *et al*, 2015) and will provide a level of UV (sunlight) protection. Exposure to UV (see **Section 4.6.7**) can cause the matrix at the surface to develop micro-cracking, and this subsurface degradation will promote an increase the moisture diffusion.

The effect of any swelling stresses from the long-term uptake of water to a saturation level is to be taken in account (Barbero, 2011) in design.

When considering a particular matrix/fibre combination and composite processing method for an intended environment, the degree of exposure, the concentration of the corrosive element(s) and the temperature of the environment needs to be known. The relative performances of polyester, vinyl ester and epoxy based matrices have been introduced in **Section 4.1.6**. The designer can consult corrosion resistance guides from resin suppliers and composite producers that have been prepared using test results from exposing materials to chemical environments at various concentrations and temperatures. These guides will provide recommendations for the applications of FRP products.

Because of the challenge in knowing how to manage the uncertainty with the change in mechanical properties over the working life there is no consensus approach on how long-term effects are dealt with in the guidance from Clarke (1996), Ascione *et al* (2016) or ASCE (2010). They all apply a pragmatic engineer's approach by having 'knock-down' factors to account for expected (conservative) changes in resistances that are calculated using mechanical property data (see **Section 4.6.1**) determined for an FRP material soon after matrix curing. The presentation of the approach in Ascione *et al* (2016) is likely to be the most helpful, and is presented in **Section 5.1.10**. It is based on the correct selection and processing of the laminate and application of protective measures. The approach is to multiply together specified conversion factors (Clauses 2.3.5 and 2.3.6 in Ascione *et al*, 2016) that should account for the changing effects of temperature, humidity, creep and design actions (for fatigue). If post-curing is present the 'knock-down' factor can be > 1.0.

The designer has to be aware that environmental stress corrosion (ESC) cracking is the process that can take place when a glass fibre laminate is subject to permanent stress. Should an aggressive corrosive medium penetrate into stressed laminate, such as via a surface matrix crack, the fibres may corrode and fail. This form of durability degradation allows the matrix crack to propagate to adjacent fibres, which in turn become exposed to the aggressive medium, and they will in time fail because of ESC. So the 'matrix' crack will continue to propagate as long as the stress is applied, and this can result in catastrophic failure. E-glass fibres are susceptible to ESC, and so to mitigate against ESC resistant CR-glass reinforcement is recommended.

In Clause 3.2 of Ascione *et al* (2016), 19 ASTM and ISO standards are listed that can be used in durability testing with FRP materials and adhesively bonded joints. It should be understood that none of the test results from using these standards will provide very reliable data on how the FRP material or bonded joint will actual perform in the field. One challenge for those working on the durability of polymer and FRP materials is that any form of accelerated ageing in the standard testing (Broughton *et al*, 1998, Bank *et al*, 2003) does not simulate what an FRP will experience on site over the decades of service working life for the component or structure. Changes in mechanical properties due to changes in temperature need to be included in the design, and the conversion factors in **Section 5.1.10** allow for this requirement.

It is recommended (Ascione *et al*, 2016) that T_g, – as determined by BS ISO 6721-11:2012 using the storage modulus measure – should be at least 20°C above the maximum service temperature of the FRP structure. In ASCE (2010) the maximum service temperature is T_g − 22°C, by ASTM D4056-16. Because T_g is a matrix property that depends on how it is measured and the chemical–physical state of the resin the authors of this guidance propose that the maximum service temperature to be T_g – 30°C. Note that by BS ISO 6721-11:2012, it is necessary for the matrix to be fully saturated with moisture. This is because the wet T_g is lower than the dry T_g (Karbhari, 2007). Aramid has a more limited thermal range than do the types of glass and carbon, with fibre mechanical properties starting to change at around 100°C.

The designer may assume that the durability performance of adhesively bonded connections and joints (**Section 5.5.4**) will be similar to that of the resin matrix in an FRP material. Information specific to the durability design for fatigue resistance is given in **Section 5.3.3**.

4.6.6 Galvanic corrosion

A design aspect that should be considered when using carbon fibre reinforcement is the potential for galvanic corrosion. To reduce the risk of galvanic corrosion the isolation of metal fixtures from carbon FRPs should be considered. This is particularly of relevance if the FRP structure with carbon fibres is in a marine environment.

4.6.7 UV protection

Matrix systems can be susceptible to degradation mechanisms under ultraviolet (UV) light from the sun (Chapter 5 in Karbhari, 2007). Epoxies are particularly susceptible. An additive in the matrix can give the laminate improved UV resistance. It is recommended that every exposed surface needs to be protected from sunlight by a suitable paint or gelcoat finish. Because absorption of UV radiation diminishes rapidly with depth the photochemical reactions are often limited to the topmost several microns to 1 mm in depth.

Colour of the FRP component may influence the temperature reached inside and so it is advisable with dark colours to check by testing that the temperature does not exceed the specified design limit. Practical experience and accelerating tests have shown that a service life of 50 years can be achieved without any problem due to UV induced degradation.

The designer is responsible for the choice of matrix system and, if required, a protective coating that provides the required UV performance of exposed surfaces of an FRP component over its design working life. Two approaches that ensure UV protection are either to have a protective fascia hiding primary structural FRP components or to check whether the loss of any FRP surface material directly exposed to sunlight has a significant detrimental effect and modify laminate thickness accordingly.

4.6.8 Fire performance

With the appropriate choice of resin, additive and fillers, FRP materials can be used to make structures to meet modern fire retardancy standards. In addition, FRP composites generally are good thermal insulators, so they can significantly limit the heat of a fire spreading in the way that can occur with metals.

With composites usage in demanding applications increasing, knowledge of their fire performance becomes a safety-critical issue. The heat from a fire may weaken the polymer and cause eventual creep, leading to structural failure. Alternatively, the polymer itself may ignite and spread the flame, releasing further heat – and potentially toxic smoke – but this can be mitigated by the inclusion of fire-retardant additives. So, as mentioned, composites are by their nature inherently fire resistant. The inert fibre-reinforcement displaces polymer resin during fire and removes fuel for the fire. When the outermost layers of a composite laminate lose their resin, they act as an insulating layer, slowing heat penetration.

Flame retardant resins are available that significantly reduce the flammability of FRP. Some resins (eg brominated vinylester) resist the spread of flames, although they do not necessarily improve ignition properties. Phenolic resins have excellent charring capabilities resisting fire ignition more effectively than other resin systems. Additives can be passive, for example inert fillers reducing organic flammable content, and smoke, active, releasing flame suppressing or cooling gases, or even intumescent, expanding with heat to provide additional heat insulation thickness. Coatings may also be used on or within a composite product to delay ignition, lower the rate of heat release, suppress lateral flame spread and extend the duration of fire resistance. Fire protection systems employed with steel structures cannot be directly applied to FRP structures (Ascione *et al*, 2016).

4.6.8.1 Improving fire performance in design

The main method of improving fire performance is by the inclusion of additives in the resin at the time of manufacture. These work in different ways, but are effective in reducing fammability and flame spread for polyester, vinyl ester, epoxies etc. Various types of additive are available, with improvements being made all the time to increase performance and reduce smoke and toxic emissions.

Coatings can also be used on FRPs to delay ignition, lower the rate of heat release, suppress lateral flame spread and extend the duration of fire resistance. Some intrinsically fire-resistant resins are also available, the most commonly used being phenolic. Its high fire performance has some trade-offs in structural performance, but phenolics are extensively used in mass transit and offshore engineering.

4.6.8.2 Fire – testing and standards

Many tests exist to measure fire performance, but it is important to make sure that tests relevant to the application are being applied. The most commonly used for FRP materials in the UK is BS 476, in particular BS 476-6:1989+A1:2009 and BS 476-7:1997 which test for flammability and flame spread.

Later parts of the same standard consider fire integrity under cellulosic fire conditions.

BS 476-7:1997 – this test measures the rate of spread of a flame front across a material surface, but it does not consider emission of toxic smoke and gas. Class 1 is the highest classification, with the slowest rate of spread.

4.6.9 Vandal protection

All infrastructure located in the public realm has the potential to be affected by vandalism. FRP composites can be developed to mitigate the risk imposed either by building in sufficient redundancy and strength reserves to tackle the problem at source or alternatively by protecting the composites section by the use of non-structural cladding panel in areas of high risk. Designers need to consider the risk of vandalism and consider how to deal with the following issues:

- impact damage (**Section 4.6.9.1**)
- fire damage (**Section 4.6.8**)
- graffiti (**Section 4.6.9.2**)

4.6.9.1 Impact damage

Composite materials are increasingly being used in the design of structures that will be subjected to impact during their lifetime. With their high specific modulus, high specific strength and the capability of being tailored for a specific application, these materials offer many interesting advantages. However, their behaviour under impact is a concern, because they occur during manufacture, normal operations and maintenance. The situation is critical for impacts that induce significant internal damage, which can be hard to detect by visual inspection. These impacts can result in reductions in strength of the structure.

A large amount of experimental data has been published, and several important features of impact damage have been identified. In particular, interply delaminations are known to occur at the interface between plies with different fibre orientation. Their shape is generally elongated in the direction of the fibres in the lower ply at that interface. The delaminated area is known to increase linearly with the kinetic energy of the impactor after a certain threshold value has been reached. The effect of impact damage on the properties of the laminate has obvious implications for design and inspection of actual structures.

4.6.9.2 Graffiti

Graffiti can either be prevented using an anti-graffiti coating or cleaned using solvents post incident. Overpainting is also another option which is often an effective strategy where the structure is in a low risk area. In general, gelcoats and paints will usually be applied to avoid UV degradation and limit moisture ingress. The designer needs to consider the combined challenge of tackling not only UV and moisture absorption/desorption, but also graffiti, fire retardance and impact damage (see **Section 4.6.9.1**).

It is practical to apply a variety of paints and/or gelcoats, with or without anti-graffiti coatings. Consideration for long-term durability can be needed from the impact of solvent cleaning.

4.7 SUMMARY

The designer can be faced with a considerable task when selecting the materials for an FRP bridge project. The decision-making process will be guided by the information in this chapter, once the structural forms of the FRP components or structure are known. The reason for this qualifier is that once at this design stage, the composite processing method or methods will be known. For structural calculations, there is in the public domain, at best, mechanical property data for preliminary design. Should a specific mechanical property value for an FRP or core be unavailable, it may be obtained from a compilation source, such as Hancox and Mayer (1994) or Quinn (1999).

For final design calculations, it is recommended to measure the mechanical properties as characteristic values with the FRP material(s) processed using the conditions for the FRP bridge components themselves. Accounting for the change in mechanical properties of materials in design owing to durability effects will be by the application of conversion factors (Ascione *et al*, 2016), which are effectively ‘knock-down’ values to account for the influences of temperature, humidity, creep and fatigue.

Good practice learning points

- **Passive protection.** Use replaceable cladding panels (FRP or other) as a solution. This provides an option for aesthetic improvements and permits closer attention to fibre reinforcements in high stress areas such as connection details and locations.
- **Materials for impact.** If necessary, consider (where needed) the use of aramid, carbon, glass hybrids in thick FRP sections with in-built damage tolerance can improve impact strength.

As with all issues in design there is always a compromise to be struck between the different material properties needed for a bridge engineering project. If fire resistance is a critical design requirement FRPs can often be the most cost-effective material solution.

Considerations for design include:

- **Resin selection.** Phenolics generally provide the best protection. Note that they can be a challenging resin to work with. Phenolic handrail system has been deployed on oil rigs where the specified safety and performance requirements have shown this FRP solution to provide significant value.
- **Additives.** One filler to improve fire resistance is alumina trihydrate in a resin matrix. This matrix system is used to create panels for cladding structures at the Ferrari Land theme park in Spain.
- **Design approach.** Early consultation with the intended manufacturers will be beneficial for understanding their preferred methods and manufacturing processes. Typical areas to discuss are the manufacturer's proposed post-cure process (temperature/duration), which will have a bearing on FRP strengths. Understanding these processes will allow for the appropriate materials factor of safety to be adopted for the different approaches (see **Section 5.1.9**). Limitations of processing equipment can be established and technical information can be obtained relating to the preferred constituent materials they use.
- **Materials characterisation.** It is worth noting that for moulded components material characteristics may vary between suppliers working with the same constituent materials. This is because of the effect of the surrounding environment on the final mechanical properties. It is important to know that limited product and material data is available for numerous practical resin and fibre reinforcement configurations. For moulded structures detailed testing is required to have the design and actual material and mechanical properties.
- **Specifications.** Design specifications have to include reference to all parts (Parts 1, 2 and 3) of BS EN 13706 for pultrusions where the standard specifies the minimum requirements for the quality, tolerances, strength, stiffness and surface of structural profiles.
- **Minimum properties in BS EN 13706.** Some pultrusion may have properties greater than those specified, and this is especially pertinent for thicker and heavier sections. The design engineer should discuss with the pultruder the anticipated values and make allowances within the design.
- **Pultrusion availability.** Not all sections are readily available, and the largest sections may need to be individually manufactured on a project-by-project basis. Understanding the availability will be an important aspect to consider in all future bridge designs.
- **Styrene concerns.** Styrene is an essential component of unsaturated polyester resins used in some FRPs. It both solubilises the resin and aids the cross-linking in the cure phase. Styrene is classified as harmful and flammable. The current UK workplace exposure limit is 100 ppm max over an eight hour period. There is a voluntary industry code of practice to work below 50 ppm. Open moulding applications are deemed a much higher risk, so a move towards the use of closed moulds and vacuum bagging is preferred. An alternative possibility it to combat the risk at source with the use of more environmentally friendly products.
- **Cleaning with acetone.** Acetone is a colourless, volatile liquid, and the solvent is used in cleaning up liquid polyester and vinyl ester resins. It dissolves liquid resin, allowing clean-up of spills, rollers, brushes and other equipment. Prolonged or repeated exposure of the skin to acetone removes natural oils, resulting in dryness or cracking. It also readily forms a vapour at low temperatures. In small or poorly ventilated rooms this vapour can build up and, in high concentrations, can cause irritation to the eyes, nose and throat. Acetone is also highly flammable.

5 Structural design

While the authors have sought to present useful and consistent information in this chapter, users of this information and guidance need to be satisfied with its suitability for the purpose for which they intend to use it.

There is a need for the designer and other stakeholders to have practical rules for the design and verification of components and structures for the execution of FRP bridge engineering. In this document, the term 'component' is used for all the individual parts that are present in a bridge structure. There is guidance available from multi-partner collaborations in countries, such as the UK, the Netherlands, Italy, Germany and the USA. Notable publications from these projects are Clarke (1996), Highways Agency (2005), CUR (2017), CNR (2008), BÜV-Empfehlung (2014) and ASCE (2010). Only Highways Agency (2005) is specific to FRP bridges. None of these sources are recognised as a national or international design standard.

Experience gained so far from FRP bridge projects throughout the world and especially in the UK (see the 23 case studies in **Appendix A1**), combined with knowledge and understanding from theoretical and experimental programmes of research does now make it feasible to prepare a comprehensive set of guidelines. In Europe, the members of Working Group 4 in CEN/TC 250 have compiled a set of rules (Ascione *et al*, 2016) that relate to the principles and fundamental requirements of the Eurocodes: *"The report presents scientific and technical background intended to stimulate debate and serves as a basis for further work to achieve a harmonised European view on the design and verification of such structures."* Ascione *et al* (2016) have sought to present appropriate and consistent information, but users need to be satisfied of its suitability for the purpose for which they intend to use it. The expectation of CEN/TC 250 is that this pre-normative document has brought together the different national approaches to a broadly accepted and coherent set of harmonised European technical rules. It is the committee's aspiration that the report should be the precursor to the preparation of a Eurocode for the structural material of FRP.

The Ascione *et al* (2016) report scopes thermoset FRP components having a fibre volume percentage of at least 15 per cent. It deals with laminated components and structures made of profiles, plates, shells and sandwich construction. Structures in which micro-cracks in the laminate skins are not permissible are not covered. The report also does not cover FRP reinforcing rods, FRP cables or using FRP as an external reinforcement to retrofit/strengthen existing structures. (For an introduction, see Cadei *et al*, 2004 and The Concrete Society, 2012.) Structural components can be produced by means of the various composite manufacturing processes introduced in **Section 4.4**, namely vacuum bagging (for a prepreg lamination), pultrusion, compression moulding, resin transfer moulding and its variants, filament winding and hand lay-up. Sandwich panels, constructed with a core (foam, wood or honeycomb) and FRP laminated skin, are included in Ascione *et al* (2016).

A standards committee within the American Society of Civil Engineers (ASCE) is following the standards development process of the American National Standards Institute with the aim of taking a pre-standard (ASCE, 2010) and developing a new consensus standard. The intended scope of the standard is for the design of new buildings and other structures constructed of pultruded glass FRP shapes, connections and prefabricated building products. Tendons and cables are not covered by this standard. The standard is applicable to pultruded FRP structural shapes that have symmetric and balanced glass fibre reinforcement and fibre architecture combined with a polymer-based matrix. The draft version (ASCE, 2010) to the standard may be obtained on request from the PIC of the ACMA.

The justification for giving these background details to national and international documents having current guidance is to stress the fact that, at the time of writing this chapter, no rules have been given national or international recognised consensus. In other words, users of the design information in this chapter should do so in the full knowledge that the guidance could change when additional knowledge and understanding supports it.

When design guidance is known and verified with confidence, and is unlikely to see a dramatic or significant change, the mandatory word 'shall' is used. Wording such as 'should', 'may' or 'might' will be avoided wherever possible because such uncertain terms do not necessarily help the designer. It is our intention that when it is impractical to give certainty, because of lack of know-how, the guidance in **Chapter 5** will say why this is so.

It is now worth introducing the status of material specification. FRP components for use in highway structures are not currently supported by product standards. There are national and international standards for FRP materials and their application in civil engineering, but none is directly applicable to bridge engineering and other highway structures. In addition, suppliers' data sheets and design guides – similar to those provided by steel, concrete and timber producers and their sector organisations such as the Steel Construction Institute, The Concrete Society and TRADA – are not available for FRPs in construction.

In accordance with Highways Agency (2005), the limit state design principles (based on BS EN 1990:2002+A1:2005 and BS EN 1991-1-7:2006+A1:2014) can be used to design highway structures in which the main structural members are of FRP material. In this chapter, the term 'structural member' can also be taken to mean a 'structural element' or 'component' and the word 'structural' will conveniently be dropped. Highways Agency (2005) gives guidance and additional/amended requirements for the technical approval of highway structures schemes using FRP. As far as practical, the Highways Agency document is a performance standard, within broad limits on permitted materials and their manufacturing processes, as presented in **Chapter 4**.

Because the effect of local stress concentrations in elastic/brittle material (**Section 4.6.1**) needs careful consideration the bridge designer is advised to seek specialist advice from an experienced FRP designer when detailing components, connections and joints.

5.1 BASIS OF DESIGN

5.1.1 Basic requirements

In general, the basis of design as set out in Eurocode standard BS EN 1990:2002+A1:2005 can be used for the design of FRP bridge structures. Specific requirements for FRP components and structures may need to be determined, following the guidance given in **Chapters 4 to 7** of this guide.

The following guidance to design for the basic requirement of durability is reproduced from **Section 2.2** in Ascione *et al* (2016):

1. The design of an FRP structure should guarantee a constant performance over time in terms of serviceability, strength and stability, considering both the environmental conditions and the maintenance programme (see **Chapter 7**).
2. The environmental conditions should be identified during the design phase to evaluate their influence on the durability of an FRP structure, with any eventual measures being included to protect material or structural components.
3. To evaluate the performance of an FRP structure in terms of its durability, theoretical models and physical tests results (see **Sections 4.6.1 and 5.1.12**) and studies on the behaviour of similar structures reported in the literature can be referred to.
4. Components that are susceptible to degradation, mechanical wear or fatigue (see **Section 5.3.3**) should be designed in such a way that inspection, maintenance and repair (see **Chapter 7**) can be carried out adequately. All components should be accessible for inspection during use and maintenance. When this is impractical the design shall include suitable protection so that structural deterioration owing to degradation is a low risk.

5 To guarantee the durability of an FRP structure, the following should be taken into account:

a function

b environmental conditions

c composition, properties and performance of the materials (**Chapter 4**)

d suitability of the verification methods (**Section 5.2** is for structural analysis)

e choice of the type of joints (**Section 5.5**)

f quality and level of realisation control (**Chapter 6**)

g planned maintenance during the service life (**Chapter 7**)

h application of protective measures that prevent or limit deterioration in a property, based on an assessment of use, design working life, loads and required maintenance (**Chapter 6**)

i allowance in the calculations or the design for a certain level of deterioration in a material/mechanical property over time or changes in load or deformation due to long-term effects that may occur, such as creep and fatigue (**Sections 4.6.5, 5.1.10 and 5.3.3**)

6 Depending on the type of the action which affects the durability and the design working life (in accordance with BS EN 1990:2002+A1:2005), an FRP structure should be designed to consider:

a the environmental conditioning over time, to include effects of:

i UV

ii temperature

iii humidity, water and chemicals

b time-dependent influences over time, to include effects of:

i creep

ii wear

iii fatigue

c accidental actions in accordance with BS EN 1991-1-7:2006+A1:2014), that shall include:

i fire

ii lightning strike (hail storm)

iii impact

iv explosion

v transportation phase (**Section 6.2**)

vi installation phase (**Section 6.3**)

vii inspection and maintenance (**Sections 7.3 and 7.4**).

7 Effects of degradation can be considered by using appropriate conversion factors (**Section 5.1.10**).

5.1.2 Design working life

In the UK, bridge structures typically have a design working life of 120 years, as set out in the National Annex (NA) to BS EN 1990:2002+A1:2005. FRP structures (particularly if executed before 2015) have often had a lower design working life (eg 60 years) which was determined on a project-specific basis and agreed with the asset owner's technical approval authority.

Irrespective of the design working life determined for a new execution, it is recommended that the design values for wind and thermal action should be no less than for a structure with a 120-year design working life.

While FRP structures are known to be durable, the materials' mechanical properties and resistances can be affected to some extent by environmental factors throughout their design working life and these effects need to be considered in design. Recommended conversion factors, introduced in **Section 4.6.5**, to take environmental effects into account in the design are discussed in **Section 5.1.10**.

The exposed environment, duration of exposure, matrix type and formulation, fibre type and resin curing methods can all influence any time-variation in the mechanical properties of a laminate. Although FRP materials do not need to be painted, in some circumstances it can be desirable to extend the design working life of a component or structure in aggressive environments using a protective coating to external surfaces (**Sections 6.2.5 and 7.4**). Protective coatings should be compatible with the underlying FRP material and approved for use by the manufacturer. Mitigation properties of such external coatings should prove to be effective over the entire design working life of a component or structure.

5.1.3 Robustness

Providing a robust structure is a key basic requirement in BS EN 1990:2002+A1:2005 for a new execution. When the structural material has a relatively very low ductility, greater care should be taken to demonstrate robustness. FRP bridges are relatively unusual in their structural behaviour because the material's lack of ductility effectively prevents plastic or ductile stress redistribution. This means that the designer needs to be particularly careful to ensure that the structural safety is not disproportionately reliant on a localised component or joint. In particular, it is not valid for the designer to rely on the lower bound theorem of limit analysis in the design of an FRP structure.

In contrast, for the ultimate limit state (ULS) design of structures that do exhibit ductility and where the overall stability is not sensitive to the deformations, the lower bound theorem is often used to justify the assumption of convenient simplified structural idealisations for analysis. For example, this approach is often used in steel or concrete bridge design at the ULS where the relative stiffnesses of members are not fully accounted for, or where self-equilibrating effects are sometimes ignored. The lower bound theorem would often appear to suggest that such an approach would be safe in design. Importantly, because of the lack of ductility in FRP structures this convenient design approach is not valid or safe.

The designer should seek to rigorously analyse the true distribution of stresses without making simplifying assumptions that cannot be justified without recourse to the lower bound theorem. In this way, the risk of local overstresses and associated local damage to the structure may be reduced. Nevertheless, it remains possible that some localised damage could occur due to, for example, fabrication defects, vandalism or unexpected accidental load events. In such a situation it is important that the local damage does not lead to structural collapse. The designer should identify any vulnerable components, connections or joints and consider how the structure would cope with the potential for disproportionate collapse (BS EN 1990:2002+A1:2005). Structures should be designed such that localised failure of a joint or member does not lead to progressive collapse of the structure. Limited guidance for robustness is given in clause B.9.1 of BS EN 1991-1-7:2006+A1:2014. A recommended approach for satisfying this principle of robustness is as follows.

It may be demonstrated that a structure is not dependent on a particular joint or member by considering an accidental design situation with the critical joint or critical member removed from the model for structural analysis, using the guidance in **Section 5.2**. The ULS design resistance should then exceed the design effect of action, E_d, in this damaged configuration. E_d may be based on the combination of actions used for an accidental design situation as defined in Clause 6.4.3.3 of BS EN 1990:2002+A1:2005, but with no accidental action, ie

$$E_d = E\left\{\sum_{j\geq1} G_{k,j}\,;\, P; \psi_1 Q_{k,1}; \sum_{i>1} \psi_2 Q_{k,i}\right\} \qquad 5.1$$

= effect of {permanent actions; prestress; frequent value of leading variable action; quasi-permanent value of accompanying variable actions}. The notation in **Equation 5.1** is defined in BS EN 1990:2002+A1:2005.

5.1.4 Principles of limit state design

Section 3 of BS EN 1990:2002+A1:2005 sets out the principles of limit state design to be used, including the design situations (eg persistent, transient, accidental), ULS and SLS.

This guide does not cover seismic design situations.

5.1.5 Actions

Actions on bridges may generally be obtained from the relevant parts of BS EN 1991. Material-specific actions may be determined as follows.

The method for determining the self-weight of the FRP to be used in design should be specified and agreed with the relevant technical approval authority and/or bridge owner. For some types of FRP manufacture, there may be a higher than normal degree of uncertainty in the self-weight (typical values in kN/m^3 are listed in **Table 4.1**).

Where the volume of the FRP component or its constituent materials is not controlled and the effect of the self-weight is unfavourable, the self-weight may be increased by an additional model factor. A recommended value for this model factor is 1.2.

Recommended load factors (γ_F) are provided in **Table 5.1**. The set A load factors are to be used with the EQU ULSs, while the set B and set C factors are to be used in the STR and GEO ULSs, as defined in BS EN 1990:2002+A1:2005.

Table 5.1 Recommended partial load factors for EQU, STR and GEO ULS design

Action	γ_F (Set A)		γ_F (Set B)		γ_F (Set C)	
	Superior value	*Inferior value*	*Superior value*	*Inferior value*	*Superior value*	*Inferior value*
FRP self-weight	1.05	0.95	1.2	0.95	1	1

5.1.6 Thermal effects

Thermal effects in FRP laminates, components or structures need to be considered at serviceability and ULSs. The coefficient of thermal expansion(s) (**Section 4.6.1**) for the FRP material/members should be specified and agreed with the technical approval authority.

The method for determining temperature difference effects should be specified. There is currently no adequate guidance on the analysis of temperature difference effects in FRP sections of bridges exposed to the sun. The temperature profiles to be used may be based on a steel bridge in the absence of data for FRP bridges. It is recommended that temperature difference effects be determined using Approach 2 in BS EN 1991-1-5:2003.

5.1.7 Differential settlements/movements

Differential settlements and movements to be considered in design of FRP bridge structures should be specified and agreed with the technical approval authority. They should be included as a permanent action at both serviceability and ULSs.

5.1.8 Partial factor for fatigue loads

The partial factor (γ_F) on fatigue loading should be taken as 1.0 unless otherwise agreed to be changed for a particular project.

5.1.9 Partial factors for materials

Partial factors for materials can be determined by testing in accordance with Annex D to BS EN 1990:2002+A1:2005. For an illustrative example of using Annex D to obtain γ_M, Nguyen *et al* (2015) applies the calibration procedure for the beam flexural failure mode of elastic lateral torsional buckling. Alternatively, they may be determined as:

$$\gamma_M = \gamma_{M1}\,\gamma_{M2}. \qquad 5.2$$

where γ_{M1} is related to the uncertainty in obtaining the correct material properties and γ_{M2} is related to the composite material processing method.

$$\gamma_{M1} = 1.0 \text{ (at SLS)}$$

At the STR ULS, recommended values for γ_M are presented in **Tables 5.2 to 5.4** (these values are based on work in development by CEN/TC 250 WG4 and reported in Ascione *et al*, 2016). Material property V_X is the coefficient of variation of property X, and is defined in Annex D in BS EN 1990:2002+A1:2005, with an introduction in Chapter 10 to Gulvanessian *et al* (2012). The tabulated values for γ_M have not been determined by the BS EN 1990:2002+A1:2005 (EC0) calibration procedure, and should be taken as appropriate estimates based on engineering experience and judgement. Table 5.3 is for γ_{M1} and laminates (see **Sections 5.3**) and the overall structure that is of FRP material. Table 5.4 is for γ_{M2} and scopes laminates and foam cores for sandwich construction of **Section 5.3.2**. The designer should consult with the manufacturer of the FRP material to decide whether the laminate is post-cured. There will be a difference in the matrix's strength and stiffness, being higher when the resin is fully cured. Pultruded shapes have laminates that are not post-cured and so it will be appropriate to take γ_{M2} for the situation on non-post-cured laminates. The designer is responsible for choosing the values of γ_{M1} and γ_{M2} for an FRP material (eg a non-foam core) and for agreeing with the technical approval authority.

A partial material factor having a ULS minimum of 1.5 is acceptable, with the requirement that, where critical, through-thickness performance should be proven by testing. The SLS partial material factor for modulus of elasticity under short-term loading should be taken as 1.0 (on mean value from tests or minimum/mean value provided by the FRP manufacturer). SLS partial material factor on modulus of elasticity under long-term loading should also be taken as 1.0, but with account to be taken on the effect of creep (duration/stress level) on modulus of elasticity known from testing or from test records (this is the method advocated in the structural Eurocodes).

Table 5.4 presents suggested partial factors γ_{M1} and γ_{M2} for adhesives that can be used in structural connections and joints. Slightly different from those in Ascione *et al* (2016), yet the same partial factors for the adhesive when the method of connection is by bonding, may be taken from Caldei *et al* (2004) or Clarke (1996). There is no value for a partial factor for the bonded connection between FRP skins and core material in sandwich construction.

Table 5.2 Partial factor γ_{M1} for laminates and structures (from Ascione et al, 2016)

Quality process and certification		γ_{M2}
Laminates and structures	Certified production process and quality system	1.0
	Material/mechanical properties derived from tests	1.15
	Material/mechanical properties derived from theory or technical literature	1.35

Table 5.3 Partial factor γ_{M2} for laminates and foam cores (from Ascione et al, 2016)

Laminate type		γ_{M2}		
		Strength verification	*Local stability*	*Global stability*
Post-cured laminates	Variation coefficient $V_x \leq 0.10$	1.35	1.5	1.35
	Variation coefficient $0.10 < V_x \leq 0.17$	1.6	2.0	1.5
Non-post-cured laminates	Variation coefficient $V_x \leq 0.10$	1.6	1.8	1.6
	Variation coefficient $0.10 < V_x \leq 0.17$	1.9	2.4	1.8
Foam core	Foam under shear	1.5	1.7	1.2
	Foam under compression	1.2	1.4	1.2

Table 5.4 Partial factors γ_{M1} and γ_{M2} for adhesives (from Ascione et al, 2016)

γ_{M1}		
Adhesives	Manual application with few controls of the thickness and surface pre-treatment	1.5
	Manual application with systematic control of the thickness and surface pre-treatment	1.25
	Identified application with defined and repeatable controlled parameters including surface pre-treatment	1
γ_{M2}		
Adhesives	Variation coefficient $V_x \leq 0.10$	1.2
	Variation coefficient $0.10 < V_x \leq 0.17$	1.5

5.1.10 Environmental conversion factors

As explained in **Section 4.6.5**, environmental factors can affect the mechanical performance of FRP structures (Karbhari, 2007) and their design working lives. The combined effect of high temperatures caused by solar irradiation, freeze–thaw cycles, both due to daily and seasonal temperature change, UV radiation, alkali environment and moisture and water ingress can affect the polymeric matrix and the matrix–fibre interphase. In certain cases, a reduction in the tensile and flexural strength, ultimate strain and both tensile and flexural stiffnesses has been observed for FRP components. Matrix dominant properties are more susceptible to durability changes. The exposed environment, duration of exposure, resin type and matrix formulation, fibre type and composite processing method can all influence the extent of the changes, usually as a reduction in the mechanical properties. Note that post-curing of an exposed FRP laminate can occur over time and that this change to the polymer matrix might increase mechanical properties. Any positive effect is limited, and so the designer should assume that the design has to account for a reduction in some or all of the design properties over a structures working life.

Some of the detrimental effects of environmental agents can be mitigated (particularly where FRP is used in aggressive environments) using adequate over-coating or painting applied to the external surface of the members. Any external coating should be compatible with the underlying material and approved for use by the manufacturer. Cladding components over an FRP superstructure can be used to aid durability performance over the design working life.

The structural design of FRP components or structures has to be established taking account of changes to the mechanical properties that may occur throughout the design working life by multiplying the stiffness (for SLS verifications) or strength (for ULS verifications) by an appropriate derived factor. The recommended approach introduced in **Section 4.6.5** is based on the approach presented in Ascione *et al* (2016), whereby the design value is scaled by a total conversion factor. Notation for the total conversion factor is η_C. This total factor comprises four conversion factors multiplied together, which take account of the effects of temperature (η_{ct}), humidity (η_{cm}), creep (η_{cv}) and fatigue (η_{cf}). In the absence of a rigorous analysis of environmental effects, the designer may use the recommended values in **Table 5.5** for these four conversion factors.

If over-coating is employed as a justification for relaxing η_c in design, then the mitigation properties of such an external layer should be proved for the design working life of the component or structure. When an adequate over-coating is present, the value of the combined conversion factors (η_{ct} x $\times$ η_{cm}) for temperature and humidity effects can be taken to be 1.0. In all other cases, these two conversion factors have to be properly reduced.

Table 5.5 Recommended values for conversion factors based on Ascione et al (2016)

	SLS (stiffness)	ULS (strength)	Notes
Temperature η_{ct}	0.9	0.9	Recommended values are applicable where the design maximum temperature for the structure does not exceed T_g – 20°C, where T_g is the glass transition temperature.
Humidity η_{cm}	0.8	0.8	Recommended values are for external bridge applications with post-cured FRP laminates.
Creep η_{cv}	1.0 for short-term effects 0.5 for long-term effects	1.0 for short-term effects 0.5 for long-term effects	In the absence of more rigorous determination of creep effects, a value of 0.5 is recommended to determine the long-term stiffness, in combination with the quasi-permanent combination of actions.
Fatigue η_{cf}	0.9	Verification should be carried out in accordance with Section 6.5 in Ascione *et al* (2016).	Fatigue is to be verified directly at ULS for structures vulnerable to fatigue. The η_{cf} factor may be taken to be 1.0 for footbridges that are not unusually sensitive to wind.

There can, of course, be other approaches than that being advocated in Ascione *et al* (2016) for European practice. In ASCE (2010) the account of time effects is dealt with by the combination of a time effect factor that depends on the load combination and adjustment factors to the reference strength. These adjustment factors will account for the durability effects of moisture, temperature and chemical environment. The product of the four factors is ≤ 1.0 and is used to scale the resistance factor, ϕ, which is also < 1.0. ASCE does have an adjustment factor > 1.0 for member strength and for stiffness on structural assemblies.

5.1.11 Combinations of actions

Serviceability criteria should be based on the combination of actions (characteristic, frequent or quasi-permanent) specified for the particular verification. The effect of creep and changes in stiffness may be accounted for through the appropriate conversion factors applied to the elastic modulus. Strains and deflections for different load effects may be combined using superposition.

The existing draft guidelines in Ascione *et al* (2016) are not clear about the method for combining the effects of different loads at the STR ULS when each load can correspond to a different conversion factor and a different component of resistance. It is proposed in these guidelines that (STR) verifications should be carried out for:

1 design resistances based on the conversion factors for short-term effects and design effects determined from the combination of actions and partial load factors for persistent and transient design situations:

$$E_d = E\{\sum_{j\geq 1}\gamma_G G_{k,j}\,;\ \gamma_P P;\ \gamma_{Q,1}Q_{k,1};\sum_{i>1}\gamma_{Q,i}\psi_0 Q_{k,i}\} \quad 5.3$$

2 design resistances based on the conversion factors for long-term effects and the quasi-permanent combination with partial load factors for the persistent design situation:

$$E_d = E\{\sum_{j\geq 1}\gamma_G G_{k,j}\,;\ \gamma_P P;\ \gamma_{Q,1}\psi_2 Q_{k,1};\sum_{i>1}\gamma_{Q,i}\psi_2 Q_{k,i}\}. \quad 5.4$$

The notation in Equations 5.3 and 5.4 is defined in BS EN 1990:2002+A1:2005. Other ULSs (eg EQU) should be verified in accordance with BS EN 1990:2002+A1:2005. Guidance on the verification of the FAT (fatigue failure of the structure or members) design with FRP is provided in **Section 5.3.3**.

5.1.12 Design assisted by testing

Where the composition or configuration of a component or structure or part of it is such that design by analysis (**Sections 5.2 to 5.6**) cannot be performed in accordance with the guidance in this chapter, their structural performance and their compliance should be established by testing (Gulvanessian *et al*, 2012). Design assisted by testing can be undertaken in accordance with Annex D in BS EN 1990:2002+A1:2005 and the associated NA to BS EN 1990:2002+A1:2005. Physical tests can be carried out on FRP materials and FRP components that are intended for use in bridges and highway structures. Testing with constituent materials and small coupons cut from laminates, as introduced in **Section 4.6.1**, can be used to ensure that the materials supplied meet the specifications set out in **Section 6.1**. This approach to prove a design is more common for FRP than for other structural materials for the reasons developed in this guide, but how to interpret the test results is outside its scope.

As required, the designer has to specify suitable tests to ensure that the components supplied comply with the specification for their manufacture. Tests on full-scale components, subassemblies and structures, including joints between components, can be used to verify their structural adequacy and support the design calculations (using guidance in **Sections 5.2 to 5.5**) and other related design information produced by the designer. These tests need to be carried out for each new design of component or subassembly. If the design or composite manufacturing process is changed, components and subassemblies affected by the change should be re-tested.

The designer should arrange to have these tests carried out by an independent laboratory with UKAS accreditation or equivalent. As an alternative to UKAS accreditation in the UK, an independent inspector can be appointed to oversee the test programme and reporting. Copies of the test results shall be passed to the bridge designer and the owner's representative. Testing can comply with the provisions in Annex A to Highways Agency (2005). Derivation of design values for a material property, a model parameter or a resistance can be carried out in accordance with the procedures given in Annex D to BS EN 1990:2002+A1:2005.

Design assisted by testing is not to override any existing product standards. This approach to design is achieved by adopting the procedure given in the informative Annex D. Design assisted by test results should achieve the level of reliability required for the relevant design situation. The statistical uncertainty due to a limited number of test results has to be taken into account. Specific guidance on design assisted by testing for steel bridges is given in Section 10 of BS EN 1993-2:2006, and this can be adapted to FRP bridge engineering by making appropriate changes to allow for differences in material behaviours between steel and FRP.

Evaluation of a predicted resistance of components or structure, or at the material level, should be made based on the mean (average) value of test results from a batch or batches of nominally identical specimens. For test result used to design connections and joints it is recommended that the batch size is specified by the purpose of the testing.

Further guidance on batch size is given next because of its importance.

- If it is to establish that a material, component, subassembly (eg for a connection or a joint) or structure is likely to have a stiffness/strength greater than required for a specified design load case or to pre-qualify that a batch of material meets its specification or to update or verify the structural analysis, then the number of tests can be small, say up to three. It might be one test, if testing a whole structure. If a single test on a whole structure is carried out it is important to carefully instrument the specimen so that both global (eg peak deflection) and local (eg joint strain) facets of the load response can be recorded. In addition, cameras should be trained on expected critical zones (eg joints near localised loads) of the structure to record likely failure modes. The voided nature of many FRP bridge decks facilitates camera insertion to record joint failures from within the deck.
- If it is to establish a characteristic property value for design calculations with resistance formulae then the number of nominally identical specimens per batch has to be higher, for example in the aerospace industry the batch size can be as high as 30 (SAE International, 2012).

It is recognised that the constraints of cost and material supply will mean the determination of a characteristic values is likely to be with fewer coupon specimens. ISO (Ascione *et al*, 2016) and ASTM (ASCE, 2010) test standards require a minimum batch size of five test specimens. To support the development of FRPs in civil engineering structural applications ASTM D7290-06 (2017) is for a procedure to compute the characteristic values for strength and stiffness. A minimum of 10 specimens per batch (Zureick *et al*, 2006) is needed to extract from a table in ASTM D7290-06:2017 the data confidence factor (Ω) needed to calculate the characteristic value (as the 80 per cent confidence bound on the fifth-percentile). Zureick *et al* (2006) states that *"most manufacturers will test at least 10 specimens to support their specification of engineering properties of a new manufactured composite structural product"*.

To further emphasise the guidance that, when characterising a material property by testing, the minimum number of nominally identical specimens should be 10, Okeil (2013) concludes in a relevant study that *"In general, it was observed that sample sizes below 10 yielded highly variable results. So, while it may be possible to reduce the number of required coupons from the recommended number of 20 as per ACI Committee 440 (2008) characterisation method, a minimum number of 10 coupons seems to be required to ensure consistency in the obtained results."*

Both DNV GL (2013) and Annex D in BS EN 1990:2002+A1:2005 provide procedures to determine characteristic strength values based on target reliability levels and the Guassian statistical distribution. The former establishes characteristic values having a 97.5 per cent tolerance (probability of not being exceeded) and 95 per cent confidence. The confidence level applied in Eurocode 0 is equal to 0.75 and is lower than in ASTM D7290-06 (2017). The Eurocode 0 approach is deemed acceptable with a batch size of 10, accepting that in the limit state design approach the partial factors for material in the resistance formulae are calibrated using the integral procedure in D8.2.2 in BS EN 1990:2002+A1:2005. Note that this acceptance criterion is not satisfied for the partial factors presented in **Tables 5.3 to 5.5**. Importantly, the characteristic value for an elastic constant is the mean value from the batch test results, and for SLS design $\gamma_M = 1.0$.

No test result shall be eliminated from reporting without a written rationale. An approach whereby every test result is included could be necessary to support acceptable design in the absence of having a reliable resistance formula for one or more distinct modes of failure observed in an FRP connection or joint. Once the test results for a material, component or structures have been shown to be acceptable in satisfying the design requirements in an FRP bridge project there will only be a requirement to repeat a programme to testing for the purpose of quality control, as given in **Section 6.4**.

5.2 STRUCTURAL ANALYSIS

5.2.1 General requirements

The designer should be mindful of the fact that FRP laminates behave differently from most conventional structural materials. The two most important differences are that:

1. FRP is an elastic material that can be observed not to exhibit ductility (Bank, 2006, Barbero, 2011).
2. Elastic properties are anisotropic or, more often by design, orthotropic (Bank, 2006, Barbero, 2011).

Unlike steel and aluminium, which are isotropic, FRP has multiple moduli of elasticity and strengths (as has timber). These two differences introduced in **Chapter 4**, together with FRP's significantly lower density (**Table 4.1**), have a major impact on the types of structural analysis carried out to calculate the responses of FRP components or structures.

The elastic–brittle nature of FRP (**Section 4.6.1**) means that internal stresses cannot be redistributed locally by means of material ductility, a phenomenon underpinning the application of plastic analysis to the design of many steel and concrete bridges. Elastic structural analysis has to be employed for FRP bridge design, and emphasis should be placed on realistic modelling of relative stiffnesses of members and imposed displacements. On a size-for-size basis, the flexural stiffness/rigidity of a glass FRP member is at least an order of magnitude lower than if the member volume were of a structural grade of steel, so an SLS, rather than a ULS, can often govern the design. For static or statically equivalent dynamic actions the outputs from structural analysis will be directed towards ensuring that deflections, vibrations and buckling stress limits are not exceeded. Checks for material strengths need to be done using outputs where shear stress concentrations occur and for the design of connections and joints (see **Section 5.5**).

It should be recognised that the (through-thickness) fibre-to-matrix interface tensile and shear strengths of FRPs are typically low. Such stresses commonly arise at complex geometries (eg connections and joints) due to local effects of nearby concentrated loads such as tyre loads (**Section 5.3.3**). So the FAT, especially due to local effects, can be very important (even critical) in design when the bridge carries vehicles. All FRP bridges (the case studies in Appendix A1 of Bonds Mill, 1994, West Mill, 2002, Mount Pleasant, 2006, Moss Canal, 2011, Church Road, 2014 and Mapledurham, 2016) subjected to fatigue analysis and actions have demonstrated compliance with testing regimes set out in Highways Agency (2005). Elastic constants in the plane of the FRP laminate can readily be determined by standard test methods, using the guidance in **Sections 4.16.1 and 5.1.12**. This is not the situation for through-thickness modulus of elasticity, through-thickness shear moduli and Poisson ratios. The same weakness exists for strengths that are paramount for predicting failure using and interaction failure criterion (Christensen, 2018).

While design based on elastic analysis may, at first sight, appear to be simpler to do and to verify, it should be appreciated that the elastic analysis is complicated by material anisotropy and shear deformation (Barbero, 2013). Anisotropy does offer the design benefit of tailoring the material stiffnesses (and strengths) to resist the predominant loading direction. Shear deformation can be of significance and should always be considered in the structural analysis methodology. The in-plane and through-thickness shear stiffnesses can be relatively low, and this will increase deflections and lower buckling loads.

A further consequence of low self-weight and low flexural/torsional stiffnesses is that vibration effects may be more significant, especially for pedestrian FRP footbridges (Živanović *et al*, 2014). Indeed, it may be that analysis of natural frequencies and damping characteristics are more critical to design than any ULS criterion. Also, as explained earlier in this section, for FRP traffic bridges fatigue design for deck-to-deck connections or joints can be critical, owing to complex stress states from local tyre loading, but there is guidance for tyre induced fatigue in **Section 5.3.3**.

There are several general requirements that have to be met in order to undertake a structural analysis. The following modelling variables have to be defined:

- the form of the structure
- the geometry of the structure
- the mechanical and physical properties of the structural material(s) (moduli of elasticity and strengths, mass per unit volume etc)
- the types, magnitudes and distributions of the actions (static, dynamic etc)
- the support conditions (simple, fixed, elastic foundations etc)
- it is also helpful to know the environment (including the ground conditions) in which the structure has to function.

The extent and precision of the different sets of information required for structural analysis will be in accordance with the stage of the design process at which the stress analysis is undertaken. At the preliminary design stage, only small subsets of information at the lowest accuracy level will be acceptable. On the other hand, at a final stage, complete and reliable and precise information, usually from testing in accordance with **Section 5.1.12**, shall be required.

The required resistance of members, connections and joints has to be determined by structural analysis for the appropriate load combinations, which are introduced in **Section 5.1.5**. It is appropriate to determine load effects on individual domains by elastic methods. The analysis has to take into account equilibrium, stability, geometric compatibility and both short-term and long-term mechanical properties of the FRP, as introduced in **Section 4.6**. The location of maximum internal forces in a non-prismatic member has to be determined by rational engineering analysis for the member geometry and required design load cases.

The following points form the basis for structural analysis (Ascione *et al*, 2016):

1 Analysis of the structural response needs to be carried out, taking into account the elastic behaviour of the FRP material(s) up to failure (**Chapter 4**) and, when necessary, their orthotropic and viscoelastic long-term nature.

2 Stresses within members and joints need to be determined through a global analysis of the structure, considering, when relevant to do so, the actual deformability of the joints.

3 Second-order (P-Δ and P-δ) effects have to be taken into account when they are of significance.

4 Analysis of thin-walled open-section shapes subjected to torsion needs to be carried out, taking into account the combination of St Venant torsion and warping torsion.

4 The method of structural analysis must be relevant to the actual behaviour that is to be simulated numerically.

5 Definition and implementation of a failure criterion has to be clearly defined and described.

6 The suitability and quality of general purpose FE (finite element) software may need to be verified using benchmark case study problems.

Section 5.5.3 gives five assumptions that have to be used to determine the distribution of forces for the design of connections and joints.

5.2.2 Idealisation of the structure

Today FRP bridges are often constructed of three structural forms:

A simple, short-span beams (typically 0 m to 30 m)

B transversely (or sometimes longitudinally) spanning multi-cellular decks

C short (typically 0 m to 30 m) span trusses.

Structural analysis will often be carried out using general purpose FE software unless beams, slabs and other simple elements can have their internal forces and moments determined without recourse to FE analysis. Category A and C structural forms can be idealised, at least for the preliminary deflection/vibration analysis, as assemblies of one-dimensional finite elements. For category A an idealisation based on two-node beam elements will suffice. Likewise, for category C two-node tie/strut elements can be used to determine compliance/violation of the deflection/vibration limit state(s). During the later design development and verifications stages, higher-order, multi-node, 1D elements may provide more appropriate idealisations of categories A and C structural forms.

For the category B multi-cellular bridge decks, a rigid-jointed truss idealisation (Vierendeel model) based on 1D elements can be used to obtain information about vertical deflections. It is likely that the deck will, at the outset, be idealised as an assembly of long plates that are rigidly connected along their longitudinal junctions. The plates will be idealised as multi-node plate/shell finite elements. Plate/shell FE idealisations can be used to represent categories A and C structural forms. Similar FE idealisations are used to analyse the dynamic response (free and damped vibration frequencies).

It should be pointed out that joint stiffnesses can be included in both one- and two-dimensional (2D) analysis models to simulate semi-rigid (mechanically fastened) joints (Minghini *et al*, 2010). The principal difficulty when preparing the FE model is the quantification of the joint (torsional) stiffnesses. These can be determined using spring models (Cooper and Turvey, 1998, but physical testing of the joint(s) is more acceptable to validate the FE modelling methodology (Girão Coelho and Mottram, 2015).

In addition to the structural idealisations used to determine the static and dynamic global response characteristics, it may be necessary to create more detailed idealisations of critical parts of components or structures for specific load cases, which arise during construction and in service. For example, patch loading on part of a deck compression flange supported by one or more webs will often be idealised as rigidly connected members, each of which will be subdivided into multi-node plate/shell elements for an FE analysis (Sebastian *et al*, 2012).

There are several important decisions to make before carrying out FE analyses with these structural idealisations (MacLeod, 2005). They include, for example, which particular types of finite elements to use. There are several types of plate/shell elements (Barbero, 2013), which are distinguished by the numbers of displacement degrees of freedom associated with their nodes and how the lamination of the

FRP material is represented. Improved numerical accuracy might often be achieved using mesh specifications with fewer higher-order elements, ie those with more degrees of freedom (translational – and rotational – displacements per node), than more lower-order elements with the same overall number of degrees of freedom (MacLeod, 2005). Other decisions for the FE analyst are associated with choosing the shapes of the elements, ie rectangular, triangular etc. The aspect ratios of rectangular elements should not be much greater than unity and the angles of triangular elements should not be too acute/obtuse (the software will provide the analyst with information on the quality of mesh detailing).

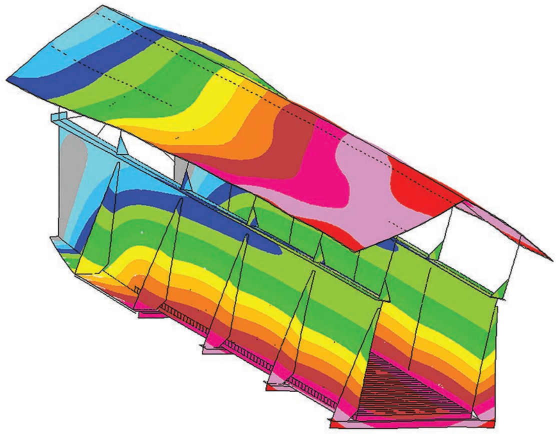


Figure 5.1 ***Modelling Dawlish Bridge (courtesy Optima Projects)***

Mesh density has to be appropriate to the objective of stress analysis, especially if it is to predict the instability resistance in the webs or flanges in beam elements (MacLeod, 2005).

It is essential for the FE analyst to give careful thought to displacement boundary conditions. Because of the large number of nodal displacements and rotations associated with higher-order plate/shell elements, there are many possible combinations of displacements at the edges of the structure. It is not always obvious which ones should be restrained or unrestrained or partially restrained to simulate the real support conditions along part or all of their lengths.

Consideration can be given to using different shapes and types of finite elements in different parts of the idealised structure, especially where cut-outs or other localised (stress concentration) features exist. Where triangular, rectangular and quadrilateral elements occur in the same structure, it is important to ensure that the local material principal axes are oriented correctly (Barbero, 2013) with respect to the structure's global principal axes, otherwise misleading outputs will be obtained, producing wrong modelling decisions.

It is important to exercise care when deciding the through-thickness position of the nodal planes within plate/shell elements. For example, if the mid-thickness plane is selected for all elements, then at a web-flange junction where side nodes of web elements are connected to side nodes of flange elements, the associated area of the junction is over-estimated. This modelling limitation can be avoided by setting the nodal plane of the flange elements to be coincident with their lower/upper surfaces. Also, it should be recognised that the multi-plate idealisation of a cellular deck ignores transition radii at such junctions. The junctions are considered 3D laminates, so the stresses within their volumes predicted by an FE simulation should be treated with caution. This is because many factors such as fibre-mat transitions, matrix fillets and mat wrinkling (**Section 5.2.6**) cannot be adequately and reliably modelled.

Equally important to structural analysis in FRP bridge engineering is for the analyst to decide what procedures to use to check the FE outputs. As a minimum, reactions at the supports for a load case or two should be checked against hand calculations. Global deflections should be checked against hand calculations for upper (fixed) and lower (pinned) bounds. In addition, symmetry or anti-symmetry of deformations and stress fields for simple load cases should be used to verify FE results. FE analysis can be an enormously powerful calculation tool in design, but the results can be very misleading when the model development is without sufficient initial care and attention. For those who are new to analysing FRP structures the best course of action to prevent learning from failure is to collaborate with an FE analyst who has a good track-record.

5.2.3 Linear elastic analysis

First-order linear elastic analysis (small displacement) is recommended to obtain numerical predictions to check that an idealised structural configuration satisfies the deflection and instability limit states and to determine the free vibration characteristics. The analysis should take into account equilibrium, stability, geometric compatibility and both short- and long-term material properties. Modelling has to be based on mean values of moduli of elasticity (see **Section 4.6.1**), which have been adjusted for end-use conditions and time (see **Sections 4.6.5 and 5.1.10**). For truss members the longitudinal modulus of elasticity should equal the minimum of the values of elastic modulus in tension and in compression in any laminate panel of the cross-section. The in-plane shear modulus has to equal the minimum of the shear modulus in the panels forming the cross-section.

For bridge category A a preliminary deflection analysis can be accomplished using closed-form formulae modified to take account of shear deformation (Turvey, 2000, 2007). Likewise, for category C virtual work (Thompson and Heywood, 1986) is appropriate to be used for preliminary deflection analysis of simple trusses. In these structures, composed of 1D elements, the transverse modulus of elasticity will not usually influence deflections significantly. More rigorous analyses can be undertaken using higher-order 1D finite elements, such as developed by Minghini *et al* (2008). These elements accommodate axial, flexural, torsional and warping deformations, though they do not account for local instability of flanges or webs. The Minghini *et al* (2010) element type is useful for dynamic analysis.

However, preliminary analysis of category B cellular decks can be undertaken using simple beam analysis of a representative width. If the deck has significant continuity transverse to its span, resort can be made to analysis by either the generalised beam theory (GBT) (Silvestre and Camotim, 2002) or plate/shell type finite strip (FS) analysis (Cheung, 1976, Dawe, 1984).

The effects of localised or patch loading on, for example, the compression flange of a category B cellular deck should be analysed using plate/shell FE analysis. A full 3D analysis using 'best estimated' mechanical properties where necessary, may be required to investigate the stiffness of the junction between the webs and flanges of the cellular deck. For this type of localised loading condition, it is necessary to corroborate the design analysis with verification tests, as introduced in **Section 5.3.3**.

Stress concentration factors for holes with rectangular or other shapes or other changes in the cross-sectional area due to local stiffening may be evaluated through FE analysis or other rational methods. For critical structural details it may be necessary to resort to a 3D FE analysis, which can require 'best estimates' of some elastic moduli (and strengths). Indeed, there may even be a need to undertake material testing in accordance with **Section 5.1.12** in order to complete the input data required for the FE analyses.

Provided that a suitable failure criterion is available (Christensen, 2018), linear analysis can be used to carry out a limiting stress check to determine the maximum load corresponding to the onset of brittle material failure. There are a number of stress-based failure criteria to choose from (Tsai and Wu, 1971, Puck and Schürmann, 2002, Girão Coelho and Mottram, 2015). Failure analysis can reveal the failure location and establish the extent to which the deflection limit is/is not exceeded at the determined failure stress state (Tsai, 2008, Barbero, 2011). For the design of FRP bridge components and structures a failure index calculated using the maximum strain criterion can be recommended because it is deemed acceptable.

A limiting stress analysis procedure is relatively straightforward. Taking a unit or other convenient value of load, an elastic analysis is undertaken. The value of the failure function is determined by substituting the stresses into the chosen failure criterion. From this value, the scaling factor (> 1) for the failure function to equal unity is established. This factor is then multiplied by the 'unit' load to give the loading which numerically just causes failure to initiate. The quality of the failure analysis is, of course, dependent on knowledge of the strengths (**Section 4.6**) used in the material failure criterion – some of which may not be readily available – and that the influence of any non-linearity in the shear modulus can be neglected.

5.2.4 Second-order effects

It is noteworthy to emphasise the modelling recommendation that second-order geometric (P-Δ and P-δ) effects should be taken into account when they are of significance. There are several reasons for believing that eccentricities may be more variable and potentially larger with FRPs. The first is that many different composite material processes are used to create FRP components. Consequently, manufacturing tolerances may be more variable in one process than in another, and member out-of-straightness may be larger due to post-manufacture residual curing. Fabrication procedures (**Chapter 6**) can also result in larger member eccentricities. Information on manufacturing tolerances for pultruded structural grade FRP profiles is given in BS EN 13706-2:2002 and ASTM D3917-12 (2012). Recommended tolerances for the fabrication of bolted joints are presented in **Chapter 6**.

Second-order geometric effects, particularly axial or eccentric loads in the presence of geometric imperfections, can degrade significantly the load carrying capacity of the structure or part thereof. Indeed, in these circumstances, elastic buckling load calculations provide unconservative estimates of the load carrying capacity. The reason for this outcome is that the geometric imperfections cause out-of-plane deflections as soon as the compression is taken by the structure, or a strut or plate. While a thin plate can, in theory, sustain a higher load than the elastic buckling load, the post-buckled reserve of stiffness before the onset of initial failure is difficult to quantify and any resistance benefit should not be relied upon.

In order to model and make rational assessments of the potential consequences of second-order geometric effects, it is necessary to resort to geometric non-linear elastic FE analysis. Moreover, because the actual shape and magnitude of the initial imperfection is generally unknown, one approach used in research is to seed the non-linear analysis with a small amplitude imperfection with an overall shape similar to the buckling mode of the member (Nguyen *et al*, 2013). This type of geometrical non-linear analysis has to be undertaken incrementally and is computationally more expensive than the straightforward linear FE analysis (**Section 5.2.3**) which can be used throughout most of the design process. With general purpose FE software, the incremental analysis proceeds with automatic adjustment of the load/displacement increment. When this does not guarantee solution convergence there are occasions for using manual intervention to achieve solution convergence.

The following guidance is to be used to design building structures of FRP material. Our justification for its inclusion within guidance for bridge structures is that it develops a consensus approach to account for geometric imperfections in structural analysis. For the analysis of unbraced frames with moment resistant joints Ziemian (2010) has recommended the 'notional load' approach, in which a notional horizontal load is applied at each storey in the frame in addition to any other lateral loads. This approach is furthered in Eurocode 3 (BS EN 1993-1-1:2005+A1:2014) and Clauses 5.3.3 for 'imperfection for analysis of bracing systems'. Now the introduction of equivalent stabilising forces accounts for initial members' out-of-straightness in the frame's geometry. The resistance is then determined directly through a second-order non-analysis, and the amplified forces can be correctly distributed within the frame. This method is consistent with computerised structural analysis and design, and is appropriate for flexible light-frame structural systems. In ASCE (2010) the proposed notional load is 0.0025 ΣP_i, where ΣP_i is the gravity load at floor level i, which corresponds to a pultruded frame geometry that is initially out of straightness by 1/400 times its height.

In the literature, there is no technical information to provide data for the level of residual stresses and their distributions in FRP components. In the pultrusion process it is assumed that they dissipate during residual curing after the profile has exited the heated die. For other composite processes presented in **Section 4.4**, such as one of the mouldings processed, it is known that component shape can change due to 'spring-in' or 'spring-out' after its removal from the mould. This indicates the existence and/or partial relief of residual stresses, but quantitative information on their magnitude and distribution does not appear to be available. However, when residual stresses do exist they can dissipate over time due to creep recovery (**Section 4.1.5**). With FRP bridge design dominated by serviceability design criteria it is recommended that residual stresses be ignored in structural analysis.

It is well known that pultruded profiles and thin laminated FRP plates can undergo relatively large deflections before failure by a ULS mode. It is unlikely that they will be of significance in design because the bridge structure will reach a deflection or dynamic SLS before deformations become geometrically non-linear. It is under localised patch loading on deck panels that localised non-linear deflections can arise and so this response may be important to fatigue design, which is dealt with in **Section 5.3.3**. Analysis of any localised design problem is best undertaken using a general purpose FE code with non-linear capabilities. It may also be necessary to undertake some experimental testing in order to verify the FE results.

There are changes to FRP materials that create non-linear behaviour. Thermal expansion and moisture ingress should be considered as causes of second-order effects. In FRP structures, the former can be more difficult to deal with because thermal expansion coefficients (**Section 4.6.1**) are direction dependent. Also, an expansion coefficient is dependent on the fibre architecture, fibre type and matrix composition. Initial guidance on coefficients of thermal expansion for pultruded shapes is given in pultruders' design manuals (Creative Pultrusions, 2017, Fiberline Composites, 2017, Strongwell, 2017).

Should the service working temperature be approaching $T_g - 22°C$ (ASCE, 2010) it will be essential in the structural analysis to use reduced elastic constants and strengths that account for the relatively high temperature. In Ascione *et al* (2016) the approach to setting a limiting temperature is slightly changed, with the cured unreinforced resin (in the matrix) satisfying the condition that T_g is, as per BS EN ISO 6721-11:2012 (taken as the onset of the storage modulus), at least 20°C above the maximum service temperature and at least 60°C. As explained in **Section 4.6.5**, the value of T_g is dependent on the standard test method used to measure this thermal property and it cannot be taken to be a constant temperature for the current state of the matrix.

Moisture ingress for water uptake (Grammatikos *et al*, 2015) is known to change mechanical properties of an FRP over the service working life of the structure. As explained in **Section 4.6.5**, over time it leads to the development of internal hygrothermal stresses and changes in stiffnesses and strengths. The conversion factor approach summarised in **Section 5.1.10** is an approach that may be used in structural analysis to take into account the environmental effects when predicting the bridge's performance at the end of the design working life.

5.2.5 Geometric and material imperfections

The analyst should account for the magnitude of geometric imperfections. BS EN 13706-2:2002 and ASTM D3917-12 (2012), provide specifications on the maximum manufacturing tolerances for pultruded profiles in the unloaded state (see also **Section 6.2.2**). It is important to understand that actual deviations from the nominal geometry are likely to be smaller than listed in a standard, and that for structural analysis imperfection input data from measurements is preferred. In addition to out-of-straightness, twist along the profile's axis can be significant (Nguyen *et al*, 2013). The magnitudes of initial geometric imperfections can increase because of fabrication into subassemblies and full-sized structures.

It should be recognised that the presence of a geometric imperfection introduced into the modelling may produce unanticipated, but correct, structural analysis results. For example, a snap-through buckling mode may result, especially if the laminate is not initially flat, when the anticipated response is for a growing plate deformation in the direction of the geometric imperfection.

There are two other types of geometric imperfection associated with pultruded profiles, neither of which has received much attention. I-and H-shaped profiles exhibit flange droop. Another manifestation of this phenomenon arises in angles where the legs are not quite mutually orthogonal. Both are spring-in/spring-out deformations due to residual stresses, and from the pultrusion processing standpoint the first might not be scoped in BS EN 13706-2:2002 or ASTM D3917-12 (2012). The second type of imperfection arises in pultruded closed-section profiles. Their wall thicknesses can sometimes differ around the perimeter, due to small movements of the internal mandrel, which is subject to high pressure and temperature in the pultrusion die.

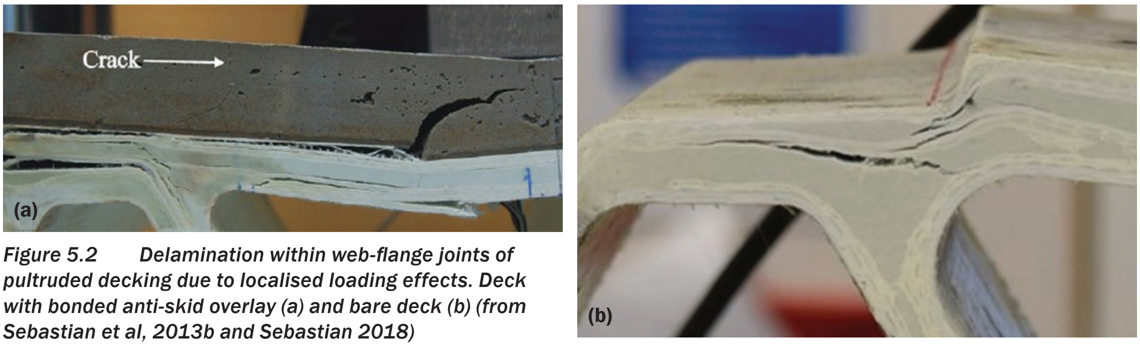


Figure 5.2 Delamination within web-flange joints of pultruded decking due to localised loading effects. Deck with bonded anti-skid overlay (a) and bare deck (b) (from Sebastian et al, 2013b and Sebastian 2018)

Wrinkling of the fibre layer architecture is a material imperfection that, in structural analysis, can be important when localised stresses are required, and this material imperfection has to be considered in design. The imperfection from wrinkling is less common in moulded components. In pultruded profiles there is usually significant wrinkling of mat layers and displacement of the unidirectional rovings within web–flange junctions and at free edges of flanges. So when the edge of a flange outstand is loaded locally, internal delamination of the junction, such as seen in **Figures 5.2a and b**, may arise, leading to a localised reduction in stiffness and strength (Turvey and Zhang, 2005a, b, 2006a, b; Sebastian *et al*, 2013a, b and c; Sebastian, 2018).

5.2.6 Initial failure and progressive damage

When initial failure happens in a notched FRP laminate, say to have a hole for a bolted connection, it is known that there can be a degree of damage tolerance (Thoppul *et al*, 2009, Mottram, 2013). The load at ultimate failure is higher than that causing the FRP to first become damaged, and this structural response is desirable in design because it imparts a degree of structural integrity.

Structural analysis for predicting initial failure and its continual progression in an FRP (notched) laminate is very complex and should not be attempted without the involvement of an experienced FE analyst. Girão Coelho (2015) has presented finite element guidelines for the simulation of delamination dominated failures, which are validated by case studies. There is a contribution by Girão Coelho *et al* (2015) for a similar fracture energy approach, which is for the analysis of damage tolerance of a notched laminate failing with the net-tension mode.

5.2.7 Structures with sandwich construction

In finite element modelling shell elements are appropriate for the laminated skins in sandwich constructions (see **Chapter 4** for an introduction). Care has to be taken to ensure that through-thickness shear is treated correctly both for through-thickness strength checks and for a reliable prediction of local buckling failure in sandwich panels. The ability to calculate a failure index for a laminate skin is useful as a check on material resistance. The ability to have structural analysis results to check for core through-thickness shear resistance in the principal directions is relevant for directional core material, such as when the core is of a honeycomb structure (Allen, 1969).

The choice of failure index should be appropriate for the structure and actions being considered. A number of important failure modes (**Section 5.3.2**), such as peel and other through-thickness mechanisms, are unlikely to be available from the failure criterion when the designer is determining failure indices using finite element simulations with shell elements. Additional design checks to account for all practical modes of failure are likely to be required. There is no published guidance for the designer to carry out these checks.

5.3 DESIGN FOR ULTIMATE LIMIT STATES

Different analysis methods may be required for verifying ULS resistances of pultruded and moulded components or structures. For pultruded members the laminate stiffness and strength properties are reasonably well defined and controlled, and information regarding the detailed fibre architecture may not be necessary. In moulded laminated structures, the stiffness and strength properties are typically less well defined and controlled. Classical lamination theory (Tsai, 2008, Barbero, 2011) can be used to establish directional laminated elastic constants for moulded FRPs, as the designer specifies the combination of fibre, matrix, and lay-up. Material strengths should be obtained or verified by batch testing (**Sections 4.1.6 and 5.1.12**), as laminate failure theories are known (Kaddour and Hinton, 2013) to have varying reliability, particularly for thicker laminates (eg > 10 mm) that are often required in FRP bridge engineering.

5.3.1 ULS design of pultruded members

Characteristic short-term resistance properties of pultruded members should be established based on verified test data for the specific products to be used in the design. These resistances should be converted to design resistances using the appropriate conversion factors and material partial safety factors. Elastic moduli may be based on mean short-term values based on verified test data for the products, while there are minimum values in design manuals that can be taken for initial design calculations (eg Creative Pultrusions Inc, 2017, Fiberline Composites, 2017, Hartley, 2010, Strongwell, 2017). The appropriate conversion factors, introduced in **Section 5.1.10**, should be used to account for long-term and environmental effects on the stiffness properties.

It will often be necessary to consider more detailed resistance calculations based on a number of SLS and ULS failure modes. There are publications (Clarke, 1996, Fiberline Composites, 2017, Ascione *et al*, 2016, ASCE, 2010) that provide, at different levels of reliability, closed-form formulae that can be used for ULS design of pultruded or other thin-walled FRP (solid) members. The effect of actions for establishing when an FRP component has an acceptable design can be determined using the structural analysis guidelines in Section 5.2. For geometries or materials or local effects that are outside the scope of these documents, the bridge designer can either use design assisted by testing (Gulvanessian *et al*, 2012) or alternatively use FE analysis to determine the localised material stress field and employ a failure criterion (Barbero, 2011, Kaddour and Hinton, 2013).

5.3.2 ULS design of laminates and sandwich panels

The scope of this section is for moulded flat or curved components and structures of either laminated shells or sandwich panels that are used in FRP bridge engineering. (For several illustrative examples see the case studies of Halgavor bridge, 2000–2001, Bradkirk footbridge, 2010, Pont y Ddraig lift bridge, 2013, Purfleet footbridge, 2013, Sedlescombe footbridge, 2015 and Mapledurham bridge, 2016, in **Appendix A1**). Laminated shells are of single skin laminations and sandwich panels are of sandwich construction (**Section 5.3.3**), consisting of a core (of foam, wood or honeycomb) surfaced by bonded facing laminates (or skins) (Allen, 1969, Davies, 2001). A component of sandwich construction is generally made up of two relatively stiff laminates on the outside surfaces with a very flexible core material between them, and an (adhesively bonded) connection between each skin and the core (McCormick, 1984). There are no publications with recognised design guidelines to provide provenance to the engineering information in this section. Scoping design for small marine craft and hull construction and for scantlings there is initial guidance in BS EN ISO 12215-5:2008+A1:2014.

Mechanical properties for laminates, both single shells and sandwich construction, can be obtained from testing. Should the shell, face or skin laminate be highly directional, having about 40 per cent of unidirectional continuous fibres in one orientation, then the effect of off-axis loads and secondary deformations, such as from Poisson ratio effect, are to be considered. This is to ensure that they do not result in premature failure of the laminate.

From the designer's standpoint it can be more practical to obtain mechanical properties of the individual plies from coupon testing, in accordance with a standard test method, and to then apply level 2 in **Section 4.6.1** to calculate laminate properties from the properties of the plies using classical lamination theory (Tsai, 2008, Barbero, 2011). For laminated structures the current recommendation is to use the first ply failure approach when determining a laminate's strength by this analytical method. The use of the term 'ply' is synonymous with the terminology 'lamina' that is used in this guidance.

The resistances for a single laminate correspond to the following eight modes of failure:

- longitudinal tensile
- transverse tensile
- longitudinal compressive
- transverse compressive
- in-plane shear
- interlaminar shear
- through-thickness tensile
- through-thickness compressive

These distinct failure modes have to be checked for the individual faces in a sandwich panel, and guidance for structural analysis and evaluation in **Section 5.2** can be used. In addition, the following failure modes should be considered for sandwich panels:

- facing failure
- transverse shear failure
- flexural crushing of the core
- local crushing of the core
- flexural buckling (I)
- shear crimping (II)
- face or skin wrinkling (III)
- intra-cell buckling or dimpling (IV)

Because Ascione *et al* (2016) presents guidance for the determination of the resistances for these panel modes of ultimate failure it will not be repeated here. Note that face or skin wrinkling has no association with mat wrinkling (**Section 5.2.6**) observed at the junctions in, for example, shapes made by the pultrusion composite processing method.

For sandwich constructions in compression or bending the panel resistance can be affected by local instability of the skins (modes I–IV), and dependent on detailing this may occur before global flexural buckling (I) (Allen, 1969, McCormick, 1984). As both skin wrinkling (III) and shear crimping (II) are local instabilities with relatively short wavelength, the panel manufacturer will specify minimum core properties for compressive stiffness and shear stiffness to be used when calculating the resistances for these failure modes. Because global flexural buckling occurs over longer wavelengths it is recommended to choose average (laminate and core) elastic constants to calculate the forces for this mode of instability. In what follows the resistance formulae are reported without account of the partial factor for materials (**Section 5.1.8**) or the conversion factor (**Section 5.1.9**) to account for time effects over the design working life (BS EN 1990:2002+A1:2005).

5.3.2.1 Panel failure modes

Skin wrinkling (III) (Allen, 1969, McCormick, 1984) is the local buckling failure of a skin under axial compression (there is no panel flexure). The critical elastic strain, ε_{wr}, for this failure mode is dependent on the skin's modulus of elasticity (E_f) in the direction of compression, and on the core material's through-thickness compressive (E_c) and shear (G_c) moduli. If sheet faces have the same properties and are relatively 'thin' (typically < 10 per cent of the core's thickness), and there is a continuous core, ε_{wr} can be approximated by the semi-empirical Hoff's formula (1949):

$$\varepsilon_{wr} = \frac{0.5\sqrt[3]{E_f E_c G_c}}{E_f}. \qquad 5.5$$

The predicted strain by Equation 5.5 is factored for design and checked against the design compression strain for the face laminate.

If the skins can be classified as 'thick', there will be an increase in the skin wrinkling buckling strain from that predicted by Equation 5.5 and to determine the critical elastic strain (ε_{wr}) the designer can use Allen (1969) or McCormick (1984).

Shear crimping (II) is another instability of a panel under axial compression and, as **Figure 5.3** illustrates, failure occurs by panel buckling, without displacements from shear deformation in the core.

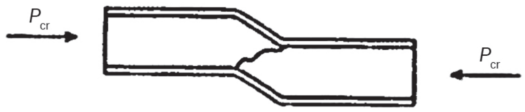


Figure 5.3 Shear crimping failure when the core is solid (not a honeycomb core)

For relatively thin skins (typically < 10 per cent of the core thickness) the critical elastic buckling load, P_{cr}, per unit width of panel can be calculated from:

$$P_{cr} = \frac{G_C d^2}{c} \qquad 5.6$$

where c is the depth of the core and $d = c + t_s$ (both skins have thickness t_s).

When skins thickness is classified as 'thick', the increase in P_{cr} can be determined using a calculation procedure found in Allen (1969).

5.3.2.2 Core failure modes

It is generally assumed that the core carries the shear forces from out-of-plane loading. The through-thickness shear strength capacity is to be checked after predicting the through-thickness shear stress in the core. The shear strength resistance has to be checked in both directions for those core materials, including honeycomb and extruded foams, having different through-thickness shear strengths in the two principal directions.

Through-thickness shearing has an interlaminar component for the complementary shear stress that can cause failure at the core-to-skin interface (adhesive) bond, especially if moisture and other environmental effects have degraded this bonding. When a sandwich panel is correctly fabricated with adequate core–skin adhesive the core-to-skin bond should not fail before the core itself, irrespective of the load case. To ensure that this design requirement is satisfied it is recommended that panel specimens be tested in a manner that can verify the core bonding process to be acceptable. Two test methods that give qualitative results for the bond strength and quality in sandwich panels are the through-thickness test ASTM C297/C297M-16 and the climbing drum peel test ASTM D1781-98 (2012). Interpretation of the numerical significance of the test results requires experience.

Through-thickness compressive failure of the core can occur in regions under concentrated compressive force, such as where the sandwich panel is connected to another component, say by steel bolting (**Section 5.5.5**). Approaches to strengthen a flexible core locally are to replace the core material with:

- high density foam (200 kg/m^3)
- a solid laminate insert, or a compression plug of syntactic foam (Klempner and Frisch, 1997)
- an extruded reinforced tube of an appropriate structural material.

5.3.2.3 Beam failure modes

Figure 5.4 shows two cross-sectional sketches that illustrate the types of beam cross-sections that can be constructed with laminate shells and laminated sandwich panels. Failure modes for the laminates are those introduced in **Section 5.3.2**. Calculation of sectional properties for a beam cross-section has to be by transformed sections to take account of the differences in modulus of elasticity of core and laminate materials.

When a beam member – such as for the two examples shown in **Figure 5.4** – is adhesively bonded to a laminate panel (at the base in the drawings) an appropriate effective width for the shell itself has to be used to calculate the section properties. This width may be affected by the beam length, its edge fixity and the magnitude of the shear lag owing to the ratio of in-plane shear modulus to in-plane modulus of elasticity of the shell when of a single laminate. A design procedure to calculate the effective width (effective extent of plating) is given in Clause 11.6 of BS EN ISO 12215-5:2008+A1:2014. When the 'shell laminate' is of sandwich construction consideration should be given in design to whether or not both skins can be assumed to be effective. Effectiveness will depend on the relative shear stiffness of the core and skin laminates. When the core is either of structural foam, such as polyvinyl chloride or styrene acrylonitrile having a minimum density of 80 kg/m³, or of another material with comparable shear stiffness, both top and bottom skins can be assumed to have the same effective width.

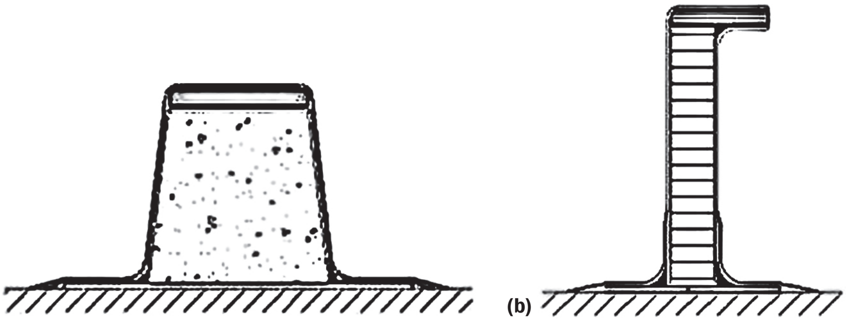


Figure 5.4 Typical moulded beam cross-sections, hat-section (a) and L-flange (b)

Beam webs and capping flange overhangs have to be checked for local buckling failure owing to the combination of shear and direct forces. One approach for a preliminary design is to use the rule-of-thumb that provided the thickness-to-depth ratio is ≥ 1/30 a compression or shear mode of failure should occur before local elastic buckling failure.

For beam members in bending, the effect of shear deformation has to be considered when the deformation is calculated to check for an SLS deflection limit. Guidelines and closed form formulae for common load situations and simply supported panels are presented in Allen (1969) and McCormick (1984).

5.3.2.4 General requirements

Design of both shell laminates and sandwich panels have to take account of the load paths in the overall structure and fabrication method. It is recommended that continuous fibre reinforcement is provided in the primary load directions throughout the laminations in the component or structure.

Laminate robustness may be improved by providing no less than a minimum amount of fibre reinforcement. The minimum fibre weight in the shell laminates and the skins in sandwich construction should depend on the core material, the structural use of the structure and the nature of the environmental exposure. A typical recommended minimum is 2000 g/m² for glass fibres in an epoxy matrix.

Further considerations for improving robustness include the provision of:

- a matrix with a high tensile strain to failure (can be three per cent)
- a toughened resin system for the matrix
- fibre reinforcement layers without short fibre lengths
- woven cloths with continuous fibre reinforcement to take the place of unidirectional or stitched fabrics, especially as the outermost layer in the laminate
- a high elongation core material, which is a core material having a shear strain at failure of 30 per cent or higher, determined by the block core shear test method in ASTM C273/C273M-16
- additional thickness/core layers such as cladding that will resist local impact actions.

A second benefit of using a high elongation core is that the panel will inherently possess a higher impact resistance and toughness. It is recommended that where there are cut-outs in a laminate shell there should be continuous fibre reinforcement having a minimum of three fibre directions, for example 0°, +45° and −45°. The designer should consider the effect of stress concentrations around penetrations, and strengthening fibre reinforcement tapes or patches can be added locally to prevent localised FRP failure.

Cut-outs in sandwich panels should have the exposed edges of the skins and core sealed (**Section 6.2.4**) to prevent damage to the core material and minimise the risk of moisture/water ingress affecting the susceptible core-to-skin bondline. Recommended methods for achieving an effective seal with sandwich components include backfill into the core region with a structural adhesive, taping to close over the ends of a hole, and a pre-made FRP moulding that exactly fits into a cut-out volume. When choosing a suitable sealing method to protect the bondline from premature failure the designer has to take account of the size and location of cut-out, as well as the laminate, the loading and the function of the FRP structure.

To make the transition from a sandwich panel to a single (shell) laminate it is recommended that the core has a chamfer of 30° to 45°. Additional fibre reinforcement plies embedded in the single shell should be extended past the core chamfer and into the sandwich skins. Overlap and taper lengths will depend on the lamina material and weight, fabric architecture, the interlaminar shear strength of the matrix and the composite processing conditions. Because of the interdependency of materials and composite manufacturing the designer is advised to seek expert advice when finalising such complicated structural details.

To resist the internal tension and compressive forces (the complementary orthogonal principal stresses) due to the shear force in the web of a beam member (**Figure 5.4**) it is recommended to have ±45° reinforcement in the lamination (0° is aligned with the beam's longitudinal centroid axis). The designer has to give consideration to local reinforcement around penetrations and cut-outs in webs, and normally a minimum of three fibre directions should be provided local to these regions. The principal stresses towards the end of a beam member are known to deviate (St Venant principle) from the theoretical prediction for pure shearing. Consideration has to be given to the provision of modifying the fibre reinforcing directions in these regions to accommodate the actual stress field, which can be determined from FE analysis and the modelling guidance in **Section 5.2**, and especially **Section 5.2.7**.

5.3.3 Fatigue assessment

A fundamental problem concerning the use of FRP is the determination of their resistance to combined states of cyclic stress. Composite materials exhibit complex failure mechanisms under static and fatigue loading because of the anisotropic characteristics in their strength and stiffness.

A predominant single crack is the most common failure mechanism in static loading of isotropic, brittle materials such as metals. There are four basic failure mechanisms in composite materials as a result of fatigue: matrix cracking, delamination, fibre breakage and interfacial debonding. The different failure modes combined with the inherent anisotropies, complex stress fields and overall non-linear behaviour of composites limits our ability to understand the true nature of fatigue.

Fatigue verification is generally required for FRP structures that are subject to cyclic loading. It is not generally necessary to assess footbridges of any structural material for fatigue unless they are flexible and very sensitive to wind actions. **Section 2.3.6.4** in Ascione *et al* (2016) has guidance for when a fatigue design is necessary. In this section the focus will be for guidance towards the design of decks of FRP subjected to vehicle actions.

The fatigue resistance of FRPs is highly dependent on factors such as change in geometry, lamina curtailment and on the quality of FRP manufacture (to minimise voidage, ensure accurate fibre placement and provide quality bond and consolidation between fibres and matrix). Owing to the range of matrices and fibres available (**Chapter 4**), methods to enable prediction of the fatigue behaviour is generally more difficult and less established than those for other structural materials. Design should consider methods to simplify the manufacture or ensure quality workmanship (**Chapter 6**), as well as considering theoretical analysis of fatigue or relevant testing to determine fatigue response. Because of the lack of test results for an extensive range of details for bonded and/or bolted joints (**Section 5.5**) design should be assisted by testing, as described in **Section 5.1.12**.

5.3.3.1 Mechanisms and typical locations of fatigue degradation

Fatigue damage progresses in FRPs by matrix cracking, debonding at the fibre–matrix interface/interphase and fibre fracture. Matrix cracking in itself may not immediately result in a significant drop in structural properties, but such cracking permits moisture/water ingress leading to long-term changes in material properties (**Sections 4.6.5 and 5.1.10**) and it can trigger matrix–fibre debonding, which has a significant structural impact.

Fatigue damage occurs due to through-thickness tensile stresses, in-plane shear stresses and direct stresses from flexure. Joints and regions near the edges of concentrated loads can be critical for fatigue performance. Typical fatigue-critical joints in deck-on-girder bridges can, due to prying action, include bonded deck-to-girder joints and, owing to local effects of tyre loads, bonded deck-unit-to-deck-unit joints. The designer should identify fatigue-critical regions in the design solution and how the fatigue behaviour of these regions should be considered.

Coogler *et al* (2005) state that a stress limit of $0.2 f_{t,d}$, where $f_{t,d}$ is the design tensile strength of the FRP material, is commonly used. (This is consistent with ACI Committee 440 (2008) for unidirectional glass FRPs under combined sustained loads and cyclic (fatigue) service loads.) The Committee further recommends stress limits of $0.3 f_{t,d}$ for aramid FRPs and $0.55 f_{t,d}$ for carbon FRPs (both for laminates with unidirectional fibre reinforcement). These limits assume tension–tension fatigue and they do not allow for the presence of manufacturing defects or environmental (durability) degradation (**Section 4.6.5**). As such, these stress limits represent upper limits, as fatigue stress reversal or compression stress can be more severe and multi-axial FRP materials are generally more susceptible to fatigue damage. Limiting the strain in the matrix to less than the relevant design matrix cracking strain at the irreversible SLS is a minimum requirement to ensure the provision of long-term fatigue resistance. Typical matrix cracking strain limits are 0.2 per cent for polyesters, 0.3 per cent for vinylesters and 0.4 per cent for epoxies. A matrix strain limit should be confirmed with the FRP manufacturer or by testing.

The designer should bear in mind that such limits on matrix strain may be a conservative way of avoiding matrix cracking (crazing) that inherently provides the structure with adequate fatigue resistance, but they do not necessarily prevent the occurrence of the other fatigue mechanisms of fibre interface debonding and fibre fracture. Where these other mechanisms are likely to occur (eg due to stress concentrations at joints or to through-thickness effects) the designer should consult specialist literature or material suppliers who may retain fatigue test data for FRP components.

Alternatively, the designer can rely on project-specific fatigue testing ('designed-by-testing' as introduced for fatigue in **Sections 5.3.3.3 and 5.3.3.4**), and this can be a method to provide less conservative fatigue limits. There is limited reliable experimental evidence of fatigue resistance for situations exceeding 100 million fatigue cycles. If such a case is specified (eg in BS EN 1991-2:3003) it is recommended that the designer refer to specialist literature on testing.

5.3.3.2 Justification for fatigue testing

Prediction of fatigue behaviour is complex and uncertain due to the need to explicitly consider factors such as local fibre waviness, matrix–fibre interface/interphase properties and crack progression, all of which can vary significantly throughout the component or structure and over time. For these reasons, it is strongly recommended that testing of relevant fatigue-critical structural components be pursued to determine fatigue behaviour. These tests should be in accordance with the guidance in **Section 5.1.12** and incorporate representative loads and boundary conditions. To do otherwise will lead either to highly optimistic or to overly conservative observations of fatigue behaviour. An example of the need to correctly represent loading is given in **Section 5.3.3.4**.

5.3.3.3 General considerations for fatigue assessment by testing

As introduced in **Section 5.1.12**, design assisted by testing can be undertaken in accordance with BS EN 1990:2002+A1:2005 and the associated NA to BS EN 1990:2002+A1:2005, and is, in particular, recommended for fatigue-critical regions of an FRP component or structure that do not fall within the simple design methods in **Section 5.3.3.1**.

If the testing is performed for a bridge project in the UK, the proposed fatigue tests should consider the relevant fatigue load model(s) from BS EN 1991-2:2003 and NA to BS EN 1991-2:2003, and consider design details such as lamina drop-off, methods of connection for joints and other attachments. The designer should consider other specific fatigue load cases that may not be adequately represented by the fatigue load models in BS EN 1991-2:2003. An example is twin-tyre load effects from lorries on FRP decks (see the case study for the Mount Pleasant bridge at Garstang, Lancashire over the M6 motorway in Appendix A1). Testing should be undertaken on material coupons that are representative of those to be used in the actual application, including the specified level of quality and workmanship (eg to know manufacturing method, voidage and fibre volume fractions).

Small-scale coupon testing should be undertaken to international standards – ISO (Ascione *et al*, 2016) or ASTM (ASCE, 2010). Large-scale component testing should simulate the actual details and actions on the component over the design working life. The number of tests required should be in accordance with BS EN 1990:2002+A1:2005, and guidance on the number of repetitive tests is given in **Section 5.1.12**.

Common instances of out-of-plane fatigue loading that would require design assisted by testing are tyre loading on road bridges and perpendicular joints between components, where a degree of moment continuity is required or may exist in the design solution. The case of tyre loading is considered in the following section.

5.3.3.4 Tyre-load fatigue approval tests

There are test results from combined FE analyses and fatigue tests on of a full-sized cellular FRP decking by Sebastian *et al* (2012, 2013c), from further testing on a cellular FRP deck system by Daly and Cunninghame (2006), and from tests by Coogler *et al* (2005) on another cellular FRP deck system bonded to steel girders. From evaluation of these data the following key points emerge that are important to the fatigue design:

1. Local tyre-load fatigue strains greatly exceed those due to global action of the bridge. For example, from tests on a full-scale FRP-deck bridge, local surface strains up to 20 times those due to global bending were recorded owing to application of a concentrated load via a plate-pad system (Sebastian *et al*, 2012).
2. The resulting fatigue degradation can be a critical design consideration for cellular FRP decks.
3. Fatigue damage can commonly occur along the fibre-mat-to-matrix interfaces in deck-unit-to-deck-unit bonded joint zones, owing to combined through-thickness tensile and in-plane shear stresses at those interfaces.
4. Magnitudes of the local fatigue strains are known to be highly sensitive to small movements of the tyre load along the bridge. For example, from concentrated patch tests on FRP decking, a 100 per cent change in strain occurred due to a movement of the load equal to only 12.5 per cent of the local span of the deck's top flange between webs (Sebastian *et al*, 2012).
5. FE simulations predicted stresses in the fatigue-critical zones that can differ significantly from reality, due in part to the material property uncertainties stated in **Section 5.3.3.2**. Daly and Cunninghame (2006) showed that the traditional S–N approach to structural design – where S is cyclic stress – is not suited to cellular FRP decks. Instead, it is prudent to conduct fatigue tests on representative deck components to determine P–N curves, where P is the peak vertical cyclic wheel load applied to the FRP deck on both sides of the flange-web joint. Sebastian *et al* (2013c, 2017) have shown through field and lab tests that the flat steel plate - rubber pad loading device must be significantly improved on, in order to adequately replicate the local tyre load distribution on cellular FRP decks.

These important observations from previous research, which apply to a spectrum of cellular FRP deck-on-girder bridges, mean that it is strongly advisable to have access to results for the local fatigue behaviour of cellular FRP deck systems (including the bonded joints between deck units) under tyre loading. The designer may ignore fatigue due to global effects unless there is a compelling reason to do otherwise, such as significant local–global interaction effects.

Rolling tyre facilities (RTFs) run only at low cycling frequencies (typically 1 Hz or less), so the cost of fatigue testing is high (Daly and Cunninghame, 2006). Also, RTFs are prone to fatigue breakdowns. For these two reasons faster (ie cost effective), and more reliable methods of fatigue testing are needed. To that end, the designer may consider employing a test method developed by Sebastian *et al* (2013c) which uses vertical rams loading steel plates faced with rubber on the deck.

In this approach the soffit of the steel loading plate should not be flat. **Figures 5.5a and b** from Sebastian *et al* (2013c) illustrates why. The interaction between the compliant pneumatic tyre and the flexible cellular FRP deck leads to a very different contact pressure distribution (CPD) on the deck top's surface from that due to interaction between the relatively stiff flat steel plate and the FRP deck. This in turn means that fatigue of the deck under a flat plate differs significantly and may in fact be much less pronounced than from that under a vehicle tyre over the same load range. This is potentially unsafe, as it means that any fatigue damage of the deck which might occur under the flat plate system will most probably be much less pronounced than the fatigue damage that would have occurred under actual lorry tyres. In order to avoid this problem by ensuring a reasonable representation of the CPD from tyre–deck interaction Sebastian *et al* (2013c) recommend that the designer should specify an appropriate curve for the soffit of the steel plate. The designer should note that the tyre fatigue load models in BS EN 1991-2:2003 define uniform pressure loading on the deck, which is inconsistent with the tyre loading reality, as illustrated in **Figure 5.5**.

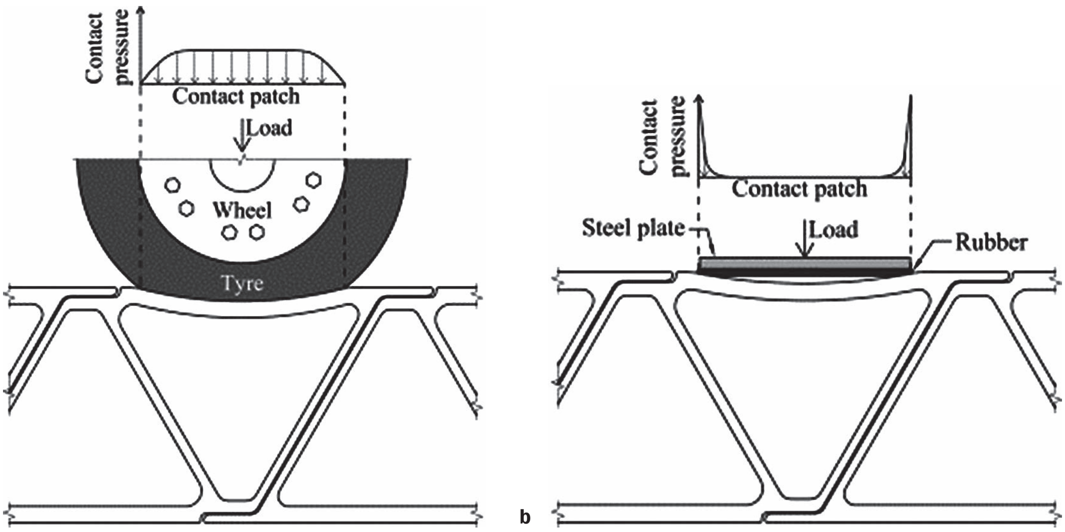


Figure 5.5 Tyre-deck interaction (a) and steel plate-deck interaction (b) (from Sebastian et al, 2013c)

5.3.3.5 Consideration of deck-and-surfacing as a system

Field observations (Triandafilou and O'Connor, 2010) show that cracking of bonded wear surfaces (eg of polymer concrete) and debonding of such wear surfacings from cellular FRP decks can be an issue in service. The problems arise from localised stresses generated from the composite action between the surfacing and the deck local to a tyre loading. The local indeterminacy of the cellular deck influences this behaviour. To study this durability problem, Sebastian *et al* (2013c) have developed a test approach that incorporates this local indeterminacy. A finding from their test results is showing that the surfacing-deck composite action can significantly improve local capacity, in one case by 90 per cent relative to the deck acting on its own. Because environmental effects such as from temperature and moisture ingress through surface crazing, are significant, it is advisable to perform fatigue tests on FRP deck-surfacing systems in tandem with appropriate environmental conditioning.

5.4 DESIGN FOR SERVICEABILITY LIMIT STATES

The following SLSs should be verified:

- deflections
- vibrations
- laminate strain limitations
- temperature limitations.

Deflections should be limited at the SLS. For bridges subjected to repetitive heavy loads, such as encountered on road bridges, it is recommended that vertical deflections under short-term loads including the effects of shear deformation (**Section 5.2.1**) are limited to span/300, as recommended in Highways Agency (2005). Short-term deflections may be calculated using the characteristic combination of actions. In the case of bridges that comprise components and finishes that would not be damaged even if vertical deflections exceeded the span/300 limit – such as for some types having a short span – higher deflections are to be acceptable and should be agreed with the authority responsible for the bridge operation and maintenance.

Additional verifications may be required, for example to ensure that adequate clearances are maintained throughout the design working life, and deflections are acceptable to bridge users. These long-term deflections (to include creep deformations) may be calculated using the quasi-permanent combination of actions. Verifications should take into account the appropriate conversion factors, as introduced in **Section 5.1.10**.

For efficient design, vibrations in footbridges should be limited in accordance with the requirements of the NA to BS EN 1991-2:2003, rather than the conservative 5 Hz value mentioned in Highways Agency (2005), above which dynamic effects are not expected to be significant. A damping coefficient of one per cent may be assumed as a realistic conservative lower limit for calculations (Ascione *et al*, 2016). For an efficient design, higher damping coefficients may be used if these have been substantiated by representative experimental data. However, it is important to recognise that the damping ratio for the bridge system varies between vibration modes (Votsis *et al*, 2017). For example, if one vibration mode involves energy dissipation in the parapet system, but another does not, the damping ratio for that mode will be lower.

It is recommended that the laminate strains for the frequent combination of actions are limited to below the longitudinal micro-cracking strain and transverse resin cracking strain for a unidirectional laminate in tension in the longitudinal or transverse direction, respectively, taking into account the appropriate conversion factors. A typical strain limit to cover all practical situations is dependent on the polymer resin in the matrix, and can be 0.2 per cent for polyesters, 0.3 per cent for vinylesters and 0.4 per cent for epoxies.

5.5 DESIGN OF CONNECTIONS AND JOINTS

5.5.1 General information

In ULS design, the strengths of joints and their connection parts may be the lowest and thereby govern ultimate resistance. It is recommended that their total number and/or detailing differences should be minimised where practical for robustness and structural integrity (BS EN 1990:2002+A1:2005). FRP moulding using resin infusion, say by vacuum moulding, will allow part consolidation in a single component for fewer connections and joints. The Bradkirk footbridge having a summary sheet in **Appendix A1** is for an example of a monolithic consolidated structure.

To be in accordance with the Eurocode terminology in BS EN 1993-1-8:2005 the term ‘connection’ is for a location in a structure at which two or more members/components meet. The term ‘joint’ is for the zone where two or more members/components are interconnected. Connections are the building block for joints. Interfaces are defined as the area or region where different structures, components or parts meet each other. All connections have physical interfaces. Requirements for interfaces, connections and joints are to be based on achieving at least the same level of reliability as the structure of which they are parts.

If a part of the connection or joint has one or more components of a different structural material they have to be designed in accordance with their relevant material standard.

The wide range of manufacturing processes and fibre reinforcement/polymer resin systems, as introduced in Chapter 4, lead naturally to a wider variety of structural component forms and connection forms than those found, say, in concrete, steel, concrete-and-steel and timber bridges. When the flexibility to tailor the directional mechanical/structural properties of the FRP material, shape or component (eg as a sandwich construction) is combined with the variety of connection types/layouts (Clarke, 1996), it is unsurprising that designers have no routine design or standard details for FRP connections/joints available to them.

FRP components may be connected to other FRP components and to other structural materials by one of the following four main methods of connection:

1. adhesively bonded (Clarke, 1996, Ascione *et al*, 2016)
2. steel bolted (Ascione *et al*, 2016) and other mechanical fasteners (Clarke, 1996)
3. hybrid (combined) steel bolted and adhesively bonded
4. mechanical interlock, with or without adhesive bonding (Clarke, 1996)

Figures 5.6 to 5.9 show examples using FRP structure of the four main connection methods. The structures for the connections illustrated in **Figures 5.7 to 5.9** are introduced in **Appendix A1**.

Figure 5.6 Typical bolted connections with pultruded shapes for the Lleida pedestrian bowstring bridge, Lleida, Spain (courtesy Fiberline Composites)

Figure 5.7 Bonded connections with pultruded shapes for the Leri footbridge, Borth, Wales (courtesy Brian Bell and Pipex PX)

Figure 5.8 Hybrid bonded–bolted connection with pultruded shapes for the Launder Aqueduct, England (courtesy Brian Bell and Pipex PX)

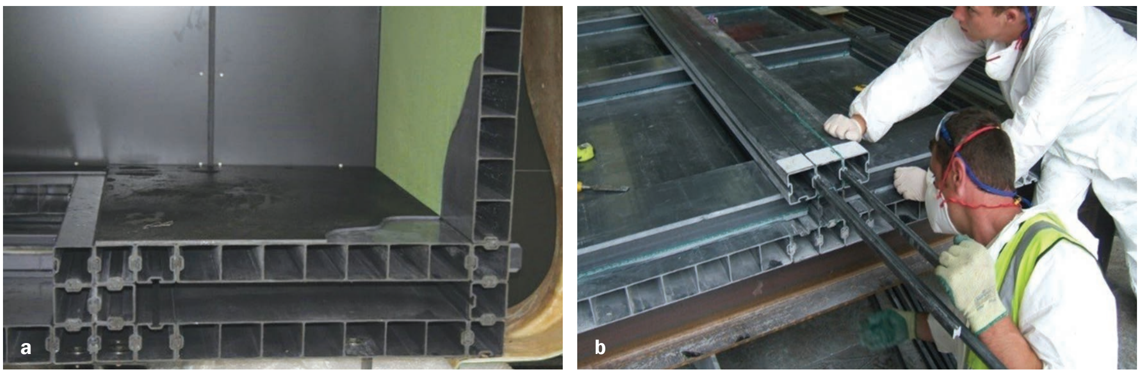


Figure 5.9 Mechanical interlock connection with pultruded ACCS as used in the St Austell footbridge, near St Austell, England (2007). Bridge cross-section (a), and assembling mechanical interlocking connection (b) (courtesy Brian Bell and Pipex PX)

For other practical methods of connection, leading to assemblies, laminated joints, moulded joints, bonded insert joints and cast-in joints, Clarke (1996) has guidance towards their design in Section 5 on connection design.

For steel bolted connections (see **Figure 5.6**) the guidance on the design of connections between solid FRP components has to conform with connection design for steel structures presented in BS EN 1993-1-8:2005.

It is assumed in this section that the FRP component being joined to another component is a solid laminate and that there is no sandwich core in the thickness of the FRP component. If a core is present, the design of a connection has to be based on the sum of the resistances of the individual (outer surface) FRP skins, which are laminates. According to DNV GL (2013) all design aspects related to laminated, bonded and bolted connections apply to sandwich panels. Sandwich panels (**Section 5.3.2**) have internal bonded connections between the core and skin and between cores. These connections have to be evaluated independently with their properties treated as an integral part of the sandwich construction. It might be necessary to modify the local core properties, as introduced in **Section 5.3.2.2**, to ensure that the required connection strength is achieved.

When two sandwich components are joined together there can be complicated stress fields within the sandwich panels. Stresses within the core material can be very different near to a connection compared to the calculated (average) stresses elsewhere. In the neighbourhood of connections, such local variations in the core may become critical in design (DNV GL, 2013). A metal ferrule (or insert) through the full depth of the sandwich panel can be used to overcome failure by crushing of a core when a bolt is tightened. Mara *et al* (2015) have proposed that the same connection method can be used with solid laminates to minimise slippage when conventional steel bolting has clearance holes.

Closed-form formulae to determine connection (and/or joint) resistances, when one or more components are of FRP material, are presented in several sources of design information (Clarke, 1996, CNR, 2008, Ascione *et al*, 2016, ASCE, 2010). They are not reproduced here because they require context and/or specific design provisions that are found only where they are sourced. The exception to this reporting is with the resistance formulae in Clarke (1996) for a single-lap shear joint with bonded connection because it is necessary to eradicate the typographical mistakes in the original source. This inclusion in **Section 5.5.4** can be used to emphasise the guidance that the designer is responsible to ensure that a closed-form formula used to determine resistance for a specific mode of failure is relevant and reliable with the input properties to design with.

Important background information for the three main methods of connection is presented in Clarke (1996), although the publication (known as EUROCOMP) has no legal standing. It provides guidance on many dos and don'ts, and can help the designer choose appropriate types and forms of connections and joints. Moreover, it reports and illustrates what are the main modes of failure in FRP lap-shear connections joining plate-to-plate components. Weaknesses in both the simplified and rigorous design approaches developed in Section 5 of Clarke (1996) suggest that they should not be used to design either bolted or bonded connections. There are known mistakes (Turvey and Wang, 2002) in the design provisions (formulae and charts) when the method of connection is bolting. None of the design procedures from Clarke (1996) have been calibrated using a reliability analysis, such as given in Annex D in BS EN 1990:2002+A1:2005, with laboratory test results for the distinct modes of failure. So, there is no verification on the appropriateness or otherwise of the estimates for the partial factors for resistance in Clarke (1996).

For a second source with background information that is accompanying mandatory design guidance, there is the commentary chapter on bolted connections in ASCE (2010). Design guidance is specific to pultruded thin-walled shapes (see **Sections 4.3 and 5.3.1**) and does not have specific design clauses for connections and joints for FRP bridge engineering.

When actions are to be transferred across an interface between components, all aspects related to the connection method have to be considered (DNV GL, 2013). If interfaces only make contact with each other, their frictional wear has to be considered in the design process. Fluids accumulating between interfaces, in voids or in debonded areas may break a bond. The durability effect of fluids, and water when frozen as ice in particular, is introduced in **Section 4.6.5**, and has to be assessed in the process of design verification.

The effect of thermal stresses and strains, displacements and movements has to be considered for all connections and interfaces in the joints (Mosallam, 2011).

5.5.2 Resistance of connections and joints

All connections and joints need to have a design resistance that is sufficient for the structure to satisfy all the basic design requirements given in BS EN 1990:2002+A1:2005. Design properties of connections and joints can be designed by testing using the guidance in **Section 5.1.12**.

Connections and joints may be designed according to one of four different approaches:

1 an analytical approach, whereby connections forces for distinct modes of failure are calculated using closed-form formulae for resistance and compared with the connection forces obtained for the design load cases (see Ascione *et al*, 2016 and ASCE, 2010)

2 an analytical approach, whereby the stress/strain levels at all relevant parts, including at connection interfaces, are determined by means of advanced stress analysis (eg by FE analysis using guidelines in **Section 5.2**), and compared with relevant calculations for strength using a composite failure criterion (also discussed in **Section 5.2**)

3 design by qualification testing, which can be full-size or scaled down subassembly specimens for the connection or joint that are tested under relevant conditions such that the required strength (BS EN 1990:2002+A1:2005) of a joint can be determined

4 a combination of an analytical approach (either 1 or 2) with physical testing (3).

5.5.3 Design assumptions

Connections and joints have to be designed based on a realistic assumption of the distribution of internal forces and moments. The following assumptions should be used to determine the distribution of forces using the analysis methods introduced in **Section 5.2**:

1 The internal forces and moments assumed in the analysis are in static equilibrium with the forces and moments applied to the connections.

2 Each connection in the joint is capable of resisting the internal forces and moments transferred through that connection.

3 The deformations implied by this distribution do not exceed the deformation capacity of the method of connection and/or the connected parts.

4 The assumed distribution of internal forces and moments should be realistic with regard to relative stiffnesses of components within the connection and the joint.

5 When a moment is applied to a joint, the distribution of the internal forces has to be linear, ie proportional to the distance from the centre of rotation (for an analysis see Chapter 8 in Owens and Cheal, 1989).

Because of geometric tolerances/imperfections, clearance holes and the limited scope for stress redistribution in ‘brittle’ FRPs (**Section 4.6.1**), the distribution of connections forces in, say, a group of bolts need not be uniform, and this is to be accounted for in design.

The level of all stresses (strains etc) in all relevant zones of a connection or joint, including stress concentrations, should be determined according to the same procedures as specified for the rest of the structure. Special emphasis has to be put on possible stress concentrations and localised effects. It has to be recognised that the stress concentrations in the executed structure may be different from those determined by structural analysis using the guidelines in **Section 5.2**, for example, owing to the modelling simplifications used in the structural analysis.

If the mechanical properties, especially at a connection interface, cannot be determined with sufficient accuracy and reliability it is recommend that design be assisted by testing.

The long-term performance of a connection or joint can be determined based on long-term material properties (**Sections 4.6.5 and 5.1.10**), especially when there is known to be a clear link between the changing mechanical properties and the closed formulae being used (with confidence) to establish the resistance in the short term.

It is likely that the most practical approach in design is to use a combination of information from analysis and testing, with knowledge from historical precedence providing more engineering data into the decision-making process. A large conservative bias may be necessary in the analysis to account for the many uncertainties in a joint's design, so there is the option to use updating procedures to obtain a better use of the joint. Section C400 in Section 10 of DNV GL (2013) provides clauses for a procedure for updating the predicted resistance of a component.

Highways Agency (2005) states that if an FRP roadway (here a cellular FRP deck) is designed to act compositely with the supporting members (of any structural material) the designer needs to ensure, through appropriate analysis and detailing, that the connections provide sufficient longitudinal shear strength without causing local damage to the FRP components (Keller and Gürtler 2005 and 2006). It is essential to provide the data to prove that the long-term behaviour of the connections is not compromised by fatigue (**Section 5.3.3**) or environmental actions (**Section 5.1.10**).

5.5.4 Design approach for bonded connections

It is recommended that when the engineering team is, for the first time, designing and executing an FRP structure with adhesively bonded connections and joints (see **Figure 5.7**) it seeks advice from those with expert knowledge of field applications. The experts will include material suppliers, fabricators, consultants and academics, known to have experience of working with bonded connections. This was the situation for the Leri footbridge (2009), which is shown in **Figure 5.7**, and introduced in **Appendix A1**. To date there is no guidance in a recognised design standard, and adhesive bonding, as a method for primary connections, is not scoped in ASCE (2010). There is however guidance in Ascione *et al* (2016), which is a preparatory work towards a future FRP Eurocode. It can be beneficial to look outside the construction profession and to consult with specialists in the aerospace and automotive industries, where bonded structural joints in FRP structures (often with carbon fibre reinforcement) have received most in-house attention, as seen by the knowledge and understanding in US Department of Defense (1999).

There are several texts on adhesive bonding, with that by Mays and Hutchinson (1992) specific to civil engineering. Other sources for background information are Lees (1984), Clarke (1996), Hutchinson (1997) and The Concrete Society (2012). Lees (1984) is particularly important as it gives guidance on 'dos' and 'don'ts'. Sections 3.7, 3.9.7 and 5.6.6 in The Concrete Society (2012) give useful information on adhesives and laminating resins for bonded connections between FRP plates or fabrics and concrete structures. For site preparation of adhesive bonded connections Sections 10.5 to 10.7 in The Concrete Society (2012) are for storage, site conditions, and mixing and application. Section 10.9 covers quality control testing and Section 10.10 has an introduction to non-destructive evaluation (NDE) to inspect the quality of the cured bond surface.

Section 4.5 in this guidance document is to assist the designer in the selection process for a suitable adhesive for structural bonded connections. Guidance for NDE testing is to be found in **Section 7.3** of this guidance.

Many users of adhesives will intuitively understand the importance of combining bonding with mechanical interlocking (see **Figure 5.9**). This connection method is often referred to as 'keying' of two or more interfaces before the bonding application. This combined method for having structural connections/joints is used in the advanced composite construction system with the **Appendix A1** case study bridges of Aberfeldy (1992), Bonds Mill (1994), Parsons (1994 to 1995) and St Austell (2007), whose cross-section is shown in **Figure 5.9**. The fabricator should improve adhesion by using mechanical abrasion, and the benefits of sound surface preparation are guidance from **Section 6.2.4**.

DNV GL (2013) gives the following design recommendations for adhesively bonded connections:

- All issues related to connecting laminates together by curing (**Section 6.2.4**) also apply to the connection of cured laminates by adhesive bonding (Clarke 1996).
- Geometrical details should be clearly specified, especially at points of stress concentrations, such as along the edges of a connection.
- The relationship between all elastic constants of both adherends and the adhesive should be carefully considered, as mismatches may introduce stresses or strains that can cause failure of a connection or a joint.
- Thermal stresses should be considered, and this requires knowing one or more linear coefficient of thermal expansions.
- The long-term performance of the adhesive should be established with great care. It is not only influenced by the properties of the adherends, the adhesive and the interface, but also by the surface preparation, adhesive application, cure and local environment.
- Relevant long-term data should be established for the combination of materials, geometry, surface preparation and fabrication procedures used in a bonded connection.
- An adhesive joint might introduce local through-thickness stresses into the FRP laminate, which can lead to internal failure local to the connection region.

For single lap-shear connections it is recommended that the two adherends of FRP material should be of the same thickness.

Clarke (1996) provides simplified and rigorous design procedures. The simplified approach is likely to be very conservative and should only be used for preliminary dimensioning. The rigorous approach uses closed-form formulae having application provenance in aerospace engineering. Their development is based on the analytical treatment by Goland and Reissner (1944). A description of the design approach is given in Section 5.3 on bonded joints in Clarke (1996). Note that the publication by Clarke (1996) uses the word 'joint' for both a 'connection' and a 'joint'. In the following, when giving the equation number from Clarke it is prefixed with 'E' (EUROCOMP). The notation in **Equation E5.6.4** is that in Clarke (1996).

Let us consider the case of a single-lap bonded connection subjected to tension that can be defined by the modelling diagram in **Figure 5.10**.

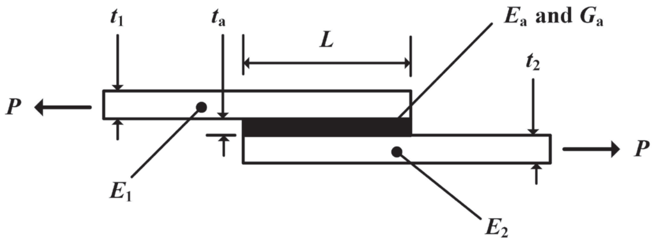


Figure 5.10 Notation for a single-lap shear joint

In Clarke (1996) **Equation E5.6.4** has two signs incorrect, and the term R_3 is not defined. The corrected expression for the normal (peel) stress s_0 is:

$$\sigma_0 = \frac{4Pt}{L^2 R_3}\left[\left(R_2\lambda^2\frac{k}{2} + \lambda k' \cosh\lambda \cos\lambda\right)\cosh\frac{2\lambda x}{L}\cos\frac{2\lambda x}{L} + \left(R_1\lambda^2\frac{k}{2} + \lambda k' \sinh\lambda \sin\lambda\right)\sinh\frac{2\lambda x}{L}\sin\frac{2\lambda x}{L}\right], \qquad \text{E5.64}$$

where the parameters are:

$$R_1 = \cosh\lambda \sin\lambda - \sinh\lambda \cos\lambda$$

$$R_2 = \sinh\lambda \cos\lambda - \cosh\lambda \sin\lambda$$

$$R_3 = \left(\frac{\sinh 2\lambda + \sin 2\lambda}{2}\right)$$

$$\lambda = \frac{L}{2t}\left(\frac{6E_a t}{E t_a}\right)^{\frac{1}{4}}$$

$$k = \frac{\cosh\left(\frac{u_2 L}{2}\right)\sinh(u_1 L)}{\sinh(u_1 L)\cosh\left(\frac{u_2 L}{2}\right) + 2\sqrt{2}\cosh(u_2 L)\sinh\left(\frac{u_1 L}{2}\right)}$$

$$u_1 = 2\sqrt{2}u_2$$

$$u_2 = \frac{1}{\sqrt{2}t}\sqrt{3(1-v^2)\frac{P}{tE}}$$

$$k' = k\frac{L}{2t}\sqrt{3(1-v^2)\frac{P}{tE}}$$

and:

P is the load per unit width of the single-lap bonded connection

L is overlap length of the bonded surfaces

t is the adherend thickness with t_1 equal to t_2 and of the same laminate material

E is the adherend tensile modulus of elasticity in direction of P, and E_1 equals E_2

v is the Poisson's ratio of the adherend

τ_a is the uniform adhesive bondline thickness

E_a is the modulus of elasticity of the adhesive

G_a is the shear modulus of the adhesive (= $E_a/2(1 + v_a)$), where v_a is the Poisson's ratio of the adhesive.

As seen in **Figure 5.10** subscripts 1 and 2 are for the two adherend plates that are connected by the adhesive bonded connection, represented by the black shaded area.

For the double-lap configuration shown in **Figure 5.11**, the maximum load per unit width is specified by the lesser of the values calculated from **Equations E5.72 and E5.73** (Clarke, 1996). The corrected equations are:

$$P = \sqrt{2\tau_p t_a\left(\frac{\gamma_e}{2} + \gamma_p\right)2E_i t_i\left(1 + \frac{E_i t_i}{2E_o t_o}\right)} \qquad \text{E5.72}$$

and

$$P = \sqrt{2\tau_p t_a\left(\frac{\gamma_e}{2} + \gamma_p\right)4E_i t_i\left(1 + \frac{2E_o t_o}{E_i t_i}\right)}, \qquad \text{E5.73}$$

where:

τ_p is the plastic adhesive shear stress

γ_e is the elastic adhesive shear strain

γ_p is the plastic adhesive shear strain at failure.

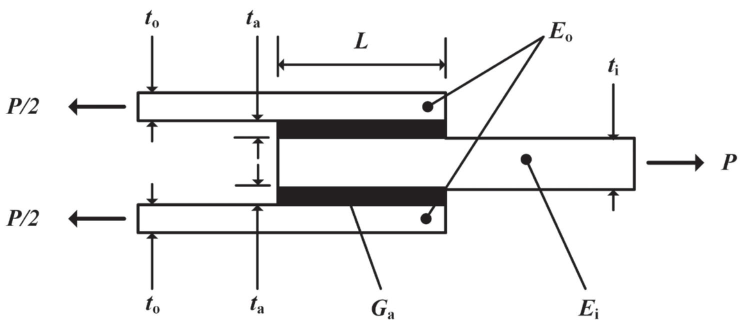


Figure 5.11 Notation for a double-lap shear joint

The step-by-step procedure for the design approach in Clarke (1996) for single-lap and double-lap connections (or joints for connecting two and three adherends, respectively) subjected to tension load may be implemented as follows:

1 The overlap length, L, is to be determined first. Unless a more detailed stress analysis using the guidance in **Section 5.2** is carried out, the length shall be:

$L = 50t/\beta$ a single lap connection

$L = 25t/\beta$ a double lap connection

where $\beta = \sqrt{\frac{8G_a t}{E t_a}}$.

(This is Equation E5.10 (Clarke, 1996), corrected to be without the non-dimensional parameter β incorrectly divided by thickness t).

It is noted that longer lap lengths than given by Step 1 will give no additional connection resistance, but shorter lap lengths will reduce resistance.

2 For the proposed connection arrangement and factored load cases, determine the net design force per unit width P_d, and the average direct stress in the adherend, of thickness t, from $\sigma = \frac{P_d}{t}$. .

3 The shear stress, τ_0, and the normal (peel) stress, σ_0, in the adhesive layer of the bonded connection are to be determined.

For the double-lap bonded connection in **Figure 5.11** the procedure in Clarke (1996) to predict the maximum stresses is by Equation E5.12 for τ_{0max} and Equation E5.17 for s_{0max}.

For a single-lap bonded connection in **Figure 5.10** the maximum stresses are given by Equation 5.65 for τ_{0max} and a corrected Equation E5.68 for s_{0max}:

a maximum shear stress

b maximum peel stress $\sigma_{0\,max} = \sigma\lambda\left(\frac{t}{c}\right)^2\left(\frac{k\lambda}{2} + k'\right)$, providing overlap length satisfies $\lambda > 2.5$

4 The shear (τ_{0max}) and peel (τ_{0max}) maximum stresses are compared to the design strengths of the adhesive, which are determined from their corresponding characteristic strengths divided by γ_M for the adhesive property (which are in Section 5.1.10 of Clarke, 1996). The characteristic value of the peel strength may be taken as the characteristic tensile strength of the adhesive. The characteristic value for shear strength may be taken as the maximum shear stress from a stress analysis of a standardised single lap-shear specimen (BS ISO 4587:2003 or ASTM D3163-01, 2014), subject to P equal to the characteristic value of the joint's strength determined by testing (**Section 5.1.12**).

5 When the design strengths calculated in Step 4 exceed the design values for the maximum shear and/or peel stresses, respectively, the bonded joint detailing has been successfully designed.

There is guidance in Clarke (1996) to design and fabricate adhesively bonded connections with compression, in-plane shear and combined load cases and for the connection/joint geometries of scarf, butt, step-lap, angle and tee.

An alternative approach to the design of bonded connections is to employ fracture mechanics. There are clauses for this approach in Section 5.5 of CNR (2008), an Italian guide for construction of structures made of FRP pultruded members, and for a wider range of FRP adherends, in Section 8.4 of Ascione *et al* (2016). The partial factors adopted in both these sources are taken from Clarke (1996). There are closed-form resistance formulae for hand calculations. A fracture mechanics approach is recommended by Cadei *et al* (2004) in a UK CIRIA design guide for externally bonded FRP strengthening for metallic structures.

Cyclic fatigue actions (**Section 5.3.3**) should be carefully considered in the verification for the reliability of a bonded connection over the working life of the FRP component or structure with the joint it is part thereof.

5.5.5 Design resistance for bolted connections

The design of bolted connections (see **Figure 5.6**) should take account of all the possible mechanisms of failure related to the FRP substrate and the fasteners themselves. Design approaches for verifying bolted connections in FRP are provided in Ascione *et al* (2016) and ASCE (2010). Both documents are referred to in this section. They have many similarities in their technical approach, and while the Ascione *et al* report is aligned with Eurocodes and European practices, the ASCE's source is to have recognised status when it is published as a standard. Pultruded FRP pedestrian and trail bridges have been manufactured and installed in North America since 1989 with other 45 projects completed.

ASCE (2010) has guidance for the design of frame structures of pultruded profiles and has information on the design of bolted connections where there is no requirement for fatigue and slip-resistant joints. Its rules are based on bolt holes that have a nominal clearance and this arrangement should not be used where there is a requirement for fatigue or slip-resistant connections, unless other provisions have been made. Provisions in its Chapter 8 on bolted connections apply to bearing-type bolted connections. Note that in the ASCE document the term 'connection' is used for both a 'connection' and a 'joint'.

For the pultruded FRP shapes scoped by ASCE, its Table 8.1 defines the minimum geometric requirements for steel bolted connections. These requirements are likely to be acceptable for an FRP laminate manufactured by a difference composite material processing method (see **Section 4.4**), but they will change if the volume fraction of mat/fibre reinforcement is higher than about 30 per cent and it is not of a CFM (or a continuous strand mat). The minimums in **Table 8.1** are based on multiples of the bolt diameter that can be taken as multiples of the hole diameter to be in accordance with BS EN 1993-1-8:2005 convention.

The recommended geometries and a number of strength (resistance) formulae for failure modes in pultruded bolted connections are appropriate to FRP bridge engineering. Conventional steel bolting is recommended with bolts tightened to the snug-fit condition of pre-tensioning (ASCE, 2010). Although ASCE permits bolt thread in bearing, this guidance recommends that there should be a plain shaft for the bearing contact over all or most of the laminate thicknesses in the connection. The inappropriateness of using high strength friction grip bolts (HFSG) bolting for FRP connections and the requirement for a nominal bolt hole clearance (1.6 mm or 1/16 in) does mean that the ASCE guidance has to be used with caution when fatigue and/or slip-resistance is a design requirement. There is no change on having HFSG bolting in the predicted resistances on using the closed-form formulae in (ASCE, 2010) for the distinct failure modes of shear out, net tension, cleavage and block shear. This is because they require only the shear and direct strengths of the FRP laminate as determined by standard material (coupon) ASTM test methods. For the zero hole clearance situation the bearing strength per bolt predicted by the formula for the bearing failure mode will be higher because the material's characteristic bearing strength will have been determined for the physical situation of having a clearance hole.

In the case of unsymmetrically connected members, such as angles and channels, the eccentricity of the bolts in the end connections and the effects of the spacing, the end and edge (or side) distances of bolts have to be taken into account when determining resistance. Until resistance formulae are established, the design of unsymmetrical or unsymmetrically connected members should be confirmed by testing, in accordance with **Section 5.1.12**.

In ASCE (2010), steel bolts, steel nuts and steel washers are to American specification standards. The types of bolts to be used have to be for bearing-type connections, as FRP materials are not suitable for pre-tensioned or slip-critical connections. The structural properties of proprietary FRP bolts (ASCE, 2010) are unlikely to be suitable for the design requirements in FRP bridge engineering.

Bolts should not be over-tightened, to prevent compressive crushing failure of the FRP material in the through-thickness direction. In Part 3 of Clarke (1996), there is a report on a series of tests with five different nominally pinned beam-to-column joints having web-cleats. One of the design recommendations is that bolt tightening is to a bearing pressure over the washer surface area that is no higher than one third of the laminate's through-thickness crushing strength and in no event higher than 68 N/mm^2. Another guideline in Clarke (1996) is to have oversized washers of diameter 2.5 times the bolt diameter, with rounded edges. ASCE requires hardened flat circular steel washers having an outer diameter at least twice the nominal bolt diameter and a thickness not less than 4.0 mm (5/32 in). At least one such washer has to be used at the head of the bolt and at the nut. In addition to flat washers the use of lock washers between the nut and the flat washer is permitted.

To simplify the design process the ASCE standard requires gusset, splice plates and angles connecting members to be of a ductile metal and their design has to be in accordance with the relevant American standard for that material (AISC, 2016, and The Aluminium Association, 2010). The standard permits the replacement of metal members with FRP material members. Pre-qualification testing (see **Section 5.1.12**) needs to be carried out to verify that the connection design is fit for purpose over the design working life of the structure. It is recommended that this requirement can be relaxed providing the designer is satisfied by calculation that gusset, splice plates and angles connecting components can be of an FRP laminate.

Double row joints may be justified over only a single bolted row for stability to resist compressive loads. The number of bolt rows is not to exceed three (ASCE, 2010).

To prevent the nut from becoming loose due to creep relaxation, a thread-locking sealant, locking washer, locking nut or jamb nut may be used. The practice in steel design of deforming the steel bolt thread is not advisable.

To highlight a reason for why guidance might be seen as lacking, Mottram and Turvey (2003) reviewed, up to 2002, the working practices and the main findings from an independent series of connection strength tests. The reviewers explain that the test data covered a wide range of pultruded FRP bolted connection variables, with varying degrees of completeness. They made the observation that one reason for the large number and range of variables was the lack of a single coherent and recognised specification for the design and fabrication of bolted connections for pultruded structures. In other words, the absence of a design standard in 2003 meant that testing was often not with variables in accordance to what is to be mandatory in ASCE (2010) and recommended in Ascione *et al* (2016).

Scoping a wide range of FRP materials, Ascione *et al* (2016) provides similar design guidance to ASCE. Notable differences from the American standard that is specific to pultruded shapes are the following:

- Bolts and nuts of structural grade steels have to be in accordance with BS EN 1993-1-8:2005, and those of structural grade stainless steel have to be in accordance with BS EN 1993-1-4:2006+A1:2015.
- Diameter of the steel bolts should not be less than the thickness of the thinnest connected FRP laminate and should be not greater than one and half times the thickness of the thinnest connected FRP laminate.
- Steel or stainless steel washers of diameter greater than twice the bolt diameter and conforming to BS EN ISO 7093-1:2000 or BS EN ISO 7093-2:2000 should be inserted under the bolt head as well under the nut.

The following guidance is universal and applies to all bolted connections and joints:

- Several members meeting at a node should be arranged with their centroidal axes intersecting at a point. Any form of eccentricity in the joint has to be taken into account.
- Groups of bolts at the ends of any member, which transmit axial force into that member have to be sized so that the centroid of the bolt group coincides with the centre of gravity of the member (clearly not applicable to end joints of statically loaded angle, double angle or other unsymmetrical shaped members).
- Eccentricities up to 10 per cent of the controlling connection dimensions, between the centroid axis of single and double angle members and the centre of gravity of connecting bolts may be ignored as having negligible effect on the static resistance of the member.

DNV GL (2013) provides the following advice for when designing mechanically fastened connections:

- Mechanical connections with FRP materials are often very sensitive to geometrical tolerances.
- Creep of the FRP materials should be considered.
- The pre-tension of bolted connections should be chosen by considering the viscoelastic creep of FRP under the washers. This guidance recommends that the designer does not rely on bolt pre-tensioning for enhancing the structural properties of a steel bolted connection.
- If practicable, it should be the preference to design the bolted connection such in a way that its performance is independent of the matrix. By adopting this advice, matrix cracking (eg crazing) or degradation of matrix mechanical properties (due to environmental and loading effects) are not important to the connection's structural performance.

It is necessary to take into account the effects of slip at bolt holes having hole clearance and similar deformations on the general calculation of action effects.

The definitions and design procedure in BS EN 1993-1-8:2005 for shear connections and tension connections in steel structures are applicable to equivalent steel bolted connections with FRP laminates. The closed-form formulae for design with steel grades of structural material cannot be used directly with FRP. ASCE (2010) and Ascione *et al* (2016) present the modifications needed for determining resistances for the FRP failure modes of bearing, shear per shear plane (shear-out), tension, punching shear (pull-through) and block tearing (block shear) when the steel bolting is in accordance with Category A in BS EN 1993-1-8:2005.

Table 8.1 in both Ascione *et al* (2016) and ASCE give appropriate recommendations for minimum and maximum geometries to define positioning of holes for bolts. A minimum spacing of four times the nominal bolt diameter is specified in both orthogonal directions relative to the principal load direction. A line of bolts perpendicular to this load direction is called a row of bolts. A maximum pitch spacing can be specified when the compression force can lead to failure between bolt rows from local plate buckling. The end distance for a single row of bolts should be no less than four times the bolt diameter. This can be reduced to twice the nominal bolt diameter when there is more than one row of bolts. The minimum side distance for a flat panel is 1.5 times the bolt diameter in ASCE (2010) and 2.0 times the bolt diameter in Ascione *et al* (2016) (the higher value of 2.0 times is recommended here). Note that if the panel with the bolting has one (L-angle) or two (channel or box) orthogonal connected panels the recommended minimum side distance on the side with the orthogonal panel is relaxed. Both sources permit staggering the bolting, and the diagonal spacing is to be at least 2.8 times the bolt diameter. Because there is only marginal additional strength to be gained by having more than three rows of three bolts, the recommended maximum for the total number of bolts is nine.

The bearing design resistance of a group of fasteners has to be taken as the sum of the design bearing resistances of the individual fasteners provided that the design shear resistance of each individual fastener is greater than or equal to the design bearing resistance. The design resistance of a group of fasteners should be taken as the number of fasteners multiplied by the smallest design resistance of any of the individual fasteners.

Equation 3.5 in BS EN 1993-1-8:2005, for long joints, has not been shown to be applicable when the material is FRP. Specified by ASCE (2010) is the provision that in the direction of the connection force the maximum bolt spacing shall be 24 times the (pultruded) FRP material thickness or 305 mm.

When the bolt material is of stainless steel it is important (see Appendix A in BS EN 1993-1-4:2006+A1:2015) to make an informed selection of an appropriate grade of stainless steel for a particular application, or to correctly apply the available guidance on good detailing practice in order to avoid corrosion. Microbial induced corrosion is an aggressive form of corrosion that can affect some stainless steels (Mackey *et al*, 2015), particularly in locations where sea water can accumulate. Measures should be taken to ensure that standing water does not accumulate around stainless steel bolts. Galvanised steel bolts are not recommended because experience has shown that they are not durable.

5.5.6 Slip-resistant and hybrid connections

One approach for the provision of a 'bolted' connection with both slip and fatigue resistance is to completely fill the voiding created by having a non-zero hole clearance with a compatible (room temperature curing) thermoset polymer. Qureshi and Mottram (2012) present information on how to fabricate resin-injected bolted connections with FRP components. Test results using pultruded material are presented in Zafari *et al* (2016) to demonstrate that resin injected bolting has promising fatigue and slip-resistance under SLS actions. The method for specimen preparation is in accordance with Section 3.6.2 of BS EN 1993-1-8:2005. Clause 3.6.2.1(1) indicates that *"Injection bolts may be used as an alternative to ordinary bolts and rivets for category A, B and C connections specified in 3.4."* Clause 3.6.2.1(2) states that *"Fabrication and erection details for injection bolts are given in 1.2.7 reference standards: group 7."* This directs the designer to the informative Annex K for hexagon injection bolts in BS EN 1090-2:2018. It is noted that there is no mention when employed with steel structures that the bolts for resin injection can be of stainless steel.

Preliminary studies have been conducted with the objective of developing a slip-resistant bolted connection using pre-tensioned steel bolting with metal inserts offering the through-thickness stiffness against laminate crushing. In the study by Mara *et al* (2015) metal inserts are shown to significantly reduce bolt preload relaxation and increase the stiffness in bolted connections. The authors say that the detailing is promising for providing slip-resistance at SLS loading. They recommend that additional tests are required to validate their preliminary findings.

A third approach that has been successfully applied many times in existing FRP structures is to adhesively bond the mating surfaces in a bolted connection. Unlike the previous two approaches this hybrid connection method (see **Figure 5.8** for a joint in the Launder Aqueduct, 2007) cannot be disassembled without severe FRP material damage. It can be designed to provide a good degree of robustness, as well as slip-resistance. When the method of connection is hybrid bonded and bolted, the connection force should not be considered to be shared between the bonded and bolted elements of the connection for design. Until the bond fails the connection force is carried by the adhesive bond.

There are two approaches for the design of hybrid connections:

- Design the adhesive bond only to provide slip-resistance for SLS load effects, and design the bolted connection for the full ULS load effects with no contribution from the adhesive bond.
- Design the adhesive bonded connection for the full ULS load effects, and provide additional robustness through the provision of the bolts. Only in the event of a failure of an adhesive connection – for example due to an accidental design situation – will the bolts in that joint become effective. It is recommended that the design resistance of the bolts to (Ascione *et al*, 2016, ASCE, 2010) may be based on the effects determined from the accidental design situation as defined in Section A.1.3 of BS EN 1990:2005.

If the slip-resistant connection is to join together FRP and metallic components, the design of the metallic connection has to be in accordance with that material design standard. Specific design attention is, however, required to consider the effect of stresses from any differential heating and cooling rates of the components. This can be seen to be most important in slip-resistant connections when a metallic component is exposed to sunlight and the FRP component is not. This guidance will also be appropriate to bolted connections having clearance holes if the differential expansion that is due to the metallic and FRP components being at different temperatures cannot be accommodated.

5.6 SUMMARY

At the time of writing, there are no national or international recognised standards for the design of FRP components in bridge engineering. Finite element analysis can be seen as the preferred approach for structural analysis, both for the whole bridge structure and when component design requires a localised stress field. Considerable design guidance with closed form formulae and supporting technical information is available for shapes (steel-like sections) and systems (eg FRP cellular decks) produced by the pultrusion composite processing method. Similar universal guidelines and accompanying technical information is much less developed or available for design with moulded FRP components, with or without sandwich construction. There are connection methods using mechanical fastening and adhesive bonding that will provide the bridge engineering requirements of joints being fatigue- and slip-resistant at SLS loading.

Illustrative examples in **Appendix A1** for FRP bridges show that the current standing of not having national or international design standards is not an impediment to successful design and execution. The information and guidance presented in this chapter will be supportive of future projects because it allows the designer, composite manufacturer, fabricator, client and other stakeholders to know what to do and what not to do, and where to find relevant engineering information for structural design.

6 Execution of FRP bridges

This chapter provides information and guidance for the execution of new FRP bridge components and structures. After summarising procurement and specifications, the section on fabrication is linked to the composite processing methods introduced in **Chapter 4**. The reader will find items of guidance repeated in **Chapters 5 and 6** where this is deemed helpful to the designer.

6.1 PROCUREMENT AND SPECIFICATIONS

Guidance on the specification of FRP components is available from nationally recognised standards such as BS EN 16245, which also gives the minimum general information to be declared for materials to be used for manufacturing FRP products, or in BS EN 13706:2002 which establish a data block system for the specification of pultruded profiles to grades E17 and E23. Further sources for specifications are trade organisations such as the ACMA and specialist designers, manufacturers and contractors. This chapter describes examples of good practice identified from several of these sources, but it should not be used directly as part of a contract specification for procurement of an FRP component.

Given the specialist nature of the fabrication and installation of an FRP structure, both on and off site, it is recommended that these activities are carried out by a specialist contractor and operatives with demonstrable experience and training in the installation of structural FRPs or equivalents.

6.2 FABRICATION

For quality fabrication, it is essential that the FRP components are specified with known mechanical/design properties and tolerances.

6.2.1 Identification and control of material

Before any fabrication taking place, the following should be prepared:

- a statement of the relevant characteristic values of mechanical properties of the proposed construction, together with independent test certificates, where appropriate. (It should not be assumed that profiles supplied to BS EN 13706:2002 represent characteristic values with the reliability required for design, in accordance with BS EN 1990:2002+A1:2005, see **Sections 4.6.1 and 5.1.12**.)
- a representative sample of the proposed FRP material(s)
- details of quality control (**Section 6.4.1**) and other testing procedures.

6.2.2 Dimensional tolerances and working lines

All FRP components (including fixings and joints) should be designed and constructed to ensure compliance with requirements for dimensional accuracy for fabrication and erection, and to accommodate permissible deviations in the dimensions of the whole structure. Provision should be made for dimension adjustments if required. Annexes B and C in BS EN 13706-2:2002 set out geometric tolerances for the manufacture of pultruded shapes. Normal dimensional criteria and tolerances for standard shapes of pultruded FRP are also specified in ASTM D3917-12 (2012).

Fabrication tolerances for pultruded shapes are shop-controlled deviation limits from work lines placed upon the cutting, drilling and machining. In order to allow for proper alignment and assembly using bolted fasteners with, say hole diameters 1.6 mm greater than the specified bolt diameter, fabrication tolerances should not normally exceed those given in **Table 6.1**, which are taken from ACMA (2012).

Table 6.1 Fabrication tolerances for connections with pultruded shapes

Cut lengths	± 3 mm
Squareness of cuts	± 1°
Hole locations	± 1.6 mm
Hole diameters up to 12.7 mm	0.4 mm
Hole diameters 12.7 mm to 25.4 mm	0.8 mm
Hole diameters greater than 25.4 mm	± 1.6 mm
Slots (any dimensions)	± 1.6 mm

Note

For certain applications, such as load-bearing columns and fit-up of certain connections, the squareness of cuts will need to be more onerous than indicated. For these special conditions notes on shop drawings are required to designate these particular requirements.

6.2.3 Preparation of materials

The presence of dust and moisture inside FRP materials will reduce quality and strength, and could adversely affect component durability. Surfaces to be joined need to be thoroughly clean, dry and free from oil and release agent. Facilities where FRP components and structures are manufactured and fabricated should be at or about normal room temperature, dry, clean, well ventilated and well lit. Moulds, tools and other equipment for composite processing should be clean, dry and at a similar temperature to the ambient temperature of the workshop. It is recommended that mould work (**Section 4.4**) should not be carried out when the temperature of the workshop, equipment moulds or constituent materials falls below that stipulated by the resin manufacturer, or below 17°C, or below the Dew Point temperature, whichever is the highest.

Pultruded shapes have a synthetic surface veil (see **Table 4.2** for description) to encase the fibre reinforcement and add a layer of matrix at the surface. A surface coating will further reduce the long-term effects of ultraviolet radiation and can enhance the aesthetics. This can be achieved using oil-based, polyester, epoxy, latex or urethane paints according to the manufacturers' specifications and instructions. Before applying the coating paint, they should be tested for compatibility with the resin system used in the pultruded structure.

The manufacturer and/or fabricator has to furnish material safety data sheets (MSDS) upon request.

6.2.4 Laminating, bonding and connections

In laminating the reinforcement layers with random fibres they should be distributed uniformly through the thickness and non-random reinforcements should be correctly positioned and aligned such that the fibres can be fully wetted out by the matrix. To assist wetting out, mould processes such as VARTM (**Section 4.4**) may require a flow medium, either a shear core or an extremely low volume fraction layer. The FRP should be well consolidated. The allowable air voids content required by the design and the method of measuring it, should be agreed by the designer following consultation with the manufacturer, but in general it should not exceed five per cent by volume. Dry spots with fibre not wetted-out and too high concentrations of voids in critical design locations are unacceptable for a quality laminate having the required design mechanical properties.

All core materials (**Section 4.4**), ties, ribs, fixings and accessories should be adhesively bonded (**Section 4.5**) to the FRP over their full contact surface area. In general, a flow coat, or other resin rich surface layer, should be applied to all external facing surfaces of the finished components that are not gelcoated and to all cut edges, holes etc, to protect fibre ends.

For moulded components (**Section 4.4**), vacuum tightness, surface requirements, radii of corners and consequences of shrinkage should be considered in any project specification, together with the quality criteria in BS EN 13121-3:2016 which is for GRP tanks and vessels for use above ground. The laminate lay-up, especially in corners and transitions, should avoid wrinkling of fibres, moving into runners, and having matrix pockets or voids. A minimum radius of twice the laminate thickness has been shown to be practical and allows sound manufacture without significant generation of interlaminar voids.

Moulded laminates should be cured in accordance with the resin manufacturer's recommendations. Curing should normally be carried out at a temperature of not less than 50°C for at least eight hours. Care should be taken to ensure that FRP components are not distorted while being cured, due to matrix shrinkage. Their finished dimensions should be such that the structure, when erected, complies with the contract and fabrication drawings and that all dimensions fall within the permissible tolerances.

Bolts, other fixings and metal inserts should be of a suitable type of stainless steel, non-ferrous metal or FRP and should be such as to avoid galvanic corrosion (ASCE, 2010). Holes may be formed using a diamond-tipped or tungsten carbide drill or by turning and milling. It is sound practice for holes to be either match-bored or jig or CNC drilled to minimise potential for mismatches that can cause stresses during installation. In all cases, components should be properly supported using a suitable backing piece to avoid splitting or cracking of the laminate.

Bolts should be tightened to a predetermined torque (ACMA, 2012). Care should be taken not to over-tighten the bolts (Clarke, 1996), which could cause crushing of the laminate or could restrain fixings intended to permit lateral movement. For critically loaded connections, the use of close tolerance metal ferrules at bolt locations can be used both to increase the bearing area on the composite and to prevent/limit the amount of compression generated in the composite from bolt tightening (Mara *et al*, 2015). If a slip and fatigue resistant method of connections is required, as introduced in **Section 5.5.6**, the designer could specify resin injected bolted connections (Zafari *et al*, 2016).

Holes that are drilled and not moulded can be sealed to protect the fibre ends. Drifts or bars should not be used to align holes for the insertion of bolts because they may cause FRP damage, and punching of holes should be avoided for similar reasons.

The dimensions and tolerances of adhesively bonded connections (**Section 5.5.4**), including bondline thickness and angles of scarf tapers, together with details of surface preparation and adhesive application and curing should be as specified by the designer and be in accordance with the adhesive manufacturer's recommendations. Achieving a sound bond quality may be affected by the choice of adhesives (**Section 4.5**) and bonding process. The most important concept to understand is that surface preparation has to be validated with each substrate and adhesive combination before use. A suitable method of surface preparation can be obtained from the adhesive manufacturer and/or the FRP component manufacturer. To achieve a satisfactory bond strength, which is durable, it is essential that the surfaces to be joined are clean and dry and free from dust, frost, oil and mould release agent. Consequently, immediately before fabricating the bonded connection, surfaces may need to be degreased, abraded and cleaned. The fabricator should improve adhesion by using mechanical abrasion of some form, because it will increase the effective surface area for bonding by surface topography and roughness. With pultruded materials, it is necessary to grind off the thin surface polyester veil. Where exposed to view, edges of connections or joints should be masked with tape before priming. The masking tape should be removed immediately after sealing.

Due to the irreversible processes involved in making adhesively bonded connections, components to be joined should be rigorously checked for position and alignment before completing this final irreversible assembly.

6.2.5 Cleaning, sealing and coating

Cleaning can be carried out by wiping with a suitable solution, by steam cleaning or by pressure washing with water, provided good working practice is followed when using these techniques (The Concrete Society, 2003). Over-zealous steam cleaning or pressure washing may cause damage to the FRP material. Not all techniques will be applicable to all types of lamination, and advice should be sought from component manufacturers about the most suitable cleaning method for a particular FRP.

Resin sealing can be used as a surface treatment and/or to enhance the aesthetics of drilled, cut, sanded or otherwise broken surfaces of FRP components. In general, it does not change the initial structural performance (ACMA, 2012). The rate of water/moisture ingress or chemical absorption may be slowed if a coating or adhesive layer is applied to cut edges. Catalysed resins, acrylic lacquers and oil-based polyester, epoxy or urethane paints can all be used as sealants. It is essential that the coating is compatible with the matrix.

FRP laminates often have a synthetic surface veil that encases the reinforcement and adds a resin-rich layer at the surface. Surface coating further reduces the long-term degrading effects due to water uptake and ultraviolet (UV) radiation, and their presence enhances the aesthetics of the bridge components. Protective coating can be oil-based polyester, epoxy, latex or urethane paint according to the manufacturer's specifications and instructions, but should be tested for compatibility with the resin matrix. A suitable gelcoat can be applied in a mould and, to avoid sanding and degreasing, a primer should be provided for the top coat.

6.2.6 Repair procedures

Repairable defects are those that can be repaired without affecting the serviceability state of the FRP structure. Unless prohibited by the designer, repairable material defects include: chips, die-parting lines, gouges, intermittent disfigurement, scale, scuffing, stop marks, wire brush surface and resin voids where no blisters or delamination occurs (see ASTM D4385-13 for specific information). For pultruded profiles defect acceptance limits are given in Annex A to BS EN 13706-2:2002.

It is recommended that specialist advice is sought with regard to the most appropriate repair technique for a particular defect. Manufacturers/fabricators of FRP structures and components will usually have established and proven procedures for the repair of common defects. The advice already given for environmental conditions and cleanliness during laminating and making adhesively bonded connections equally applies to repairs.

6.2.7 Handling and storage

Complete records should be kept for each component, including details of the control of delivery. The manufacturer's and/or fabricator's records should include the estimated weight of each type and size of principal components, including accessories and secondary components added during manufacture, details of design verification, quality control and other testing procedures, methods of transportation, handling and erection and assembly requirements.

Protection until the erection stage has finished should be provided to prevent mechanical damage and disfigurement to the structure. Component parts should be separated during transport and storage to prevent chaffing. Similarly, all slings, ropes, bearers, ladders and other lifting equipment that will make contact with the FRP should be encased with an easily compressible padding material.

Guidance from the ACMA (2012) for pultruded shapes and structures is given next in general terms:

- Care should be exercised in the lifting and handling to prevent chipping, cracking, breaking, twisting or bending of the components. If the materials are handled by fork lift, the lift should be centred and evenly distributed over the forks. If materials are to be handled by an overhead crane, nylon lifting slings should be used.
- Banding material used to package or palletise components should be of either nylon or plastic, or if steel banding is used, packaging material such as cardboard be incorporated to prevent the steel from scratching or scraping the FRP while it is being handled.
- Materials should be stored on cribbing, timbers or other dunnage (which is loose wood, matting or similar material used to keep components in position) capable of fully supporting the product and preventing twisting, bending or otherwise distorting of the materials.
- When FRP components are stacked, the storing dunnage should be positioned so as not to over-stress or induce matrix cracking.

- Pultruded FRPs should not be stored where temperatures exceed 50°C. Cold temperatures are not a concern. FRPs should be stored in a manner to prevent water from collecting in the product and freezing.
- Fabricated structures should be delivered in such a sequence as will permit most efficient and economical performance of both off-site fabrication and on-site installation. If the bridge owner wishes to prescribe or control the sequence of delivery, such right shall be reserved and defined in the contract documents. If the owner contracts to separate delivery and installation, the owner should co-ordinate the planning between the fabricator and the contractor.

6.3 INSTALLATION

6.3.1 Method of assembly

During assembly, components should be supported on a level surface free from sharp protrusions so that they do not bow, twist or distort. A temporary supporting structure including fixing inserts should be surveyed before erection of the FRP structure. Where appropriate, temporary spacers should be used to suit the survey results and ensure consistent spacing. The relative positions of components to be connected together should ensure that the connections and joints perform as intended structurally. Where required, they may be sealed or otherwise made weather tight. The finished work should have a satisfactory appearance and be square, regular, true to line, level and plane with a satisfactory fit at all interfaces. The dimensions of the structure shall be within dimension tolerances specified by the designer.

6.3.2 Temporary supports

Temporary supports and attachments may be required to prevent overstressing of FRP components during installation. The global and local impacts of these supports need to be considered by the contractor and designer.

6.4 QUALITY CONTROL

6.4.1 Conformance to design and specifications

As part of the general quality control process outlined in Chapter 8 of Clarke (1996), testing (following our guidance in **Sections 4.6 and 5.1.12**) should be carried out in approved laboratories in accordance with international standards and under approved accreditation/quality schemes, such as from United Kingdom Accreditation Service (UKAS) or by BS EN ISO 9000:2015. Traceability and conformability of the materials should be ensured in all cases and comply with BS EN 16245. All physical testing to characterise materials should be carried out in accordance with the relevant ISO or EuroNorm (EN) standard (see Section 4.6). Where such standards do not exist, national or internationally accepted standards should be used or alternatively fully detailed test arrangements specified by the designer.

To verify FRP material quality, test samples should be made from additional materials obtained when fabricating the components. Tensile strength, flexural modulus, interlaminar shear strength, heat deflection temperature (HDT) or T_g should be determined as a minimum. Pultruded profiles should be batch tested by the manufacturer in accordance with standard BS EN 10204:2004, to Certificate 3.1 level.

Adverse temperatures, direct contact by rain, dust, or dirt, excessive sunlight, high humidity or vandalism can damage an FRP component during the installation stage and cause improper resin/matrix/adhesive cure. Temporary protection, such as tents and plastic screens, may be required for quality control during installation and until all resin/matrix/adhesive systems have cured. If temporary shoring is required, the FRP system should be fully cured before removing the shoring and allowing the structural member to carry the design loads.

In the event of suspected damage to a FRP component or structure during installation, the responsible professional engineer should be notified and the manufacturer consulted.

If a large number of components are to be produced, an extended testing programme can be performed to establish a set of characteristic properties, including for stiffnesses, compressive strength and in-plane shear strength. This testing in accordance with guidance in **Sections 4.6.1 and 5.1.12** should be undertaken in advance of, and in addition to, quality control tests during any composite manufacturing process.

To validate the performance of an FRP component, an overall load test of the structure, or a representative part, could be performed and measurements of deflection and vibration taken to determine structural properties, including strength (Canning *et al*, 2012a). As per **Section 5.1.12** three nominally identical tests should preferably be carried out to establish the failure mode and strength in accordance with BS EN 1990:2002+A1:2005.

Bonded or laminated connections and joints should be tested separately. The shear strength for the bond of the adhesive to the FRP can be determined by using a single overlap shear test in accordance with ASTM D3163-01 (2014). The suitability and adequacy of the preparation of FRP surfaces (**Section 6.2.4**) can be demonstrated by 'pull-off' testing to ASTM D4541-17 (2017). These tests should be undertaken before production bonding begins, although representative equivalent materials supplier data might be acceptable as verification of suitability. Additional tests should be undertaken during production bonding operations. For the purpose of quality control, the adhesive should be tested for its T_g, tensile modulus of elasticity and tensile strength and compared against accepted values. The supplier's instruction for the method of application, adhesive thickness and curing conditions needs to be strictly adhered to.

6.4.2 Material inspection

Technical details of the fibres, mats, cores, matrices etc used to manufacture the FRP components, including mechanical, durability data and associated COSHH information, should be included in a quality plan for inspection, prepared before manufacture of the FRP components. Any quality plans should be project specific and should be commensurate with the task in hand. The quality plan should cover areas such as (but not limited to):

1. **goods inwards** – including delivery and materials notes, purchase orders and acceptance checklists
2. **materials schedules and storage** – including handling and storage, COSHH, preservation, retrievability
3. **works order package** – drawings, moulds and materials, performance specification
4. **plug preparation and CNC** – geometry and machining, CNC program and drawings, raw material, tolerances
5. **preparation of mould** – staff and skills, fabrication drawings, finishes, COSHH, quality cards
6. **fibre and consumables lay-up** – fabrication drawings and lay-ups
7. **infusion process** – volumes of materials, monitoring, environmental conditions, tests, simulations, bagging/process design
8. **cure conditions** – temperature, durations, acceptance criteria
9. **de-moulding** – checks, process, identification of risk areas, acceptance criteria
10. **final assembly and inspection** – tolerances, bonding needs, cosmetic treatments, storage requirements, coatings
11. **dispatch** – logistics, delivery notes.

6.4.3 Fabrication and installation inspection

Material properties and the process conditions should be checked and recorded during the fabrication and bonding operation, together with details of matrix batches and their constituent proportions. The completed FRP bridge and its individual components should be examined for delaminations, debonding and voids using one or more of the non-destructive evaluation techniques introduced in **Section 7.3**. **Section 7.4** is for guidance should it be necessary to repair a defect before the bridge is handed over.

6.5 CERTIFICATION

6.5.1 Design

In the UK, the approval and certification process will usually follow the procedures specified by the particular bridge owner, such as in Highways Agency (2012). Experience in the UK (Farmer *et al*, 2006) has shown that FRP bridge projects are successful when their design teams have a role in the inspection and monitoring works during the fabrication and installation phases and the designs are subjected to independent checking by other suitably experienced professional engineers.

6.5.2 Construction

It is vital that all operatives engaged in the fabrication and installation of FRP components have undergone supervised training in the use of FRP materials, fixings and adhesive bonding products.

As for most bridges, the contractor should certify that the 'works' have been executed in accordance with the requirements of the 'design' as described in the contract documents, which should include drawings and technical specifications.

6.6 LOAD TESTING

It may be beneficial to help validate the design for load tests to be undertaken on individual components and/or the complete structure, in accordance with the guidelines given in **Section 5.1.12**. For every project, representative samples of FRP materials should be tested statically to check compliance with the specified material properties. After the bridge installation is complete a load test can be carried out to establish its response and to provide a benchmark for future testing that will monitor structural performance. It is recommended when performing whole structure load tests to measure the vertical deflection at three points transversely across the deck surface at the longitudinal spanning position of maximum deflection. If practicable, strain measurements should be recorded at positions in two directions near to mid-span or at other positions on the bridge known to be at higher strains.

7 Long-term inspection, monitoring and maintenance

Monitoring, inspection, and maintenance of bridges are wide-ranging post-execution topics and are well covered in industry practice documents. This chapter considers the topic in relation to the specific characteristics of FRP components in bridge engineering. Naturally, the guidance draws together areas already covered elsewhere in **Chapters 4 to 6**. The guidance in **Sections 7.1 to 7.4** is predominantly for asset management actions that can be taken with the aim of minimising the risk that an FRP bridge becomes unfit for purpose before the end of its design working life. Throughout this chapter, lessons gained from the execution of the existing UK FRP bridge stock are highlighted for information.

7.1 DESIGN WORKING LIFE FOR IN-SERVICE PERFORMANCE

If the recommendations in this guide are satisfied, the design of FRP components and their interfaces with other FRP or other material components will have accounted for the service environment. The technical requirements are set out in **Chapters 4 to 6**. Explicit consideration of maintenance and repair during design, good detailing, the establishment of benchmark information and the provision of design information are all essential for delivering an FRP bridge that can be maintained.

As illustrated by the case studies in **Appendix A1**, FRP bridges can possess unique structural free-form components, or can be formed from standard components, such as proprietary pultruded shapes. A combination of bespoke free-form moulded and standard components in the structure is an option too. The designer needs to account for the possibility that equivalent FRP components may no longer be manufactured by the time the bridge is reaching a major age milestone. Looking to the future, maintenance and evaluation of the structure's performance will be more dependent on the information provided by the designer, composite manufacturer and fabricator than is the case with conventional structural materials.

It is recommended that the maintenance manual/health and safety file should include sufficient detailed information for the bridge owner to properly carry out their responsibilities. Without having access to information they may not be aware of the most vulnerable parts of the structure or of signals which might indicate that a structural engineering problem is arising.

The expected long-term behaviour of the FRP materials and components can be estimated though coupon or subassembly testing, as summarised in **Chapters 4 and 5**. Knowledge and understanding will have led to the choice of the mechanical properties (**Section 4.6**), partial factors (**Section 5.1.9**) and conversion factors (**Section 5.1.10**) for the design calculations (**Chapter 5**). Available test data and assumptions for chemical and UV resistance, uptake of moisture, resistance to freeze/thaw and de-icing salts and mechanical impact of the FRP/matrices should also be documented. Any bound limits on the service conditions should be documented to enable reliable periodic monitoring. This will

Box 7.1 Material samples

It is recommended that samples of the FRP material(s) be sourced from a bridge's components and stored indoors as part of a documented maintenance strategy. These samples may be chosen to enable comparisons of mechanical properties (**Section 4.6**), such as (wet) T_g, percentage moisture uptake (Grammatikos *et al*, 2015), strengths or stiffnesses, to be made through standard testing as introduced in **Section 4.6.1**. The purpose of this approach is to provide benchmark information for visual or acoustic inspection, or to provide calibration data for a suitable non-destructive evaluation (NDE) technique to be introduced in **Section 7.3.4** for special inspections. Additional samples can be installed at the bridge (attached or adjacent to) for future testing, avoiding the need to extract samples from the working structure, ie as undertaken for traditional structures – concrete cores/steel rebar samples.

enable inspectors to identify if changes in site conditions are of importance. The documentation can be essential with regard to temperature, moisture, chemical spillage, fatigue (**Section 5.3.3**) or in response to vandalism.

Laminates can be susceptible to through-thickness impact damage from concentrated loads such as vehicle wheels, falling debris and accidental actions. Documentation should include a strategy for inspection and rapid replacement of damaged regions when the working design life of the FRP bridge has not be surpassed.

Interfaces in connections and joints should have accounted for potential differential movements. A relative area of weakness will commonly be the wearing surface or surface course on an FRP (cellular) deck. Because it will be project specific, this important aspect of design for durability is not covered in this guidance. A method statement for replacement of the wearing surface should be documented in the bridge's maintenance manual/health and safety file.

7.2 MONITORING

Monitoring a structure during its serviceable life is an important aspect of ensuring that the structures remain fit for their intended purpose. Historically, monitoring is undertaken via routine regular visual inspections. To date 'structural health monitoring' (SHM) is generally undertaken by bridge owners on a reactive basis following the identification of an area of concern within the structure. However, the post installation of apparatus and sensors can be time consuming and costly. With the adoption of new advanced materials such as FRP composite and the need to limit disruption to the networks that these structures operate within, the use of SHM provides a useful tool to understand the long-term performance of a structure. This allows bridge owners to obtain a useful dataset that can help them to make more informed maintenance decisions in the future. The production of intelligent data using sensor technology complements the current digital transformation that the construction industry is currently undergoing. The use of 'big data' will be a trend that changes the way industry works and digital asset management will form a key component. FRP composites can use sensor technology embedded in the construction during off-site manufacturing. This technology can help with quality control issues during manufacture (as described in **Chapter 6**) and provide a useful dataset to understand the structure's performance against the design assumptions and analysis models while also predicting future trends.

For all structures, the specific monitoring strategy should be set out for the bridge owner by the designer and included in the maintenance manual and health and safety files. Inspection during construction is covered in **Section 6.4.3** and inspection and testing during, or on completion of, construction is covered by **Section 6.6**.

Monitoring equipment can include a data logging system, electrical resistance strain gauges, fibre Bragg grating sensors (Ye *et al*, 2014), laser/hydraulic levelling equipment and laser levelling targets. For long-term monitoring to be successful it is recommended to build in redundancy into the sensor provision and ensure adequate fixings and weather protection to enable long-term operation of sensors, cabling and monitoring equipment.

A few FRP bridges include permanent instrumentation to provide feedback for in-service sensor monitoring and structural health monitoring. Instrumentation has been used in initial load testing and planned load testing at five to ten year intervals.

7.3 INSPECTION

As a general guide, routine visual inspection would occur every one or two years, with a more detailed inspection at least every six years. Inspectors should be knowledgeable about FRP components and structures and be trained in the installation of FRP bridges. If a novel or innovative FRP system has been included in the structure it may be appropriate to have inspections at more frequent intervals, especially during the early life of the bridge. It is recommended to have detailed inspection carried out more frequently after installation to confirm, for example, the performance of adhesively bonded connections in the structure. Special investigations will occur when predefined milestone or trigger points are reached, if a concern has been identified or if an abnormal or accidental action or circumstance has occurred.

Routine inspections may form part of a maintenance regime for a whole series of assets in the same locality, and these inspections may lead to recommendations for maintenance actions or the need for a special inspection. Different types of inspections are introduced next.

Routine inspection should include:

- visual appearance of the FRP laminate surfaces, with specific emphasis on recording any localised material damage or change in colour
- change of use of the bridge structure (eg increase in maximum vehicle load for road bridges) or change in site environment, which may lead to the need of a structural review as stipulated, for highway structures, in Highways Agency (2011).

A more detailed inspection should also consider the integrity of the FRP components or structure and their interaction with the ground and the overall performance of the FRP structure. The maintenance manual/health and safety file should set out what might be signs of deterioration that are known to affect the ability of the bridge structure to perform as intended.

For Highways England bridges the requirements for inspection are set out in Highways Agency (2017), with reference to Highways Agency (2007a and b). The Concrete Society (2003) has an inspection proforma in Appendix E for inspecting applications of FRP strengthened concrete structures that can be revised for FRP bridge inspection, while Appendix C provides training log for inspectors.

Possible causes of structural engineering problems can be workmanship defects, high ambient temperatures, foundation movements, trapped water and the effects of the weather such as lightning strikes and UV radiation. Because FRP materials are relatively new in the service environment there is not a body of knowledge on their durability to provide advice.

7.3.1 Visual inspection

Although FRP is adopted as a low maintenance and durable (non-corroding) material, inspectors need to be aware of the role of the matrix rich external surfaces, with or without a coating, in protecting the reinforcing fibres from the environment. Inspectors should also be aware that adhesive bonded connections may not have been cured under the same fabrication conditions as the main FRP components and could be more susceptible to degradation from environmental actions.

The design and execution processes developed in **Chapters 4 to 6** will allow for the long-term effects of humidity (moisture), temperature and creep and fatigue actions. Because these actions might have a deleterious effect on structural performance it is good working practice to ensure that seals, weep holes, fillets and other water-shedding details are in place and regularly maintained. Changes in the usage of the FRP bridge, which can lead to more frequent loading, should be recorded so that this change can be compared to fatigue assumptions, such as given in **Section 5.3.3**.

Evidence of moisture collecting or passing through an FRP deck should be noted, especially if the deck is of sandwich construction. Many FRP decks are made of a cellular structure and are very lightweight (O'Connor *et al*, 2011). Water collecting within the deck may generate unexpected load and environmental actions.

The structural design may have relied on a degree of composite action between FRP and other material components, for example, the Mount Pleasant bridge (2006), with a summary in **Appendix A1**, has an FRP deck adhesively bonded onto two steel girders. If this is the case, any relative movement between these components should be monitored for a change that could signal a reduction in the degree of action.

FRP components in a variety of environments and applications have been reviewed after a period of 30 years (Hollaway, 2007). Many of these have shown excellent durability. Those components performing less well exhibit the following kinds of defects:

- uneven colour
- crazing (micro-cracking)
- some corners devoid of gelcoat
- leakage between joints
- loss of sealant
- dirt
- organic growth (algae, lichen, moss)
- other evidence of water
- cracking and debonding of surfacing
- cracking at construction joints with other components
- FRP delamination from corroded brackets
- surface chalking, secondary cracks
- cracking at angles owing to thermal stresses.

Many of the applications observed to have such defects were still fit for purpose despite the evident reduction in structural properties. Modern materials (especially the matrix) have changed over the 30 years, with the systems common today expected to offer superior FRP material performance to their predecessors.

It is recommended that in a visual inspection the following be recorded:

- surface condition, including discolouration, crazing, blisters, delamination, cracking, loss of surface, fibre exposure or significant surface scuffing
- variation in appearance from one area to another over the structure
- any other visible damage, vandalism or evidence of chemical spillages
- evidence of relative movement in any joints or connections
- cracking, delamination or loss of fillets in any joints or seals
- integrity of cut ends of FRP components, including loss of any protective or sealing treatment
- loss of isolation details against any electrical conduction between metallic components and FRP components with carbon fibre reinforcement (The Concrete Society, 2003)
- ponding around bonded or cut FRP or loss of efficiency of water-shedding details.

The surface condition of the FRP may provide some insight into defects arising within the component or structure itself. Unlike steel and concrete structures, FRP materials are 'brittle', in the sense of possessing linear elasticity to failure (**Section 4.6.1**). This means that redistribution of stresses is likely, in the short-term, not occur, although matrix cracking and excessive local deformations can occur well before ultimate failure. For these reasons a professional engineer with experience of FRP structures should assess the structural implications of the inspection findings and identify any post-inspection remedial actions required.

7.3.2 Position survey

If there are concerns about the bridge raised as part of a periodic inspection regime, a position survey can be recommended to identify what is the long-term creep or other action movement. The results of the survey can further help to identify any reduction in structural performance that cannot be detected by a visual inspection.

Dynamic testing can be undertaken. It is important first to establish an initial position survey and determine the dynamic response soon after construction to provide a benchmark for subsequent dynamic monitoring. Thermal movements can be significant, and temperatures should be recorded for all forms of survey and inspection.

7.3.3 Detailed survey

A detailed structural survey will provide the opportunity for close inspection of the more inaccessible areas of the bridge. This longer form of inspection will be less frequent (say every six years), and so the opportunity should be taken for a more rigorous approach. For many periodic inspections, this will take the form of a more detailed visual with or without an acoustic NDE technique of inspection.

7.3.4 Special inspection

Following a bridge inspection in accordance with guidance in **Section 7.2**, if the investigators raise concerns about the durability of the structure, a special inspection may be required. Hidden damage may not be picked up by routine visual inspection. Such material damage includes disbonds between the skin and core of sandwich constructions and internal damage from low energy impact or from an unexpected action. There is also the possibility of damage in an unexpected area. In these circumstances a variety of NDEs can be considered. There are several NDE techniques that can be used to inspect FRPs. Some of the techniques are appropriate for use on site and a number are not. When material samples can be taken from an FRP component then destructive mechanical property tests, as introduced in **Section 4.6.1**, can also be used. Changes in T_g from the initial dry value straight after the FRP material was manufactured may be used to identify changes in the matrix owing to the mechanism occurring over time in the presence of moisture and temperature variations.

The choice of NDE techniques (Kapadia 2007) for inspection of FRP bridges may include:

- enhanced visual inspection
- acoustic impact testing
- transient thermography
- laser shearography
- ultrasonic testing
- radiography.

ASTM D4385-13 provides the framework for inspectors to classify visual defects in thermosetting reinforced pultruded shapes. In accordance with ACI Committee 440 (2008) inspection methods should be capable of detecting delaminations of area 1300 mm^2 or greater.

The technique or techniques employed can be specific to the FRP component or structure and to the expertise of the inspection teams. **Table 7.1** lists 15 types of defects found in FRP laminates (Kapadia, 2007). For eight NDE methods the table provides guidance on field acceptance and on which of the 15 defects the techniques can be used to identify. A number of techniques, including ultrasonic scans A to C have a British Standard for test procedure and result evaluation.

Table 7.1 Range of NDE techniques and what they can detect

Defect type	Inspection techniques							
	Acoustic testing	*Laser shearography*	*Thermography*	*Visual*	*Ultrasonic depth*	*Ultrasonic A*[1]	*Ultrasonic B*[2]	*Ultrasonic C*[3]
Delamination	✓	✓	✓	✓	✓	✓	✓	✓
Cracking	✓	~		✓				
Disbond	✓	✓	✓		✓	✓	✓	✓
Void	✓	~	✓	~	✓	✓	✓	✓
Impact (BVID)[4]	✓	✓	✓	✓	✓			
Porosity		✓	✓	✓	✓			
Inclusion	✓	~	✓	✓	✓	✓	✓	✓
Erosion		✓	✓	✓	✓	✓		✓
Core disband	✓							
Core crushing	✓							
Matrix cracking								
Fibre breakage								
Kissing bond			~					
Environmental ingress		~	✓	✓				
Crazing				✓				

Notes

1 A-scan is for a single point image

2 B-scan is for a single line image

3 C-scan is for a 2D image

4 Barely visible impact damage

Surface defects can be identified through enhanced visual inspection (The Concrete Society, 2003) by plain sight enhanced with magnifying glass, touch or a hand light. Using illumination, shadows can give indications of surface undulations. Visual inspection can be enhanced further with the use of digital cameras, endoscopes or special lighting. This simple method of inspection can identify the defects due to delaminations, wrinkles, crazing, fractures, surface indentations and voids. Enhanced visual inspection can be completed without a qualified NDE inspector. The testing has its limitation because it is subjective, requires line of sight with careful lighting conditions and will be affected by surface condition, such as organic growth. One strategy is to use the information gained from a visual inspection to decide if a detailed NDE inspection of certain areas is justified where there is an engineering concern.

Knowledge of the original as-built FRP bridge may assist the inspector in identifying defects that are outside the design assumptions. These design requirements should be set out in the original specification and will include the acceptance for small voids, pinholes, hairline cracks, scale, scouring and localised discoloration. This information should, as highlighted previously, form part of the maintenance manual/ health and safety file.

The most common methods of acoustic impact testing are coin or hammer tapping tests (The Concrete Society, 2003, 2012) because these are most amenable to bridge site conditions. FRP laminates resonate in response to tapping the surface with either an instrumental modal hammer or a coin. A difference in resonance will result from changes in composition and defects. Tap testing can identify a number of defects including: disbands, crushed cores, repairs, delaminations $>$ 10 mm in size and other cracks.

These tests are highly operator subjective and cannot give much detail on a specific defect. Mainly they give an indication of where there may be a defect, because a test response can be affected by impact damage. The hearing ability of the operator is a key factor in reliability of coin and tap tests and there should be continuity in the operator used for the inspection programme.

Where the site is quiet enough to use electronic acoustic transducers, the responses from the FRP can be graphical plot, so differences in response can quickly be observed and analysed. The main drawback with many bridge structures is that sensitive electronic equipment requires a sound-proof enclosure to get reliable and precise results.

With transient thermography, the surface is heated by a pulse from a flash lamp and the change in surface temperature with respect to time is monitored with an infrared camera (The Concrete Society, 2003). To detect deterioration, the surface areas with defects cool slower than the rest of the surface. The change in temperature required for detection is small enough to avoid lasting damage to any component. Delaminations, adhesive disbonds, BVID and corrosion are all defect types that are detectable. This NDE technique is not necessarily suitable for the detection of vertical cracks and inclusions (where the inclusions are of a similar material to the rest).

Handheld devices are available that can both heat the surface and record the change in surface temperature. It is a quantitative and relatively well established NDE technique. An advantage to recommending transient thermography is that this NDE method can be easily applied on site, because it does not require complex supporting frames or surface contact. One drawback is that the penetration depth into the laminate is limited. There is no need for a skilled operator once the equipment is set up. For reliability of measurements the infrared camera requires tuning for the material being analysed. Once the IR video has been recorded, data analysis by an expert is usually done off site.

Laser shearography can be recommended to detect delaminations and disbanding, as well as impact damage and erosion. This NDE technique can be employed to detect air and gas pockets (voids or porosity) and any excess of adhesive bonding or matrix constituent. Results take the form of visual qualitative strain maps for the surface in response to an applied stress.

Applications of laser shearography on site to inspect FRP repairs and strengthening can, over time, lead to future developments for the routine inspection of FRP bridge components and structures. A significant limitation is that current systems are not appropriate when the surface of the FRP is wet. Compared to other NDE techniques it is easy to set up because it requires no supporting frame and no coupling to the inspected material. There are a number of standard ways to stress the surface from thermal to vacuum induced loading. The inspection can be done quickly by recording, say 30 frames a second and the results can be analysed by an off-site expert.

There are four types of ultrasonic testing available, which are known as A-scan, B-scan, C-scan and depth-scan. Ultrasonic pulses are reflected by interfaces between materials having different properties. Portable machines are available that assess all of these in one pass of the equipment. Owing to the nature of the results involved, highly trained operators are required. The feasibility and success of this NDE will depend on the geometry and accessibility to the component or structural feature in question. A combination of the three types of scans A to C can effectively assess the size and location of defects. Ultrasonic testing is being used to assess defects in glass reinforced plastic pipelines in the field and so is amenable to use on site. Pipe inspection relies on the regular and repeated geometry and this positive condition is less likely to be found in FRP structures.

The ultimate aim should be to have standard specification for materials and workmanship, into which an NDE framework for routine and special inspections would fit, but the UK is not at that stage yet.

A new evolving inspection technique currently being deployed on a number of bridges is the use of digital image correlation. This process (special inspection technique) is discussed as follows.

Digital image correlation

The principal difficulty with adding lots of monitoring systems to bridges is that they produce vast quantities of data that need to be screened to remove the 'background noise'. Bridge operators can struggle to interpret this data unless there are very clear trigger levels and interventions defined.

For pultruded bridges the installation of sensors will most likely include a number of stress gauges and thermocouples. These will require connections to be made with cable runs supported along the structure. While this solution provides a dataset the engineer can assess, the longevity of these sensors and cable runs is a long-term challenge for FRP bridges fabricated using pultruded elements due to the sensors and cable runs being exposed to the external environment.

However, other structures such as moulded structures using infusion techniques have the benefit of being able to incorporate sensors and cable runs within the moulded sections. In addition to this the introduction of fibre optic sensors into the structure (ie located through fibre stacks) at bespoke locations is possible.

Where bridges have been manufactured with no such sensors or where existing sensors/cables have failed, a new technique using high quality imagery can provide quick cost-effective in-situ stress measurements. This technique, called digital image correlation (DIC) is discussed below in more detail with some examples discussed.

DIC is an evolving measurement technique that has been proposed to enhance bridge inspection for the past 25 years or so, but is only recently starting to be used outside of the research community. DIC can be used for monitoring by imaging a bridge periodically and computing strain and displacement from images recorded at different dates or under different operating conditions. DIC measurement can provide information about strain (all directions), vertical and horizontal displacement, crack size, rotation and acceleration. This data can be held to track the history of a defect and inform about its cause and a suitable intervention.

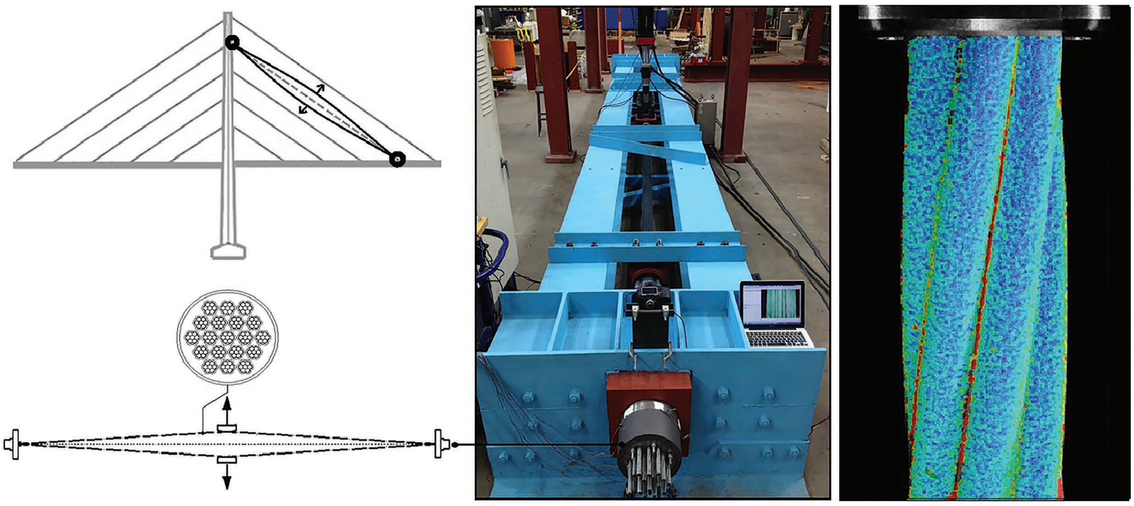


Figure 7.1 Digital image correlation example for cable fatigue and serviceability (courtesy Atkins)

DIC is a photogrammetry technique used for accurate measurements of surface deformation. The digitised images are compared to match facets from one image to another by using an image correlation algorithm. Image analysis involves capturing a reference image of a bridge component surface in its undeformed state. As the load is applied (eg truck load), additional images are collected. The algorithm (which can either run in real time or post process), involves a stage-wise analysis, in which each stage consists of one image resulting in a description of displacements occurring on the surface of the bridge component. The evaluation of a correlation measurement results in co-ordinates, deformations and strains of the surface. The DIC method allows high precision surface deformation measurement that can reach the accuracy of a few micrometres (Winkler and Hendy, 2016).

7.4 MAINTENANCE AND REPAIRS

Although FRP components are expected to be durable it is advisable to have a programme of maintenance to ensure that water, with or without pollutants, is not collecting on concave or flat horizontal surfaces and that the FRP surfaces are periodically cleaned to remove graffiti and build-up of organic growth. Guidance for steam cleaning and pressure washing as cleaning methods for pultruded FRP structures is given in The Concrete Society (2003) and Strongwell (2016).

FRP laminates can be repaired (see also **Section 6.2.6**), and there is guidance from the pultrusion processors in America (Strongwell, 2016, ACMA, 2012), and by way of national guidance for the application of FRPs to strengthen concrete structures (The Concrete Society, 2003, 2012, ACI Committee 440, 2008) or metallic structures (Cadei *et al*, 2004). Repairs should not, however, be undertaken without first identifying and addressing the root cause(s) of the damage and to apply a solution to mitigate against it/them happening again.

Highways Agency (2005) has the following guidance to the technical information that has to be provided by the designer to the bridge owner:

- methods of cutting and drilling, including protective treatment to cut surfaces
- methods of repairing local damage during construction and criteria for assessing the structural adequacy of damaged parts
- data to enable repairs to be carried out to FRP components during the working service life of the bridge, including sufficient details of the materials to enable compatible repair materials to be independently sourced
- sufficient data to enable a replacement surfacing system to be specified and independently sourced, including details of the system installed at the time of construction, plus chemical and mechanical characteristics of the FRP material at the surface of the deck
- guidance on inspection and the significance of defects

Highways Agency (2005) requires the designer to provide sufficient information and data to the bridge owner to enable the FRP bridge to be maintained in a serviceable condition throughout its design working life. The information has to be sufficient to allow materials for repair and/or replacement to be sourced independently of the FRP designer or supplier of, for example, an FRP deck. The engineering information provided should include method statements and material/loading data for the following:

- removal of the surfacing system
- installation of a replacement surfacing system
- replacement of a section of the roadway deck
- replacement of movement joints
- replacement of bearings
- reinstatement of a parapet following vehicle impact (where standard anchorage details are offered by the FRP designer or supplier)
- decommissioning and recycling

Box 7.2 Signage

> It is good practice to have warning signs installed alongside instructing site workers to seek specific guidance for the FRP bridge before any work is carried out.

The method of repair will depend on the causes of the damage, the type of FRP material, the form of degradation and the level of damage. Minor damage should be repaired, including localised FRP laminate cracking or abrasions that adversely affect structural integrity. Minor damage can be repaired by bonding FRP patches over the damaged area (The Concrete Society, 2003, 2012, Cadei *et al*, 2004, ACI Committee 440, 2008, Strongwell, 2016, ACMA, 2012). When applying an FRP patch it should possess the same characteristics of thickness or laminae orientations, as the original laminate. Patches are to be installed in accordance with the material manufacturer's recommendations. Minor delaminations between layers in the laminate can be repaired by resin injection or filling. Major damage may require removal of the affected area with replacement of a section of the FRP laminate or full component. Options for partial replacement include splicing with plates using adhesive bonding (**Section 5.5.4**) or mechanical connection (**Section 5.5.5**), or by over-wrapping the damaged component with further FRP layers.

Strongwell (2016) has guidance for repairable defects for pultruded components which, after checking, should be valid for other FRP materials. Repairable defects are those that can be repaired without affecting the serviceability of the structure. Unless otherwise specifically prohibited, repairable defects include chips, die-parting lines, gouges, intermittent disfigurement, scale, sluffing, stop marks, wire brush surface and resin voids where no blisters or delamination occur (see Section 7 in ASTM D4385-13 for further description and information on defects). Unless otherwise prohibited, fabrication defects that are repairable include surface scuff marks and an incorrect hole location.

The recommendations in **Chapter 6** regarding fabrication (**Section 6.2**), installation (**Section 6.3**) and quality control for workmanship (**Section 6.4**) should be applied to the process of repair. For FRP bridges, the environment surrounding the repair work may be more challenging than the environmental conditions present during the original construction phase. The repair should be seen as a specialist operation and consideration should be given to the long-term performance of the repaired structure, as well as the immediate restoration to the designed structural performance. If water/moisture ingress has occurred, because of a defect, then the required achievement of dry FRP before repair may well need to form part of the method statement.

Procedures for adhesively bonded repairs should follow any guidance included in the original construction documentation for the bridge, as well as good practice guidance that has developed since construction was completed. Good practice guidance should be sought with regard to the surface preparation, environment for bonding and cure, quality control, testing and personnel executing the work. Guidance can be drawn from the supplier of the original FRP component, the supplier of the bonding system and existing guidance regarding bonding of FRP in a construction environment (The Concrete Society, 2003, 2012, Cadei *et al*, 2004, ACI Committee 440, 2008).

Repairs and intrusive investigations may include removing damaged material back to a substrate suitable for repair. In this circumstance, light hand sanding is generally the standard approach. More aggressive methods may heat the matrix, clog equipment and further damage the FRP component. Once the area has been cleaned back, the true extent of defects/damage may be exposed. Any further defects/damage should be recorded and reviewed by the engineer responsible for the design of the repair before the repair proceeds.

Any surfaces that have been abraded or cut, or with exposed fibres, can be sealed to give protection to the fibre ends. Abraded surfaces should be vacuumed and wiped with a lint-free cloth before bonding or sealing. In Strongwell (2016) there is the important qualifier that resin sealing does not, in general, change the structural performance, the water absorption rate or the ability of a pultruded FRP component to resist chemical corrosion in most environments. Surface preparation for adhesion (**Section 6.2.6**) should be done immediately before adhesive bonding to avoid the possibility of recontamination of the surface.

Repair may involve jacking of the undamaged structure to remove load or facilitate a restoration of the original geometry. FRP components are often thin-walled structures deriving their stiffness from their overall shape. FRP has little ability to redistribute concentrated actions and so components could be vulnerable to concentrated point loads exerted during jacking and other remedial repair operations. It could be necessary for the FRP component or structure to require temporary stiffening and load dispersal to be in place in order to avoid further FRP damage during these site operations.

The bridge maintenance manual/health and safety file needs to be updated following repair. As with the original structure, it may be advisable to provide repair samples that can be stored on site and/or indoors to be destructively or non-destructively tested at a later date, in accordance with information presented in this guide.

8 Sustainability

In this chapter the sustainability credentials of FRP materials for bridge engineering are introduced by comparing attributes of several structural materials through case studies. It is recognised that products made of FRP materials can offer significant environmental benefits because of a positive combination of low mass, favourable mechanical properties (**Chapter 4**) and resistance to corrosion. One major benefit of reduced structural weight is that it enables faster installation and reduced impacts, such as from highway diversions or rail line closures. This is also the case for life cycle maintenance activities where the inherent durability of the material results in lower impacts during the operational phase.

This chapter ends with four sections to further support the sustainability credentials by introducing essential information on FRP material impacts, the end of life options for FRP, some empirical guidance on the environmental impact of FRP bridges and the overall sustainability of FRP materials in terms of economics, environment and society.

8.1 ENVIRONMENTAL IMPACT AND EMBODIED ENERGY: CASE STUDIES

When deciding on the sustainability credentials of a structural material in bridge engineering it is appropriate to consider information obtained from case studies that have assessed environmental impact and embodied energy. There are few life cycle impact assessments publicly available. The three independent case studies summarised do assess alternative material designs for real or typical bridge projects in terms of embodied carbon and/or carbon dioxide emissions. There appears to be a consensus that considering only carbon impacts is acceptable for comparison purposes, because other impacts are relatively small.

The Noordland footbridge case study paper by Daniel (2003) does include water and air pollution, and demonstrates that the impact of the FRP bridge is the lowest. It may be concluded that considering only carbon impacts will tend to be conservative from the perspective of demonstrating the actual environmental benefits of FRP bridges, though fuller studies would clarify this.

The case studies are summarised in **Sections 8.1.1 to 8.1.3** (use sources referenced for detailed information) and some guidelines are drawn from them.

8.1.1 Noordland Footbridge, Netherlands

This case study (Daniel, 2003) is for the replacement of a corroded steel pedestrian footbridge, consisting of two 13.5 m spans having deck width of 1.6 m, which was required in Noordland inner harbour in the Netherlands. This location experiences severe weather conditions and high chloride levels. The client demanded a bridge solution that offered the most ecological benefits.

Five material options were considered, and **Table 8.1** summarises the life cycle assessment (LCA) results for structural steel, stainless steel, FRP (pultruded shapes), aluminium and RC. In the table, column 2 reports the mass of the replacement bridge, which ranges from 3.2 tonnes of aluminium to 28 tonnes of RC, while the pultruded FRP bridge has a mass of 4 tonnes. In column 3, material energy consumptions are presented from Table 2 in Daniel (2003). Specific energy rates were taken to be accepted when this early LCA was conducted. Daniel splits the material into virgin (non-recycled) and recycled parts. The paper explains that "*The analysis was limited to the basic materials. Influence of wooden bridge decks in the two steel bridges, stainless steel or other metal bolts in the aluminium and plastic bridges, etc., was ignored.*" In the arithmetic calculations, the first number is for the consumed energy and energetic material value in MJ/kg, and the second number is for energy stored in the product in MJ/kg. An energetic value, called exergy, represents the potential of the energy stored in materials to deliver work. The energy consumptions on delivery in giga joules (GJ) are presented in the fourth column. They are established from the non-recycled and recycled energy consumption data and bridge masses in the table's columns 2 and 3. Column 5 gives estimates for the energy consumption during use in GJ, with the final column reporting the total energy consumption given by the addition of the GJ values in columns 5 and 6.

Table 8.1 LCA comparison of alternative designs for Noordland footbridge (from Daniel, 2003)

Material	Mass (t)	Material energy consumption (MJ/kg) and assumed (%) of primary or secondary material	Energy consumption on delivery (GJ)	Energy consumption during use (GJ)	Total energy consumption (GJ)
(1)	(2)	(3)	(4) = (2) × (3)	(5)	(6) = (4) + (5)
Structural steel	6.0	Virgin 80% 46 – 7 = 39 Recycled 20% 36 – 7 = 29	222	72	294
Stainless steel	5.6	Virgin 70% 69 – 11 = 58 Recycled 30% 54 – 11 = 43	300	30	330
FRP (pultruded shapes)	4.0	33 – 9 = 24	96	24	120
Aluminium	3.2	Virgin 60% 137 – 33 = 104 Recycled 40% 45 – 33 = 12	215	54	269
RC	28.0	11 – 2 = 9	252	25	277

Daniel notes that the recycled content assumed for aluminium may be optimistic, and that the analysis is sensitive to this. He also notes that in 2002 there was a lack of available consistent environmental material data. He concludes that, despite some disputable assumptions, the bridge with a superstructure of pultruded FRP shapes is a clear winner.

This bridge has a total energy consumption of 120 GJ which is only 45 per cent of the next lowest, which are for the structural materials of aluminium and RC. The stainless-steel bridge has a total energy consumption that is 2.75 times higher.

8.1.2 LCA for an FRP bridge

This multi-authored study by Drogt *et al* (2009) assessed alternative material options for a 12 m span road bridge of width of 9.1 m to be located in Utrecht, the Netherlands. The study takes a more rigorous approach than Daniel's (2003) to define the energy consumption of the FRP raw materials used. It is noted that the assumptions on maintenance are very empirical.

For this specific study one important assumption made is that the FRP bridges have a design working life double that for steel and RC, being reused after 50 years for an additional 50 years. A design working life is a basic requirement in design, which is introduced in **Section 5.1.1**.

The report by Drogt *et al* (2009) is in Dutch. The LCA comparison is presented in **Table 8.2** with the first column introducing the four materials. The second and third columns report masses of the bridge superstructure and its concrete substructure. The fourth column is for assumptions on their maintenance. The final three columns 5 to 7 in **Table 8.2** are for total energy consumption in GJ accounting for the 50 year design working life, the material energy consumption in MJ/kg and carbon footprint in tonnes of CO_2e (carbon equivalent).

Table 8.2 LCA comparison for 12 m road bridge in Utrecht (from Drogt et al, 2009)

Material	Bridge mass (t)	Concrete foundations mass (t)	Maintenance assumptions	Total energy consumption (50 years) (GJ)	Material energy consumption back-calculated (MJ/kg)	Carbon footprint (t CO_2e)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
Glass FRP	20.7	17.0	No maintenance. After 50 years bridge is reused in different location with new foundation. Discarded after further 50 years.	652	31	75
Carbon FRP	10.4	8.5		2156	207	103
RC	150	150	Over 50 years, 5% of the material is replaced. After 50 years bridge is replaced.	1978	13	145
Structural steel	–	–		3380	–	178

For the BECO study (Drogt *et al*, 2009), Mara *et al*, (2014) explain that the following assumptions were made in the LCA analysis:

1 A bridge's life span (its design working life) is set at 50 years.

2 No maintenance is required for the FRP bridge alternatives during their design working lives.

3 Reuse of the FRP bridges after 50 years.

4 Incineration, with energy recovery at end of life for the FRP materials would recover some 16 700 kJ (4000 kcal) per tonne of heat energy. This may be realistic for glass FRP, but should be considerably higher for carbon FRP.

Although these assumptions can be disputed, the difference in total energy consumption between the glass FRP bridge and the others is very pronounced compared with RC or steel. This demonstrates an important advantage in engineering structures of glass FRP. The decrease in energy consumption for the two FRP bridges is attributed to the material savings in the concrete substructure owing to the superstructure's light weight. Comments by Mara *et al*, (2014), from the EU-funded PANTURA project (CORDIS, 2013), provide a useful set of findings to further enhance the case study results reported in **Table 8.2**.

8.1.3 An 8 m × 1 m footbridge

Table 8.3 is for a comparison of embodied carbon and energy 'cradle-to-gate' (IStructE, 2014) for a typical-sized short-span footbridge using traditional structural and FRP materials. Column 1 introduces the material system and the mass of the structure is listed in the second column. The fourth column is for the bridge's embodied energy (Strongwell, 2016) and the value is obtained from the product of the row values in columns 2 and 3. Column 2 is for the material mass in tonnes and column 3 is for the embodied energy coefficients in MJ/kg for the structural material. Column 5 is for the embodied carbon coefficient, which when multiplied by the material mass (column 2) gives an estimate of the embodied carbon in column 6 in tonnes of CO_2. Note that in this study the maintenance/use of the bridge has not been assessed.

As with the previous two case studies in **Sections 8.1.1 and 8.1.12** this case study for cradle-to-gate shows a relatively low embodied energy/carbon for the FRP option, though very similar in terms of embodied carbon to the timber option. By considering cradle-to-grave and the design working lives it is recognised that timber has a lifespan that will be less than FRP and so the FRP option ranks top. (Further operational/life cycle footprinting is included in **Section 8.3**.)

Table 8.3 Cradle-to-gate LCA comparison of alternative designs for typical 8 m × 1 m footbridge (courtesy Lifespan Structures Ltd)

Material system	Material mass (t)	Embodied energy coefficients (MJ/kg)	Embodied energy (GJ)	Embodied carbon coefficient ($t\ CO_2/t$)	Embodied carbon ($t\ CO_2$)
(1)	(2)	(3)	(4) = (2) × (3)	(5)	(6) = (2) × (5)
Timber	3.0	10	30	0.31	0.93
Steel sections	3.0	28.1	84.3	2.12	6.36
Hybrid steel beams with timber deck	Timber 1.25	Timber 10.0	47.6	Timber 0.31	3.04
	Steel 1.25	Steel 28.1		Steel 2.12	
FRP deck and handrails	0.75	26	19.5	1.23	0.92

8.2 MATERIAL IMPACTS

While carbon fibres give greater weight savings, their environmental impact, as FRP reinforcement, is about 10 times that of glass fibre. The main reason for this is that the manufacture of carbon fibre precursors and the carbon fibres themselves is energy intensive. To reduce this negative impact, carbon fibre from recycled sources can be used. Recycled carbon fibres are available as short chopped fibres and as non-woven mats (see **Section 4.2**), though their use in primary structural applications will be limited by lack of fibre alignment. In the future, carbon fibres produced at plants where renewable energy is used and from bio-based precursors may further reduce the environmental impact in terms of the energy required to manufacture carbon fibres.

In glass FRPs, the polymer resin in the matrix has the highest material impact. In the future the use of bio-based or partially bio-based resins may reduce this. Values quoted for embodied energies of materials vary widely (IStructE, 2011). The list of ranges in **Table 8.4** is taken from Song *et al* (2009). It provides a useful guide, by highlighting practical ranges for the common constituent materials in FRP, derived from various sources. Note that the polymer resins are for matrices without additives and fillers. The reason for these matrix additives is introduced in **Section 4.1**.

Table 8.4 Embodied energy of common constituents of FRP

Material	Embodied energies (MJ/kg)
Carbon fibre	180–290
Glass fibre	13–32
Polyester resin	63–78
Epoxy resin	76–80

Table 8.5 presents a comparison of embodied energy values in MJ/kg for six bridge engineering materials using data from the first three case studies summarised in **Sections 8.1.1 to 8.1.3** (columns 2 to 4) and from other sources. Column 5 is for the cradle-to-gate (factory gate) case study by Kara and Manmek (2009). In this 2009 report, for each of six manufacturers' products, a figure per kg is given for embodied energy of raw materials plus transport to the factory. Then Kara and Manmek (2009), calculate the whole-life impact for the product compared to a traditional material. To create column 5 the material energy has been added to the process energy component of the calculations from the case studies. The results in **Table 8.5** demonstrate wide variation for apparently similar products due to sensitivities in the energy calculations owing to transport distance of raw materials and processing energy.

It is noted that the Jones and Hammond (2011) figure of 100 MJ/kg for glass FRP is considerably higher than the others at about 30 MJ/kg, and is based on a single source from 1998. The comparison in the table indicates that it might not be a representative value. The main observation from the information in **Table 8.5** is that the design engineer has access to various sources of data purporting to be for the embodied energies of structural materials. Its application in LCAs should be done with care because the data has variability and uncertainty. It is recommended that an expert is contracted to carry out the LCA that is appropriate to each FRP bridge project.

Table 8.5 Embodied energies for composites and typical structural materials from various sources (MJ/kg)

Material	Noordland Footbridge (secondary/ recycled in brackets)	Utrecht bridge	Lifespan structures footbridge	University of New South Wales report cradle-to-gate case studies (material energy) + (process energy) = (total energy/kg)	University of Bath, Inventory of Carbon and Energy database (Jones and Hammond, 2011)
(1)	(2)	(3)	(4)	(5)	(6)
Carbon FRP	–	207	–	315 + 814 = 1129 (aircraft hinge fitting)	–
Glass FRP	33	31	26	26 + 4 =30 (pultruded I-beam) 28 + 4 = 32 (hand laminated boat hull)	100
Structural steel	46 (36)	–	28 (from ICE v 2.0, assumes 35.5% recycled)	–	20 (general)[1] 29–45 (virgin) 9–13 (recycled)
Stainless steel	69 (54)	–	–	–	57
Aluminium	137 (45)	–	–	–	155 (general)[1] 214–226 (virgin) 25–34 (recycled)
Concrete	11 (reinforced)	13 (reinforced)	–	–	0.7–1.0 (unreinforced) plus 1.04 for each 100 kg of steel reinforcement per m^3 concrete
Timber			10	–	10 (general[1] or sawn hardwood)

Note

1 'General" is for a typical mix of recycled and non-recycled material.

8.3 LIFE CYCLE ASSESSMENT

In understanding the sustainability implications/impacts in providing a new bridge asset, a useful tool for practitioners relating to the environmental footprint of a new asset is brigde carbon calculator developed by the British Constructional Steelwork Association (BCSA), TATA Steel and Atkins.

The Carbon Calculator assesses the total tons of CO_2 associated with building and operating a bridge during its life cycle. A review (Smith *et al*, 2013) of the life cycle footprint of bridges concluded that *"The material quantities, the comparative assessment illustrated that traffic delay was the main contributor to carbon dioxide emissions for the construction and maintenance of the bridge, accounting for around 75 per cent of the total emissions. Investigating options for managing the traffic and keeping it free flowing is fundamental to reducing the overall emission burden"*. A simple example is given in **Box 8.1** highlighting the source of carbon dioxide emissions.

It can be seen that for a traditional structure a significant percentage of the CO_2 produced comes from 'traffic delay' as a result of the construction duration and subsequent maintenance operations where traffic will be subject to disruptions as a result of the associated traffic management. In the above instance, 62 per cent of the emissions relate to traffic.

The use of FRP composites can significantly reduce these values because of their durability (thereby requiring a leaner approach to asset management) and the time to construct can be significantly reduced. Selecting an FRP bridge will result in sustainability savings realised during their life cycle.

Box 8.1 Sustainability assessment

Structure configuration = 9 span bridge, steel/concrete composite construction, 20 m spans, 14 m deck width, 300 mm RC deck, plate girder beams, assumed 26 week construction period with an RC piled substructure.

Typical quantities used in assessment = foundation RC – 302 m^3, substructure RC – 250 m^3, bearings No – 27, steelwork – 325 tonnes (painted), deck RC – 735 m^3, other assumptions: design life 120 years, 19 principal inspections, 41 interim inspections, 13 routine maintenance.

Total CO_2 – 7707 tCO_2eq of which traffic delay contribution is 4811 tCO_2eq (62%)

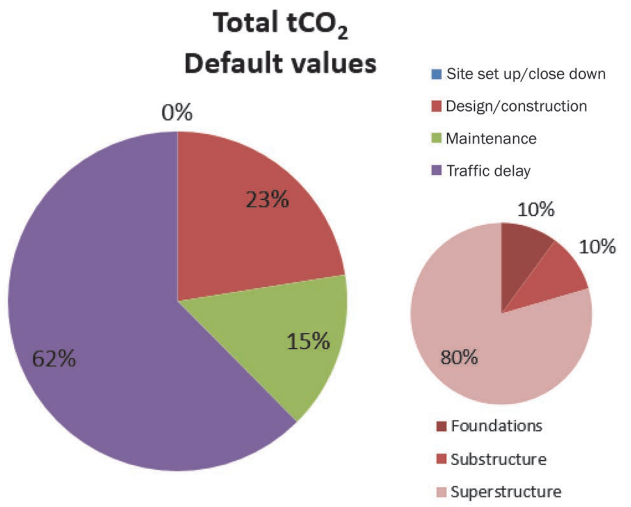


Figure 8.1 Total tCO_2 default values

8.4 END-OF-LIFE

This section considers the issues of reuse, recycling or other safe disposal of FRP materials. It is important, at the design stage, to consider safe disassembly to enable best use of structural materials when the bridge components reach the end of their design working lives. In some cases it may be possible to disassemble the structure and reuse whole FRP components, such as beams or deck panels.

The choice of using an FRP material to manufacture products through all engineering sectors is growing annually according to the Composites Leadership Forum (2016). Inevitably the amount of waste is growing too, though in some sectors advances in composite manufacturing are leading to leaner processes with less manufacturing waste. The 'composite' nature of FRPs and the predominantly cross-linked (thermoset) matrices used give them a good property portfolio for bridge engineering as introduced in **Chapter 4**. This advantage however makes them difficult to recycle. Solutions have emerged and continue to be improved for gaining value from end of life FRPs, contributing to a circular economy. The circular economy is an alternative to a traditional linear economy (make, use, dispose), in which resources remain in use for as long as possible, extract the maximum value from them while in use, then recover and regenerate products and materials at the end of each service life.

Several companies now exist globally to recycle carbon FRP waste. These all use variations of a pyrolysis process that thermally decomposes the resin matrix, leaving clean carbon fibres. Applications are mainly in milled and chopped fibres (very short or short lengths), typically compounded with thermoplastics for strength and electrical conductivity. Increasing quantities of these recycled fibres are being used in reinforcing mats, which can be pressed into parts, eg for automotive panels. It is unlikely that recycling of carbon fibre will produce the continuous fibres required for long spanning structural engineering components, but these short length recycled fibres could be used for a variety of smaller load carrying elements such as expansion joints and bearings replacing fabricated steel sections and extruded metallic components.

There are several potential routes for glass FRP waste, though recycling is more challenging than it is with carbon, because the monetary value is an order of magnitude less than for carbon fibre. Routes that can be exploited are:

- **Cement kiln processing.** Waste can be co-processed with other wastes as solid recovered fuel in cement kilns. This recovers energy from the organic matrix, and mineral fillers and the glass become feedstock for cement clinker.
- **Incineration.** Heat energy (16.7 MJ per tonne) is recovered from the organic matrix fraction of the waste. The incinerator bottom ash may be processed into aggregates or used in construction applications, though in some cases it is still landfilled.

- **Mechanical recycling to fine filler**. Waste can be ground to a fine filler material. This processing is done in some cases in-house with manufacturing waste. It is not generally economical, because the energy input is not viable to grind down to a filler material, which will effectively replace a low-value product, such as calcium carbonate.
- **Mechanical recycling with fibre retention.** Waste can be ground to a lesser degree, leaving bundles of glass fibres having reinforcing properties. This uses less energy and provides a more valuable product than the fine filler. Processing is done in-house to a small degree, but there is potential for higher volume applications for regrind in the UK, for example in infrastructure products with recycled mixed plastics or in reinforced fibre grouts and mortars.

While there are no commercial precedents at present, FRP waste is quite inert and could be shredded and used as a lightweight aggregate. Further comments on end-of-life options can be found in Job *et al* (2016).

Legislation is important because there can be a cost to what happens at the end of life. Landfill tax in the UK now stands at £88.95/tonne (2018/2019 rate), making the cost of landfill, including gate fees and transport, typically £130 to £140 per tonne of waste. While sharp increases in landfill tax are not expected, Germany and several other European countries have already largely banned landfill. The European Commission's circular economy package (EC, 2015) seeks to increase recycling rates and reduce the amount of municipal waste that can go to landfill to 10 per cent by 2030. It is not yet clear to stakeholders how this will affect industrially derived and construction waste other than packaging (for which 75 per cent must be recycled by 2030).

Directive 2008/98/EC (Waste Framework Directive) sets the basic concepts and definitions related to waste management. This framework develops a polluter pays principle, which is known as the extended producer responsibility. One of the requirements is the national application of the waste management hierarchy: prevention, reuse, recycling, recovery, disposal (IStructE, 2014). Article 11.2 stipulates that *"by 2020 a minimum of 70 per cent (by weight) of non-hazardous construction and demolition waste… shall be prepared for reuse, recycled or undergo other material recovery"* (including backfilling operations using waste to substitute other materials).

In summary, sectors other than automotive and electrical/electronics do not, as yet, have a regulatory requirement prohibiting the landfill of FRPs, but the increasing cost of landfill, the drive to a more circular economy and the increasing production of FRP products is surely going to encourage an increasing drive to recycle.

The carbon FRP recycling industry is now established, though the rapid market growth is such that in 2016 demand outstripped capacity, and more markets for recyclate are needed. Glass FRP recycling is more challenging economically, but incineration or partial recycling routes, such as the cement kiln process, are acceptable. UK industry would welcome a higher value recycling route, such as mechanical recycling with fibre retention, and some companies have indicated an intention to set up such a facility in the UK.

8.5 EMPIRICAL GUIDANCE FOR ENVIRONMENTAL IMPACT OF BRIDGES

Drawing on the lessons from the case studies in Sections 8.1 and 8.2 and from Collings (2006), the following empirical design guidance can be made:

1. Material embodied energy/carbon of FRP bridges is usually lower, by a significant margin, than with other structural materials. This is because of less material mass and because the lower structural weight typically saves on foundations and substructure costs. This may be less significant for FRP deck replacements, unless the substructure is weakened and a lighter FRP deck removes the need for strengthening other bridge components.
2. Longer spans and more architectural forms tend to increase both cost and environmental burden. This leads to Collings' conclusion that the environmental burden of a bridge is approximately

proportional to the cost. This finding, however, does not follow at the construction material level because while the initial material cost is usually higher for FRP, the material environmental impact can be seen to be lower.

3 Emission impacts of traffic disruption/diversions are a very significant fact, though the level is heavily dependent on the level of traffic on affected roads. This highlights the importance of rapid installation, robust traffic management and limiting construction delays. The ability to install FRP bridges manufactured off site, with short installation times, can have a major effect on design choice in terms of cost, environmental and societal impacts.

4 There is an ongoing environmental burden during maintenance from paintwork, bearings, joints etc. Where use of FRP reduces the ongoing need for repainting, and the lower structural weight reduces wear on bearings, there will be significant service-life savings in both cost and environmental impact. Ease of maintenance of FRP bridge components or structures should be considered during the design stage. Benefits of FRP may be more significant in coastal areas where corrosion resistance because of high chloride levels is essential.

5 The appropriate use of a construction material in bridge engineering is a key issue for achieving a lower environmental burden. Different forms/spans lend themselves to choosing different materials. There will be optimum forms/spans for FRP bridges depending on the composite processing method, which are introduced in **Section 4.4**.

6 Material embodied energy/kg for carbon fibre is much higher than for glass fibre, though specific stiffness/strength is also much higher. So, the use of carbon fibre reinforcement may be justified in bridge engineering, for example where depth is restricted or where the high specific stiffness enables a longer span.

7 Pollution impacts from the manufacture of FRP are known to be lower than for other structural materials used in bridge engineering.

8 Designs should consider disassembly at end of life, and any benefits of using hybrid material systems should be considered in view of the effect on recyclability.

8.6 OVERALL SUSTAINABILITY – ECONOMICS, ENVIRONMENT AND SOCIETY

Ultimately, the client, the designer and the rest of the engineering team will consider a number of different factors in order to decide on the material and form for a bridge project. A graphical method has been proposed by Spencer *et al* (2012) for assessing a sustainability index. For bridges it addresses the following aspects:

- Economy
  - initial cost
  - whole-life costing (IStructE, 2014)
  - user delay during construction
- Environment
  - extent of loss/disruption to habitat
  - noise during construction
  - noise during service
- Society
  - aesthetics
  - user delay during construction
  - consumption of natural resources
  - use of recycled material(s)
  - ease of modification/demolition

- Climate change (IStructE, 2014)
  - carbon footprint for construction
  - carbon footprint for maintenance.

This may be a useful method to compare in one index several bridge design options from economic, environmental and societal perspectives. Both new and existing bridges can be indexed to provide a comparison across an asset manager's bridge stock.

When using such an index, it is important that the climate change impact of the construction phase is calculated to include any traffic disruption, which is not explicit in the assessment methodology. The index methodology from Spencer *et al* (2012) does not appear to account for disposal at end of life, though this may have a minor impact overall, and would be difficult to assess given that waste disposal and recycling practices may have changed significantly by the time a new FRP bridge reaches the end of its design working life.

8.7 CONCLUSION

The case studies discussed here are comparing the sustainability credentials of FRP with other structural materials. Direct comparisons show FRP elements to have positive environmental footprints where the inherent durability of the material plays a major part in reducing the life cycle environmental impact by tackling areas which have the greatest impact (emissions from traffic queuing due to cyclic maintenance). The reduced operational environmental impact is a key characteristic of FRP designers should be aware of.

9 Summary and recommendations

9.1 SUMMARY

FRP as a structural material for bridges (and other pieces of civil infrastructure) is a developing technology that is seeing major leaps forward in its application. FRP has many unique selling points, tackling many of the issues the UK currently face with existing materials (ie sustainability, maintenance requirements and durability). So, the ability to tailor the material properties for individual applications and manufacture a lightweight structure allowing for easier handling is a key differentiator.

FRP materials offer bridge designers the advantages of high stiffness-to-weight and high strength-to-weight ratios when compared to conventional construction materials such as steel and RC and it can also be formed into complete structural units with a freedom of form (shape) not seen in other traditional materials.

The cost of FRP bridges will be very dependent on the production volume because reuse of tooling (moulds) will ultimately affect the outturn cost of structures. The development of bridge modules or the adoption of standard designs will allow savings to be realised through reuse of tooling allowing for the cost of tooling to be recovered over several structures.

In general, the initial cost (at the time of writing) of FRP bridges will be higher than that for traditional construction. It is estimated that the initial cost of footbridges could be circa 10 per cent more than traditional alternatives, with road bridges potentially being 25 per cent more. Savings in the construction costs due to reduced programme for installation and lighter cranage needs will often reduce the initially higher outturn costs when using FRP. When considering life cycle costs, FRP bridges when detailed appropriately should be able to outperform traditional materials as the extent and cost of maintenance will be significantly lower.

The outlook for the use of FRP in the construction sector is very positive and there are numerous technological advancements, such as the development of nanotechnology, that could have a further profound effect on the use of FRP in the future, by enhancing the favourable materials properties of FRPs. Along with the development of greener solutions using natural fibres and bio-based resins, this presents an exciting opportunity for the use of FRP in bridge engineering. The success of FRP bridges will, however, ultimately be dependent on how well the bridges are executed, including the adequacy of detailing such as parapet connections, surfacing details and joining techniques.

9.2 RECOMMENDATIONS

Several recommendations are made throughout this guidance document. These are further summarised below for reference:

1 **Consider whole-life cost models.** To recognise the true savings and benefits of FRP, whole-life cost models have already demonstrated that FRP composites can outperform many traditional materials, and this enables a leaner life cycle management strategy to be developed.

2 **Consider life cycle sustainability issues and targets.** Significant benefits can be seen by reducing maintenance intervals, which can reduce disruption to traffic which then has a major impact on the bridge's 'operational environmental footprint'.

3 **Develop effective water management/drainage strategy.** FRP bridges are relatively inert to salt-laden water. Positive drainage is still recommended to limit water penetration and deterioration via freeze/thaw cycles, so waterproofing the deck will be beneficial with particular attention being given to bonded/bolted joints. Modern waterproofing systems designed to be used on concrete/steel decks should in general bond well to FRP materials.

4 **Impact design.** Where impact through vandalism is a concern, solutions using different fibres are practical, and building in resiliency in the fibre lay-up, cladding using FRP or traditional materials such as timber can also be an effective option.

5 **Design resilience.** Many effects such as impact/UV and fire can be mitigated by building in extra resilience. Damage tolerance can easily be built into a structure, albeit at an additional cost. For example, a 14 m span (weighing 4t) footbridge could use an extra tonne of FRP material in the external skin without compromising the weight for erection.

6 **Use on electrified rail schemes.** With an ever-greater emphasis shifting rail towards electrification, the need for insulation and protection is growing. GRP is an insulator which can mitigate conductivity risks, so there are numerous areas where FRP can be used for bridges or other infrastructure.

7 **Graffiti.** This can be tackled either by the application of anti-graffiti coatings, removal by solvent application or by over-coating/cladding. Understanding the preferred method employed by the bridge owner will affect the FRP materials selection during design. Cladding will have the added benefit of UV and impact protection. Care should be taken with solvent use to ensure that no damage to the FRP or its designed method of coating occurs.

8 **Design considerations.** Manufacturing process can be pultrusion or infusion. Pultrusions will have known mechanical properties and known cross-sections, which make their application easier for the bridge engineer. A key challenge in their application is understanding and detailing the connections/joints in an effective manner. Infusion methods will limit the number of – if not eliminate the need for – connections, allowing more freedom in the geometry. A different challenge in using these processing methods relates to the materials and fibre lay-ups to give the intended material classification, and further controls may also be needed to monitor the manufacturing process. A different approach is needed by the bridge engineer for these two predominant FRP bridge building methods.

9 **Site conditions.** Where bonding at site is required, consider the temperature and environment limitations of the material being used. Assume that poor weather is a likely possibility. The preferred solution will target 100 per cent off-site build, though in some instances site bonding may be unavoidable.

10 **SHM sensors.** Health monitoring can provide an alternative asset management strategy, and this will support the digitalisation transformation within the construction industry. Consider how to capture and use this data and consider design envelopes to act as triggers for data reporting.

11 **Surfacing details.** Recommendations include using (a) additional GRP plates bonded to the surface of the deck – for road bridges, this will alleviate the high induced stresses associated with local tyre loading, allowing for load dispersal, (b) sacrificial plates (coloured), as a protective layer similar to the historic red sand protection of waterproofing, (c) bond promoters and gritted plates to aid bond with surfacing and (d) flexible full depth conventional bituminous surfacing as opposed to thin surfacing, and testing accordingly.

12 **Highway alignment.** Avoid flat spots and promote positive drainage.

13 **Design uncertainties.** Owing to the abundance of FRP material combinations it can be difficult to classify materials and obtain performance data without testing. Where required, a number of composite testing houses can give materials information, but where areas of uncertainty exist (eg creep and fatigue characteristics) concerns can be managed through design by testing.

14 **Innovations.** The FRP composites industry is seeing a large amount of research being undertaken, with new FRP materials and new processes being developed. FRPs are replacing many traditional materials and their evolution as structural materials will continue at a rapid pace.

15 **Materials H&S.** It is important to understand H&S implications because some materials have COSHH implications (although alternative materials can be used). Add this caveat into the design risk assessment.

16 **Pultrusion standard.** Using BS EN 13706 (parts 1 to 3) inclusive is recommended.

17 **Moulded structures.** Engineers should consult with fabricators familiar with laminate design/fabrication early in the design process. Many suppliers will have preferred FRP materials tailored for their individual processes.

18 **Fire.** In general, FRP composites are naturally insulating, so their properties permit the material to perform well during fire instances, but fire protection can be built into the design using specific resins and fillers. Phenolic resins are generally deployed for such structures where the risk is higher.

19 **UV protection.** Paint, gelcoats, surface veils and a combination of these can provide adequate protection.

20 **Manufacturing controls.** Consult with manufacturers and agree manufacturing QC plans and discuss materials classification and typical mechanical properties, which they can obtain and demonstrate by coupon testing.

21 **Durability.** A recommendation for all FRP bridges would be to install non-structural material samples attached to the bridge at agreed locations. This will facilitate future material tests to understand long-term material performance without having to mechanically extract them from the bridge.

References

ACI COMMITTEE 440 (2008) *Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures*, ACI 440.2R-08, American Concrete Institute, Farmington Hills, MI, USA

ACMA (2012) *Code of standard practice for fabrication and installation of pultruded FRP structures, first edition*, American National Standards Institute (ANSI), American Composites Manufacturers Association, Arlington, VA, USA

AISC (2016) *Specification for structural steel buildings*, ANSI/AISC 360-16, American Institute of Steel Construction, Inc., Chicago, IL, USA
https://www.aisc.org/globalassets/aisc/publications/standards/a360-16-spec-and-commentary.pdf

ALLEN, H G (1969) *Analysis and design of structural sandwich panels*, Pergamon Press, London, UK

ANONYMOUS (2003) "Transparent bridge" *Advanced Composites Bulletin*, April, HighBeam Research, Chicago, USA
https://www.highbeam.com/doc/1G1-99171112.html

ASCE (2010) *Pre-standard for load and resistance factor design (LRFD) of pultruded fiber reinforced polymer (FRP) structures*, Arlington, VA, USA

ASCIONE, L, CARON, J-F, GODONOU, P, VAN IJSELMUIJDEN, K, KNIPPERS, K, MOTTRAM, T, OPPE, M, GANTRIIS SORENSEN, M, TABY, J and TROMP, L (2016) *Prospect for new guidance in the design of FRP*, Joint Research Centre Science for Policy Report, Publications Office of the European Union, Brussels, Belgium (ISBN: 978-9-27954-226-8)

ATKINS (2011) *Departures from Standards: procedures for local highway authorities*, UK Roads Liaison Group, London, UK
http://www.ukroadsliaisongroup.org/en/utilities/document-summary.cfm?docid=80C69D67-CABC-4428-815B8143D0833943

BANK, L C (2006) *Composites for construction – structural design with FRP materials*, John Wiley & Sons, New Jersey, USA (ISBN: 978-0-47168-126-7)

BANK, L C, GENTRY, T R, THOMPSON, B J and RUSSELL, J S (2003) "A model specification for FRP composites for civil engineering structures" *Construction and Building Materials*, vol 17, 6–7, Elsevier BV, London, UK, pp 405–437

BARBERO, E J (2011) *Introduction to composite materials design, second edition*, CRC Press, Florida, USA (ISBN: 978-1-42007-915-9)

BARBERO, E J (2013) *Finite element analysis of composite materials using ANSYS®, second edition*, CRC Press, Boca Raton, Florida, USA

BRAESTRUP, W (1999) "Footbridge constructed from glass-fibre-reinforced profiles, Denmark" *Structural Engineering International*, vol 9, 4, Taylor & Francis Online, UK, pp 256–258

BROUGHTON, W R, LODEIRO, M J, MAUDGAL, S and SIMS, G D (1998) *Review of test methods and standards for assessing long-term performance of polymer matrix composites*, Centre for Materials Measurement and Technology, NPL Report CMMT(A) 94, National Physical Laboratory, Teddington, UK

BURGOYNE, C and HEAD, P (1993) "Aberfeldy Bridge – an advanced textile reinforced footbridge". In: *Proc 5th int TechTextil Symposium*, 7–9 June, Frankfurt, Germany, paper 418

BURGOYNE, C (1999) "Advanced composites in civil engineering in Europe" *Structural Engineering International,* vol 9, 4, Taylor and Francis Online, London, UK, pp 267–273

BÜV-EMPFEHLUNG (2014) *Tragende kunststoffbauteile im bauwesen (TKB) – entwurf, bemessung und konstruktion (Structural plastic components in dconstruction (TKB) – design, dimensioning and construction)*, Springer, Wisebaden, Germany (in German) (ISBN: 978-3-83482-284-0)

CADEI, J and STRATFORD, T (2002) "The design, construction and in-service performance of the all-composite Aberfeldy Footbridge". In: A Shenoi, S Moy and L Holloway (eds) *Advanced polymer composites for structural applications in construction*, ICE Publishing, Thomas Telford, London, UK (ISBN: 978-1-85573-736-5) pp 445–453

CADEI, M C, STRATFORD, T J, HOLLAWAY, L C and DUCKETT, W H (2004) *Strengthening metallic structures using externally bonded fibre-reinforced composites*, C595, CIRIA, London, UK (ISBN: 978-0-86017-595-7)
www.ciria.org

CANNING, L (2008) "Mount pleasant FRP bridge deck over M6 motorway". In: *Proc 4th int conf on FRP Composites in Civil Engineering (CICE 2008)*, International Institute for FRP in Construction, EMPA, Duebendorf, Switzerland (ISBN: 978-3-90559-450-8), paper 7.D.4

CANNING, L (2012a) "Performance and 8-year load test on West Mill FRP bridge" *Proceedings of the Institution of Civil Engineers – Bridge Engineering*, vol 168, 1, Institution of Civil Engineers, London, UK, pp 24–29

CANNING, L (2012b) "Railway bridge FRP composite decking" *Proceedings of the Institution of Civil Engineers – Engineering and Computational Mechanics*, vol 162, 3, Institution of Civil Engineers, London, UK, pp 103–106

CANNING, L (2012c) "Developments in FRP railway bridge applications" *Advances in Structural Engineering*, vol 13, 5, SAGE journals, London, UK, pp 823–835
http://www.iifc-hq.org/proceedings/CICE_2012/08_All-FRP%20and%20Smart%20FRP%20Structures/08_749_Canning_DEVELOPMENTS%20IN%20FRP%20RAILWAY%20BRIDGE%20APPLICATIONS.pdf

CANNING, L and SPEIGHT, N (2009) "FRP railway decking – Calder Viaduct" *Proceedings of the Institution of Civil Engineers: Engineering and Computational Mechanics*, vol 162, 3, Institution of Civil Engineers, London, UK, pp 103–106

CEN/TC 250 *Structural Eurocodes,* European Committee for Standardization, Brussels
https://standards.cen.eu/dyn/www/f?p=204:7:0::::FSP_ORG_ID:6231&cs=1475B1C21B51CE51CCD000F68519ABE9C

CHEUNG, Y K (1976) *Finite strip method in structural analysis*, Pergamon Press, Oxford, UK (ISBN: 978-0-08018-308-4)

CHRISTENSEN, R M (2018) *World wide failure exercise*, Aeronautics and Astronautics Department, Stanford University, CA, USA
www.failurecriteria.com

CLAPHAM, P, ASIEDU, K and CANNING, L (2013) "The reconstruction of Moss Canal Bridge, Rochdale" *Proceedings of the Institution of Civil Engineers – Bridge Engineering*, vol 168, 1, Institution of Civil Engineers, London, UK, pp 64–75

CLARKE, J L (ed) (1996) *Structural design of polymer composites: EUROCOMP design code and background document*, E & F N Spon, London, UK (ISBN: 978-0-41919-450-7)

CNR (2008) *Guide for the design and construction of structures made of FRP pultruded elements, CNR-DT 2005/2007*, Advisory Committee on Technical Recommendations for Construction, National Research Council of Italy, Rome, Italy

COLLINGS, D (2006) "An environmental comparison of bridge forms" *Proceedings of the Institution of Civil Engineers – Bridge Engineering*, vol 159, 4, Institution of Civil Engineers, London, UK, pp 163–168

COMPOSITE LEADERSHIP FORUM (2016) *The 2016 UK Composites Strategy 2016. Lightening the load – delivering UK growth through the multi-sector application of composites*, Composites UK, Hemel Hempstead, UK
https://compositesuk.co.uk/system/files/documents/Strategy%20final%20version_1.pdf

COOGLER, K, HARRIES, K A, WAN, B, RIZOS, D C and PETROU, M F (2005) "Critical evaluation of strain measurements in glass fiber-reinforced polymer bridge decks" *Journal of Bridge Engineering*, vol 10, 6, American Society of Civil Engineers, Reston, VA, USA, pp 704–712

COOPER, C and TURVEY, G J (1998) "Semi-rigid column-base connections in pultruded GRP frame structures" *Computers and Structures*, vol 76, 1–3, Elsevier BV, London, UK, pp 77–88

CORDIS (2013) *Flexible processes and improved technologies for urban infrastructure construction sites (PANTURA)*, Community Research and Development Information Service, European Commission, Brussels
https://cordis.europa.eu/project/rcn/97331_en.html

CREATIVE PULTRUSIONS INC. (2017) *The new and improved Pultex® pultrusion design manual of standard and custom fiber reinforced polymer structural profiles, imperial version, volume 5, revision 6*, Alum Bank, PA, USA
http://www.creativepultrusions.com/index.cfm/data/product-literature/pultexc2ae-pultrusion-design-manual1/

CUR (2017) *Vezelversterkte kunstoffen in bouwkundige en civieltechnische draagconstructies, (Fiber reinforced plastics in structural and civil engineering structures),* CUR-Aanbeveling 96:2017 (tweede, herziene uitgave) (CRW AA96:2017), Civieltechnisch Centrum Uitvoering Research en Regelgeving, Rotterdam, The Netherlands (in Dutch)
https://www.crow.nl/publicaties/cur-aanbeveling-96-2017-(tweede,-herziene-u

DALY, A F and CUNNINGHAME, J R (2006) "Performance of a fibre-reinforced polymer bridge deck under dynamic wheel loading" *Composites Part A: Applied Science and Manufacturing*, vol 37, 8, Elsevier, BV, London, UK, pp 1180–1188

DANIEL, R A (2003) "Environmental considerations to structural material selection for a bridge". In: *Proc of the European bridge engineering conference*, March, Lightweight Bridge Decks, Rotterdam, The Netherlands
https://www.strongwell.com/wp-content/uploads/2013/05/LCA-Pultruded-Bridge.pdf

DAVIES, J M (ed) (2001) *Lightweight sandwich construction*, Blackwell Science Ltd, Oxford, UK (ISBN: 978-0-63204-027-8)

DAWE, D J (1984) *Matrix and finite element displacement analysis of structures*, Clarendon Press, Oxford, UK (ISBN: 978-0-19856-211-5)

DAWSON, D, and FARMER, N (2009) "Replacement FRP bridge deck for vehicle loading" *Proceedings of the Institution of Civil Engineers – Engineering and Computational Mechanics*, vol 162, 3, Institution of Civil Engineers, London, UK, pp 141–144

DNV GL (2013) *Composite components*, DNV-OS-C501, Det Norske Veritas, Norway
http://rules.dnvgl.com/docs/pdf/DNV/codes/docs/2013-11/OS-C501.pdf

DNV GL (2016) *Approval finder,* Det Norske Veritas, Norway
https://approvalfinder.dnvgl.com

DROGT, B, VAN BAARZEL, K, BOSCH, H, DE JONG, S, PEETERS, J, DE GRAAF, D, VAN ROSSUM, L, REIJME, M and DE WAAL, J (2009) *Compositietbrug Eindrapport, 2e versie, (vertrouwelllijk)*, BECO Groep, Vestiging, Rotterdam, The Netherlands (in Dutch)
https://www.fibercore-europe.com/wp-content/uploads/2018/03/onderzoek-RVO-Beco-2009.pdf

EC (2015) *Closing the loop: Commission adopts ambitious new circular economy package to boost competitiveness, create jobs and generate sustainable growth*, press release, European Commission, Brussels, Belgium
http://europa.eu/rapid/press-release_IP-15-6203_en.htm

FARMER, N, SMITH, I, LUKE, S, CANNING, L, BELL, B and COX, B (2006) "A strategic partnership approach to FRP strengthening of UK railway bridges". A Kumar, C J Brown, L C Wrobel (eds) *Proceedings of the first international conference on advances in bridge engineering; bridges – past, present and future*, volume 1, Brunel University Press, UK (ISBN: 978-1-90231-649-9) pp 259–269

FARMER, N and SMITH, I (2011) "Advanced Composite Truss System (ACTS) – development of a carbon fibre joining node". In: C Whysall and S Halliwell (eds) *Proceedings of 5th International Conference on Advanced Composites In Construction (ACIC 2011)*, NetComposites, Chesterfield, UK, pp 446–457

FIBERLINE COMPOSITES (2016) *FBD600 Asset bridge deck*, Fiberline Composites, Middelfart, Denmark

FIBERLINE COMPOSITES A/S (2017) *Fiberline design manual for structural profiles in composite materials*, Kolding, Denmark
https://fiberline.com/sites/default/files/media/online-tools/190107_dm_uk.pdf

FIRTH, I and COOPER, D (2002) "New materials for new bridges – Halgavor Bridge, UK" *Structural Engineering International*, vol 12, 2, International Association for Bridge and Structural Engineering, Zurich, Switzerland, pp 80–83

GIRÃO COELHO, A M and MOTTRAM, J T (2015) "A review of the behaviour and analysis of mechanically fastened joints in pultruded fibre-reinforced polymers" *Materials and Design*, vol 74, Elsevier BV, London, UK, pp 86–107

GIRÃO COELHO, A M (2015) "Finite element guidelines for simulation of delamination dominated failures in composite materials validated by case studies" *Archives of Computational Methods in Engineering*, vol 23, 2, Springer, The Netherlands, pp 363–388

GIRÃO COELHO, A M, MOTTRAM, J T and HARRIES, K A (2015) "Bolted connections of pultruded GFRP: implications of geometric characteristics on net section failure" *Composite Structures*, vol 131, November, Elsevier BV, London, UK, pp 878–884

GOLAND, M. AND REISSNER, E. (1944) "The stresses in cemented joints", *Journal of Applied Mechanics*, vol 11, 1, American Society of Mechanical Engineers, New York, USA, pp A17–A27

GRAMMATIKOS, S A, ZAFARI, B EVERNDEN, M C, MOTTRAM J T and MITCHELS, J M (2015) "Moisture uptake characteristics of a pultruded flat sheet fibre-reinforced polymer material subjected to hot/wet aging" *Polymer Degradation and Stability*, vol 121, November, Elsevier BV, London, UK, pp 407–419

GULVANESSIAN, H, GALGARO, J-A and HOLICKÝ, M (2012) *Designers' guide to Eurocode: basis of structural design, second edition*, Thomas Telford, London, UK (ISBN: 978-0-72774-171-4)

GURIT (2011) *Guide to composites*, Gurit Composites Component Ltd, Isle of Wight, UK
www.gurit.com/-/media/Gurit/Datasheets/guide-to-composites.pdf

HANCOX, N L and MAYER, R M (1994) *Design data for reinforced plastics. A guide for engineers and designers*, Springer, London, UK (ISBN: 978-9-40110-707-5)

HARTLEY, J R (ed) (2010) *Composite profiles*, version 4, Exel Composites, Runcorn, UK

HIGHWAYS AGENCY (2005) “Design of FRP bridges and highway structures” *Design Manual for Roads and Bridges, Volume 1 Highway structures: approval procedures and general design, Section 3 General design, Part 17, BD 90/05*, The Stationery Office, London, UK
http://www.standardsforhighways.co.uk/ha/standards/dmrb/vol1/section3/bd9005.pdf

HIGHWAYS AGENCY (2007a) *Inspection Manual for Highway Structures, Volume 1: Reference Manual*, The Stationery Office, London, UK (ISBN: 978-0-11552-797-5)
https://www.tsoshop.co.uk/bookstore.asp?FO=1159997&DI=587829

HIGHWAYS AGENCY (2007b) *Inspection Manual for Highway Structures, Volume 2: Inspectors Handbook*, The Stationery Office, London, UK (ISBN: 978-0-11552-798-2)
https://www.tsoshop.co.uk/bookstore.asp?Action=Book&ProductId=0115527982

HIGHWAYS AGENCY (2011) “Structural review and assessment of highway” *Design Manual for Roads and Bridges, Volume 3 Highway structures: inspection and maintenance, Section 4 Assessment, Part 22, BD 101/11*, The Stationery Office, London, UK
http://www.standardsforhighways.co.uk/ha/standards/dmrb/vol3/section4/bd10111.pdf

HIGHWAYS AGENCY (2012) “Technical approval of highway structures” *Design Manual for Roads and Bridges, Volume 1 Highway structures: approval procedures and general design. Section 1 Approval procedures, Part 1, BD 2/12*, The Stationery Office, London, UK
http://www.standardsforhighways.co.uk/ha/standards/dmrb/vol1/section1/bd212.pdf

HIGHWAYS AGENCY (2017) “Inspection of highway structures” *Design Manual for Roads and Bridges, Volume 3 Highways structures: inspection and maintenance, Section 1 Inspection. Part 4 Summary, BD 63/17*, The Stationery Office, London, UK
http://www.standardsforhighways.co.uk/ha/standards/dmrb/vol3/section1/bd6317.pdf

HILLMAN, J (2012) “Hybrid-composite beam technology – a cost-effective, safe and sustainable bridge construction method” *Structure Magazine*, March, NCSEA, ASCE and CASE, USA, pp 30–32

HM GOVERNMENT (2013) *Construction 2025. Industrial strategy: government and industry partnership*, HM Government, London, UK
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/210099/bis-13-955-construction-2025-industrial-strategy.pdf

HOBBS, M (2014) “Design and fabrication of two 30 m long moulded FRP decks for the Pont y Ddraig lifting footbridge”. In: *Proc FRP bridges 2014 conference*, 11–12 September 2014, London, UK

HOFF, N J (1949) “The strength of laminates and sandwich structural elements”. In: A G H Dietz (ed) *Engineering laminates*, Chapter 1, John Wiley and Sons Inc., New York, USA

HOLLAWAY, L C and HEAD, P R (2001) *Advanced polymer composites and polymers in the civil infrastructure, first edition*, Elsevier Science, Oxford, UK (ISBN: 978-0-08043-661-6)

HOLLAWAY, L C (2007) “Fibre-reinforced polymer composite structures and structural components: current applications and durability issues”. In: V M Karbhari (ed) *Durability of composites for civil structural applications*, Chapter 10, Woodhead Publishing, Oxford, UK

HULL, D (1996) *An introduction to composite materials, second edition*, Cambridge University Press, Cambridge, UK (ISBN: 978-1-13917-013-0)

HURTADO, M, BANSAL, A, PAULOTTO, C and PRIMI, S (2012) “FRP girder bridges: lessons learned in Spain in the last decade”. In: *Proc 6th int conf on FRP Composites in Civil Engineering (CICE 2012)*, International Institute for FRP in Construction, Rome, Italy, 13–15 June, Section 8: All-FRP and smart FRP structures, keynote paper 1–4, pp 1–8

HUTCHINSON, A R (1997) *Joining of fibre-reinforced polymer composite materials*, PR046, CIRIA, London, UK (ISBN: 978-0-86017-846-0)
www.ciria.org

IPA (2016) *National infrastructure delivery plan 2016–2021*, Infrastructure and Projects Authority reporting to HM Treasury and Cabinet Office, London, UK (ISBN: 978-1-91083-577-7)
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/520086/2904569_nidp_deliveryplan.pdf

ISTRUCTE (2011) *A short guide to embodied carbon in building structures*, Institution of Structural Engineers, London, UK (ISBN: 978-1-90633-519-9)

ISTRUCTE (2014) *Building for a sustainable future: an engineer's guide*, Institution of Structural Engineers, London, UK (ISBN: 978-1-906335-21-2)

JOB, S, LEEKE, G, MATIVENGA, P, OLIVEUX, G, PICKERING, S and SHUAIB, N (2016) *Composite recycling: where are we now?* Composites UK Ltd, Hemel Hempstead, UK
https://compositesuk.co.uk/system/files/documents/Recycling%20Report%202016.pdf

JONES, C and HAMMOND, G (2006) *Embodied energy and carbon footprint database,* Department of Mechanical Engineering, University of Bath, UK
http://www.circularecology.com/embodied-energy-and-carbon-footprint-database.html#.W2MUaMInbGg

JONES, C and HAMMOND, G (2011) *Inventory of Carbon and Energy (ICE) database, version 2.0*, University of Bath, UK
https://ghgprotocol.org/Third-Party-Databases/Bath-ICE

JUDD, N C W and WRIGHT, W W (1978) "Voids and their effects on the mechanical properties of composites – an appraisal" *SAMPE Journal*, January/February, vol 14, 1, Society for the Advancement of Material and Process Engineering, California, USA, pp 10–14

KADDOUR, A S and HINTON, M J (2013) "Maturity of 3D failure criteria for fibre-reinforced composites: Comparison between theories and experiments: Part B of WWFE-II" *Journal of Composite Materials*, vol 47, 20–21, SAGE Journals, London, UK, pp 2417–2426

KAPADIA, A (2007) *Non-destructive testing of composite materials. Best practice guide*, National Composite Network, TWI Ltd, Cambridge, UK
https://avaloncsl.files.wordpress.com/2013/01/ncn-best-practice-ndt.pdf

KARA, S and MANMEK, S (2009) *Composites: calculating their embodied energy, final report*, Life Cycle Engineering and Management Research Group, University of New South Wales, Australia
https://www.wagner.com.au/media/44033/sustainability.pdf

KARBHARI, V M (ed) (2007) *Durability of composites for civil structural applications*, Woodhead Publishing Limited, Cambridge, UK (ISBN: 978-1-84569-035-9)

KELLER, T (2003) "Use of fibre-reinforced polymers in bridge construction" *Structural Engineering International*, vol 12, 2, International Association for Bridges and Structural Engineering, Zurich, Switzerland, pp 66–70

KELLER, T and GÜRTLER, H (2005) "Composite action and adhesive bond between fiber-reinforced polymer bridge decks and main girders" *Journal of Composites for Construction*, vol 9, 4, American Society of Civil Engineers, Reston, VA, USA, pp 360–368

KELLER, T and GÜRTLER, H (2006) "Design of hybrid bridge girders with adhesively bonded and compositely acting FRP deck" *Composite Structures*, vol 74, 2, Elsevier BV, London, UK, pp 202–212

KENDALL, D, SMITH, I, YOUNG, C, GOUGH, W and CROSS, A (2012) "Dawlish FRP footbridge – the first FRP bridge at a UK railway station". In: *Proc FRP bridges conference 2012*, September, London, UK

KLEMPNER, D and FRISCH, K C (1997) *Handbook of polymeric foams and foam technology*, Hanser Gardner Publications, OH, USA (ISBN: 978-0-19520-929-7)

KNIPPERS, J and GABLER, M (2008) "The FRP road bridge in Friedberg Germany – new approaches to a holistic and aesthetic design". In: *Proc 4th int conf on FRP Composites in Civil Engineering (CICE 2008)*, International Institute for FRP in Construction, 22–24 July, Zurich, Switzerland, paper 7.D.6, pp 1–6

LEE, S M (1989) *Dictionary of composite materials technology*, Technomic Publishing Company Inc, PA, USA (ISBN: 978-0-87762-600-8)

LEES, W A (1984) *Adhesives in engineering design*, Springer-Verlag, Berlin Heidelberg, Germany and The Design Council, London, UK (ISBN: 978-3-662-11032-4)

LUKE, S, CANNING, L, COLLINS, S, BROWN, P, KNUDSEN, E and OLOFSSON, I (2002) "The development of an advanced composite bridge decking system – project ASSET" *Structural Engineering International,* vol 12, 2, International Association for Bridge and Structural Engineering, London, UK, pp 76–79

MACKEY, E D, SEACORD, T F and LAMB, S (2015) *Guidelines for the use of stainless steel in the water and desalination industries*, Web report 4431, Water Research Foundation, Denver, CO, USA

MACLEOD, I A (2005) *Modern structural analysis: modelling process and guidance*, Thomas Telford, London, UK (ISBN: 978-0-72773-279-8)

MARA, V and HAGHANI, R (2012) "Upgrading bridges with fibre-reinforced polymer decks – a sustainable solution". In: *Proc of conf on Civil Engineering Infrastructure Based On Polymer Composites (CECOM)*, 22–23 November 2012, Krakow, Poland, Paper 06-02, pp 1–8

MARA, V, HAGHANI, R and HARRYSON, P (2014) "Bridge decks of fibre-reinforced polymer (FRP): a sustainable solution" *Construction and Building Materials*, vol 50, January Elsevier BV, London, UK, pp 190–199

MARA, V, HAGHANI, R and AL-EMRANI, M (2015) "Improving the performance of bolted joints in composite structures using metal inserts" *Journal of Composites Materials*, November, American Society for Composites, OH, USA

MAYER, R M (1993) *Design with reinforced plastics: a guide for engineers and designers*, The Design Council, London, UK (ISBN: 978-0-85072-294-9)

MAYS, G C and HUTCHINSON, A R (1992) *Adhesives in civil engineering*, Cambridge University Press, Cambridge, UK (ISBN: 978-0-51152-959-7)

MCCORMICK, F C (ed) (1984) *Structural plastics design manual*, Manuals and Reports on Engineering Practice No. 63, prepared by the Task Committee on Properties of Selected Plastics Systems of the Structural Plastics Research Council of the Technical Council on Research of ASCE, American Society of Civil Engineers, New York, USA

MINGHINI, F, TULLINI, N and LAUDIERO, F (2008) "Buckling analysis of FRP pultruded frames using locking-free finite elements" *Thin-Walled Structures*, vol 46, 3, Elsevier BV, London, UK, pp 223–241

MINGHINI, F, TULLINI, N and LAUDIERO, F (2010) "Vibration analysis of pultruded FRP frames with semi-rigid connections" *Engineering Structures*, vol 32, 10, Elsevier BV, London, UK, pp 3344–3354

MOSALLAM, A S (2011) *Design guide for FRP composite connections*, manuals of practice 102, American Society of Civil Engineers, Reston, VA, USA (ISBN: 978-0-78440-612-0)

MOTTRAM, J T and TURVEY, G J (2003) "Physical test data for the appraisal of design procedures for bolted joints in pultruded FRP structural shapes and systems" *Progress in Structural Engineering and Materials*, vol 5, 4, Wiley Online, London, UK, pp 195–222

MOTTRAM, J T (2013) "Rationale for simplifying the strength formulae for the design of multi-row bolted connections failing in net tension". In: *Proc sixth int conf on Advanced Composites in Construction (ACIC 2013)*, 10–12 September 2013, Queen's University of Belfast, Northern Ireland, NetComposites Ltd, Chesterfield, UK, pp 1–8
https://warwick.ac.uk/fac/sci/eng/staff/jtm/presentations/jtm_acic_2013_net_tension_strength_17_09_13.pdf

MOTTRAM, J T and ZAFARI, B (2011) "Pin-bearing strengths for design of bolted connections in pultruded structures" *Institution of Civil Engineers Proceedings – Structures and Buildings*, vol 164, 5, Thomas Telford, London, UK, pp 291–305

NCE (2011) "Scotland will have UK's first recycled plastic bridge" *New Civil Engineer*, London, UK
https://www.newcivilengineer.com/latest/scotland-will-have-uks-first-recycled-plastic-bridge/8617452.article

NGUYEN, T T, CHAN, T M and MOTTRAM, J T (2013) "Influence of boundary conditions and geometric imperfections on establishing lateral-torsional buckling resistance of a pultruded FRP I-beam by finite element analysis" *Composite Structures*, vol 100, Elsevier BV, London, UK, pp 233–242

NGUYEN, T T, CHAN, T M and MOTTRAM, J T (2015) "Lateral-torsional buckling design for pultruded FRP beams" *Composite Structures*, vol 133, 1, Elsevier BV, London, UK, pp 782–793

O'CONNOR, J S, AREF, A and TRIANDAFILOU, L (2011) "Strategic development and deployment of a composite bridge deck". In: *Proc fifth int conf on Advanced Composites in Construction (ACIC 2011)*, 6–8 September 2011, University of Warwick, UK, pp 10–20

OKEIL, A M (2013) *Characterization of mechanical properties of composite materials for infrastructure projects*, Department of Civil and Environmental Engineering, Louisiana State University, LA, USA
http://www.evaccenter.lsu.edu/pub/12-17.pdf

OSEI-ANTWI, M, DE CASTRO, J, VASSILOPOULOS, A and KELLER, T (2013) "FRP-Balsa composite sandwich bridge deck with complex core assembly" *Journal of Composites for Construction*, vol 17, 6, American Society of Civil Engineers, Reston, VA, USA

OWENS, G W and CHEAL, B D (1989) *Structural steelwork connections*, Butterworth-Heinemann, London, UK (ISBN: 978-0-40801-214-0)

PUCK, A and SCHÜRMANN, H (2002) "Failure analysis of FRP laminates by means of physically based phenomenological models" *Composites Science and Technology*, vol 62, 12–13, Elsevier BV, London, UK, pp 1633–1662

QUINN, J A (1999) *Composites: design manual*, Technomic Publishing Company Inc, PA, USA (ISBN: 978-1-56676-795-8)

QURESHI, J and MOTTRAM J T (2012) "Resin injected bolted connections: a step towards achieving slip-resistant joints in FRP bridge engineering". In: *Proc FRP bridge conference*, London, UK, 13–14 September 2012, NetComposites, Chesterfield, UK, pp 56–66

SAE INTERNATIONAL (2012) *Composite materials handbook*, Volume 1 – Revision G R-422, CMH-17, SAE International, PA, USA (ISBN: 978-0-76807-811-4)

SANTOS, F and MOHAN, M (2011) "Train buffeting measurements on a fibre-reinforced-plastic composite footbridge" *Structural Engineering International,* vol 21, 3, Taylor and Francis Online, London, UK, pp 285–289

SEBASTIAN, W M (2018) "Fibre waviness in pultruded bridge deck profiles: geometric characterisation and consequences on ultimate behaviour" *Composites Part B: Engineering*, vol 146, August, Elsevier BV, London, UK, pp 270–280

SEBASTIAN, W M, ROSS, J, KELLER, T and LUKE, S (2012) "Load response due to local and global indeterminacies of FRP deck bridges" *Composites Part B: Engineering*, vol 43, 4, Elsevier BV, London, UK, pp 1727–1738

SEBASTIAN, W M, GEGESHIDZE, G and LUKE, S (2013a) "Positive and negative moment behaviours of hybrid members comprising cellular GFRP bridge decking epoxy-bonded to reinforced concrete beams" *Composites Part B: Engineering*, vol 45, 1, Elsevier BV, London, UK, pp 486–496

SEBASTIAN, W M, KELLER, T and ROSS, J (2013b) "Influences of polymer concrete surfacing and localised load distribution on behaviour up to failure of an orthotropic FRP bridge deck" *Composites Part B: Engineering*, vol 45, 1, Elsevier BV, London, UK, pp 1234–1250

SEBASTIAN, W M, WEBSTER, T, KENNEDY, C and ROSS, J (2013c) "Profiled metal plate – cork mat loading systems on cellular FRP bridge decks to reproduce tyre-to-deck contact pressure distributions" *Construction and Building Materials*, vol 49, December, Elsevier BV, London, UK, pp 1064–1082

SEBASTIAN, W M, RALPH, M, POULTON, M and GOACHER, J (2017) "Lab and field studies into effectiveness of flat steel plate – rubber pad systems as tyre substitutes for local loading of cellular GFRP bridge decking" Composites Part B: Engineering, vol 125, September, Elsevier BV, London, UK, pp 100–122

SHAVE, J, DENTON, S and FROSTICK, I (2010) "Design of the St. Austell fibre-reinforced polymer footbridge, UK" *Structural Engineering International*, Taylor & Francis Online, London, UK, vol 20, 4, pp 427–429

SILVESTRE, N and CAMOTIM, D (2002) "First-order generalised beam theory for arbitrary orthotropic materials" *Thin-Walled Structures*, vol 40, 9, Elsevier BV, London, UK, pp 755–789

SMITH, D, SPENCER, P, DOLLING, C and HENDY, C (2013) "Carbon calculator design tool for bridges" *Proceedings of the Institution of Civil Engineers – Bridge Engineering*, vol 168, 3, Institution of Civil Engineers, London, UK, pp 232–244

SONG, Y S, YOUNG, J R and GUTOWSKI, T G (2009) "Life cycle energy analysis of fiber-reinforced composites" *Composites Part A: Applied Science and Manufacturing*, vol 40, 8, Elsevier BV, London, UK, pp 1257–1265

SPENCER, P C, HENDY, C and PETTY, R (2012) "Quantification of sustainability principles in bridge projects" *Proceedings of the Institution of Civil Engineers – Bridge Engineering*, vol 165, 2, Institution of Civil Engineers, London, UK, pp 81–89

STRATFORD, T (2012) "The condition of the Aberfeldy footbridge after 20 years of service". In: *Proc 14th int conf on Structural Faults and Repair 2012*, 3–5 July 2012, Edinburgh, UK, pp 1–11

STRONGWELL (2016) *Fabrication and repair manual for EXTREN® fiberglass structural shapes*, Strongwell, Bristol, Virginia, USA
https://www.strongwell.com/wp-content/uploads/2013/04/EXTREN-Fabrication-and-Repair-Manual.pdf

STRONGWELL (2017) *Strongwell design manual*, Strongwell, Bristol, Virginia, UK
www.strongwell.com

THE ALUMINIUM ASSOCIATION (2010) "Specification for aluminium structures, aluminium design manual" *Aluminium Design Manual*, part 1, The Aluminium Association, Arlington, VA, USA

THE CONCRETE SOCIETY (2003) *Strengthening concrete structures using fibre composite materials: acceptance, inspection and monitoring*, Technical Report No. 57 (TR57), The Concrete Society, Camberley, UK

THE CONCRETE SOCIETY (2012) *Design guidance for strengthening concrete structures using fibre composite materials, third edition*, Technical Report No. 55 (TR55), The Concrete Society, Camberley, UK

THOMPSON, F and HEYWOOD, G G (1986) *Structural analysis using virtual work*, Chapman and Hall, London, UK (ISBN: 978-0-41222-290-0)

THOPPUL, S D, FINEGAN, J and GIBSON, R F (2009) "Mechanics of mechanically fastened joints in polymer-matrix composites – a review" *Composites Science and Technology*, vol 69, 11, Elsevier BV, London, UK, pp 301–329

TRIANDAFILOU, L N and O'CONNOR, J S (2010) "Field issues associated with the use of fiber-reinforced polymer composite bridge decks and superstructures in harsh environments" *Structural Engineering International*, vol 20, 4, Taylor & Francis Online, London, UK, pp 409–413

TSAI, S W and WU, E M (1971) "A general theory of strength for anisotropic materials" *Journal of Composite Materials*, vol 5, 1, SAGE Journals, London, UK, pp 58–80

TSAI, S W (2008) *Theory of composites design*, Think Composites, University of Standford, USA, (ISBN: 978-0-96180-903-4)

TURVEY, G J (2000) "Flexure of pultruded GRP beams with semi-rigid end connections" *Composite Structures*, vol 47, 1–4, Elsevier BV, London, UK, pp 571–580

TURVEY, G J (2007) "Analysis of bending tests on CFRP-stiffened pultruded GRP beams" *Proceedings of the Institution of Civil Engineers – Structures and Buildings*, vol 160, SB1, Institution of Civil Engineers, London, UK, pp37–49

TURVEY, G J and WANG, P (2002) "A critique of the EUROCOMP simplified design method for bolted joints in long fibre-reinforced polymer composite materials". In: R A Shenoi, S S J Moy and L C Hollaway (eds) *Proc Advanced polymer composites for structural applications in construction: Proceedings of the first international conference, held at Southampton University, UK, on 15–17 April 2002*, ICE Publishing, Thomas Telford, London, UK, Paper 5.3 (ISBN: 978-0-72773-122-7), pp 302–308

TURVEY, G J and ZHANG, Y (2005a) "Tearing failure of web-flange junctions in pultruded GRP profiles", *Composites Part A: Applied Science and Manufacturing*, vol 36, 2, Elsevier BV, London, UK, pp 309–317

TURVEY, G J and ZHANG, Y (2005b) 'Stiffness and strength of web-flange junctions of pultruded GRP sections" *Proceedings of the Institution of Civil Engineers – Structures and Buildings*, vol 158, SB6,Thomas Telford, London, UK, pp 381–391

TURVEY, G J and ZHANG, Y (2006a) "Shear failure strength of web-flange junctions in pultruded GRP profiles" *Construction and Building Materials*, vol 20, 1–2, Elsevier BV, London, UK, pp 81–89

TURVEY, G J and ZHANG, Y (2006b) "Characterisation of the rotational stiffness and strength of web-flange junctions of pultruded GRP WF-sections via web bending tests" *Composites Part A: Applied Science and Manufacturing*, vol 37, 2, Elsevier BV, London, UK, pp 152–164

US DEPARTMENT OF DEFENSE (1999) *Composite materials handbook-MIL 17, volume III: materials usage, design and analysis, first edition*, Technomic Publishing Company, Inc. Pennsylvania, USA (ISBN: 978-1-56676-828-3)

VOTSIS, R A, STRATFORD, T J, CHRYSSANTHOPOULOS, M K and TANTELE W A (2017) "Dynamic assessment of a FRP suspension footbridge through field testing and finite element modelling" *Steel and Composite Structures*, vol 23, 2, Techno Press, Korea, pp 205–215

WINKLER, J and HENDY, C (2016) "Improved structural monitoring of bridges using digital image correlation" *Structual Engineering International*, vol 27, 3, Ingenta Connect, Oxford, UK, pp 435–440

YE, X W, SU, Y H and HAN, J P (2014) "Structural health monitoring of civil infrastructure using optical fiber sensing technology: a comprehensive review" *The Scientific World Journal*, vol 2014, Hindawi, China, pp 1–11

ZIEMIAN, R D (ed) (2010) *Guide to stability design criteria for metal structures, sixth edition*, John Wiley & Sons, New York, USA

ZAFARI, B, QURESHI, J, MOTTRAM, J T and RUSEV, R (2016) "Static and fatigue performance of resin injected bolts for a slip and fatigue resistant connection in FRP bridge engineering" *Structures*, vol 7, August, Elsevier BV, London, UK, pp 71–84

ZHANG, C, AMADUDDIN, M and CANNING, L (2011) "Carbon dioxide evaluation in a typical bridge deck replacement project" *Proceedings of the Institution of Civil Engineers – Energy*, vol 164, 4, Institution of Civil Engineers, London, UK, pp 183–194

ZHOU, E, WANG, Y and MEGGERS, D. (2007) *Response of no-name creek FRP bridge to static loads, moving traffic loads, and impact traffic loads*, Report No. FHWA-KS-06-1, Kansa Department of Transportation, Michigan, USA

ŽIVANOVIĆ, S, FELTRIN, G, MOTTRAM, J T and BROWNJOHN, J M W (2014) "Vibration performance of bridges made of fibre-reinforced polymer". In: K B Zimmerman (ed) *Dynamics of civil structures, volume 4. Proceedings of the 32nd IMAC, A conference and exposition on structural dynamics, Orlando, Florida, 3–6 February 2014, Conference proceedings of the Society for Experimental Mechanics series*, Springer, London, UK

ZUREICK, A-H, BENNETT, R M and ELLINGWOOD, B R (2006) "Fiber-reinforced polymer composite material properties for structural design" *Journal of Structural Engineers*, vol 132, 8, American Society of Civil Engineers, Reston, VA, USA, pp 1320–1327

Standards

British

BS 476-6:1989+A1:2009 *Fire tests on building materials and structures. Method of test for fire propagation for products*

BS 476-7:1997 *Fire tests on building materials and structures. Method of test to determine the classification of the surface spread of flame of products*

BS 8905:2011 *Framework for the assessment of the sustainable use of materials. Guidance*

European

BS EN 1090-2:2018 *Execution of steel structures and aluminium structures. Technical requirements for steel structures*

BS EN 1990:2002+A1:2005 *Eurocode. Basis of structural design*

NA to BS EN 1990:2002+A1:2005 *UK National Annex for Eurocode 0: Basics of structural design*

BS EN 1991-1-5:2003 *Eurocode 1. Actions on structures. General actions. Thermal actions*

NA to BS EN 1991-1-5:2003 *UK National Annex to Eurocode 1. Actions on structures. General actions. Thermal actions*

BS EN 1991-1-7:2006+A1:2014 *Eurocode 1. Actions on structures. General actions. Accidental actions*

BS EN 1991-2:2003 *Eurocode 1. Actions on structures. Traffic loads on bridges*

NA to BS EN 1991-2:2003 *UK National Annex to Eurocode 1. Actions on structures. Traffic loads on bridges*

BS EN 1993-1-1:2005+A1:2014 *Eurocode 3. Design of steel structures. General rules and rules for buildings*

NA+A1:2014 to BS EN 1993-1-1:2005+A1:2014 *UK National Annex to Eurocode 3. Design of steel structures. General rules and rules for buildings*

BS EN 1993-1-4:2006+A1:2015 *Eurocode 3. Design of steel structures. General rules. Supplementary rules for stainless steels*

NA+A1:15 to BS EN 1993-1-4:2006+A1:2015 *UK National Annex to Eurocode 3: Design of steel structures. General rules. Supplementary rules for stainless steels*

BS EN 1993-1-1:2005 *Eurocode 3. Design of steel structures. General rules and rules for buildings*

BS EN 1993-1-8:2005 *Eurocode 3. Design of steel structures. Design of joints*

NA to BS EN 1993-1-8:2005 *UK National Annex to Eurocode 3. Design of steel structures. Design of joints*

BS EN 1993-2:2006 *Eurocode 3. Design of steel structures. Steel bridges*

NA + A1:2012 to BS EN 1993-2:2006 *UK National Annex to Eurocode 3. Design of steel structures. Steel bridges*

BS EN 10204:2004 *Metallic products. Types of inspection documents*

BS EN 13121-1:2003 *GRP tanks and vessels for use above ground. Raw materials. Specification conditions and acceptance conditions*

BS EN 13121-3:2016 *GRP tanks and vessels for use above ground. Design and workmanship*

BS EN 13121-4:2005 *GRP tanks and vessels for use above ground. Delivery, installation and maintenance*

BS EN 13706-2:2002 *Reinforced plastics composites. Specifications for pultruded profiles. Method of test and general requirements*

BS EN 13706-3:2002 *Reinforced plastics composites. Specifications for pultruded profiles. Specific requirements*

BS EN 15643-1:2010 *Sustainability of construction works. Sustainability assessment of buildings. General framework*

BS EN 16245-1:2013 *Fibre-reinforced plastic composites. Declaration of raw material characteristics. General requirements*

BS EN 16245-2:2013 *Fibre-reinforced plastic composites. Declaration of raw material characteristics. Specific requirements for resin, curing systems, additives and modifiers*

BS EN 16245-3:2013 *Fibre-reinforced plastic composites. Declaration of raw material characteristics. Specific requirements for fibre*

BS EN 16245-4:2013 *Fibre-reinforced plastic composites. Declaration of raw material characteristics. Specific requirements for fabrics*

BS EN 16245-5:2013 *Fibre-reinforced plastic composites. Declaration of raw material characteristics. Specific requirements for core materials*

BS EN ISO 527-4:1997, BS 2782-3: Method 326F:1997 *Plastics. Determination of tensile properties. Test conditions for isotropic and orthotropic fibre-reinforced plastic composites*

BS EN ISO 9000:2015 *Quality management systems. Fundamentals and vocabulary*

BS EN ISO 14126:1999 *Fibre-reinforced plastic composites. Determination of compressive properties in the in-plane direction*

BS EN ISO 14130:1998 *Fibre-reinforced plastic composites. Determination of apparent interlaminar shear strength by short-beam method*

BS EN ISO 20753:2014 *Plastics. Test specimens*

BS EN ISO 7093-1:2000 *Plain washers. Large series. Product grade A*

BS EN ISO 7093-2:2000 *Plain washers. Large series. Product grade C*

BS EN ISO 12215-5:2008+A1:2014 *Small craft. Hull construction and scantlings. Design pressures for monohulls, design stresses, scantlings determination*

BS ISO 6721-11:2012 *Plastics. Determination of dynamic mechanical properties. Glass transition temperature*

BS ISO 4587:2003 *Adhesives. Determination of tensile lap-shear strength of rigid-to-rigid bonded assemblies*

ISO 3898:2013 *Bases for design of structures. Names and symbols of physical quantities and generic quantities*

International

ISO 12815:2013 *Fibre-reinforced plastic composites. Determination of plain-pin bearing strength*

USA

ASTM C273/C273M-16 *Standard test method for shear properties of sandwich core materials*

ASTM C297/C297M-16 *Standard test method for flatwise tensile strength of sandwich constructions*

ASTM D638-14 *Standard test method for tensile properties of plastics*

ASTM D953-10 *Standard test method for bearing strength of plastics*

ASTM D1781-98 (2012) *Standard test method for climbing drum peel for adhesives*

ASTM D2344/D2344M-16 *Standard test method for short-beam strength of polymer matrix composite materials and their laminates*

ASTM D3163-01 (2014) *Standard test method for determining strength of adhesively bonded rigid plastic lap-shear joints in shear by tension loading*

ASTM D3917-12 (2012) *Standard specification for dimensional tolerance of thermosetting glass-reinforced plastic pultruded shapes*

ASTM D4056-16 *Standard test method for estimation of solubility of water in hydrocarbon and aliphatic ester lubricants*

ASTM D4385-13 *Standard practice for classifying visual defects in thermosetting reinforced plastic pultruded products*

ASTM D4541-17 *Standard test method for pull-off strength of coatings using portable adhesion testers*

ASTM D5229/D5229M-14 *Standard test method for moisture absorption properties and equilibrium conditioning of polymer matrix composite materials*

ASTM D6641/D6641M-16e1 *Standard test method for compressive properties of polymer matrix composite materials using a combined loading compression (CLC) test fixture*

ASTM D7290-06 (2017) *Standard practice for evaluating material property characteristic values for polymeric composites for civil engineering structural applications*

ASTM D7291/D7291M-15 *Standard test method for through-thickness "flatwise" tensile strength and elastic modulus of a fiber-reinforced polymer matrix composite material*

Statutes

Directives

Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (Waste Framework Directive)

Regulations

The Control of Substances Haardous to Health Regulations 2002 (No.2677)

Further reading

BOROWICZ, D and BANK, L C (2011) "Behavior of pultruded fiber-reinforced polymer beams subjected to concentrated loads in the plane of the web" *Journal of Composites for Construction*, vol 15, 2, American Society of Civil Engineers, Reston, VA, USA, pp 229–238

CANNING, L, HODGSON, J, JARMAN, A, KARUNA, R and LUKE, S (2002) 'The analysis, design and optimisation of an advanced composite bridge deck". In: A Shenoi, S Moy and L Holloway (eds) *Advanced polymer composites for structural applications in construction*, ICE Publishing, Thomas Telford, London, UK (ISBN: 978-1-85573-736-5) pp 405–415
http://www.cosacnet.soton.ac.uk/ACIC2002/Tuesday/t0940canning.pdf

ELLINGWOOD, B R (2003) "Toward load and resistance factor design for fiber-reinforced polymer (FRP) composite structures" *Journal of Structural Engineering*, vol 129, 4, American Society of Civil Engineers, Reston VA, USA, pp 449–458

FABER MAUNSELL (2003) "FRP footbridge in place. The Wilcott Footbridge" *Reinforced Plastics*, vol 47, 6, Elsevier BV, London, UK, pp 9

GRAMMATIKOS, S A, EVERNDEN, M, MITCHELS, J M, ZAFARI, B, MOTTRAM J T and PAPANICOLAOU, G C (2016) "Anomalous response of a pultruded glass fibre-reinforced polymer to hygrothermal aging" *Materials and Design*, vol 96, April, Elsevier BV, London, UK, pp 283–295

HIGHWAYS AGENCY (2001) "Loads for highway bridges" *Design Manual for Roads and Bridges, Volume 1 Highway structures: approval procedures and general design, Section 3 General design, Part 14, BD 37/01*, The Stationery Office, London, UK
http://www.standardsforhighways.co.uk/ha/standards/dmrb/vol1/section3/bd3701.pdf

HIGHWAYS ENGLAND (2012) *Risk based principal inspection intervals*, IAN 171/12, Highways England, Scottish Executive, Welsh Assembly Government (Llywodraeth Cynulliad Cymru), The Department for Regional Development Northern Ireland, UK
http://www.standardsforhighways.co.uk/ha/standards/Ghost/ians/pdfs/ian171.pdf

IEC (2013) *Electrical insulating materials – Thermal endurance properties – Part 1: Ageing procedures and evaluation of test results*, IEC 60216-1:2013, International Electrotechnical Commission, Switzerland

KENDALL, D (2010) "Developments in FRP bridge design" *Reinforced Plastics*, vol 54, 3, Elsevier BV, London, UK, pp 38–41

KOLLÁR, L P and SPRINGER, G S (2003) *Mechanics of composite structures*, Cambridge University Press, Cambridge, UK (ISBN: 978-0-51154-714-0)

MOURITZ, A P and GIBSON, A G (2006) *Fire properties of polymer composite materials solid mechanics and its applications*, vol 143, Springer Nature, Switzerland (ISBN: 978-1-40205-356-6)

OLIVEUX, G, DANDY, L O and LEEKE, G A (2015) "Current status of recycling of fibre-reinforced polymers: review of technologies, reuse and resulting properties" *Progress in Materials Science*, vol 72, July, Elsevier BV, London, UK, pp 61–99

ROBERTS, T M (2002) "Influence of shear deformation on buckling of pultruded fiber reinforced plastic profiles" *Journal of Composites for Construction*, vol 6, 4, American Society of Civil Engineers, Reston, VA, USA, pp 241–248

VOTSIS, R A, CHRYSSANTHOPOULOS, M K and STRATFORD, T J (2009) "Dynamic assessment of a FRP suspension footbridge". In: *Proc fourth int conf on Advanced Composites in Construction*, 1–3 September 2009, Edinburgh, UK, NetComposites Ltd, Chesterfield, UK, pp 144–155

WESTAWAY, D (2001) "Building a future for composites: composites are becoming a more economical option in many infrastructure applications" *Reinforced Plastics*, vol 45, 9, Elsevier BV, London, UK, pp 62–66

Standards

BS EN 13121-2:2003 *GRP tanks and vessels for use above ground. Composite materials. Chemical resistance*

BS EN 13706-1:2002 *Reinforced plastics composites. Specifications for pultruded profiles. Designation*

BS EN ISO 75-3:2004 *Plastics. Determination of temperature of deflection under load. High-strength thermosetting laminates and long-fibre-reinforced plastics*

BS EN ISO 62:2008 *Plastics. Determination of water absorption*

BS EN ISO 175:2010 *Plastics. Methods of test for the determination of the effects of immersion in liquid chemicals*

BS EN ISO 4611:2010 *Plastics. Determination of the effects of exposure to damp heat, water spray and salt mist*

BS EN ISO 4892-1:2016 *Plastics. Methods of exposure to laboratory light sources. General guidance*

BS EN ISO 4892-2:2013 *Plastics. Methods of exposure to laboratory light sources. Xenon-arc lamps*

A1 Case studies of UK FRP bridges

The following is a name order listing of bridge structures in the UK with FRP components that have specific case studies located on the Composites UK website. The listing of UK FRP bridges is not complete and is representative of projects to September 2016. In brackets is the location using Google Earth. Not all of the structures are accessible to the public and those that are not accessible have an asterisk (*) after their names.

1	Aberfeldy Footbridge, 1995	(56° 37′ 31.10″ N and 3° 52′ 14.06″ W)
2	Bonds Mill Lift Bridge, 1994	(51° 44′ 37.38″ N and 2° 13′ 59.09″ W)
3	Bradkirk Footbridge, 2010	(53° 47′ 30.67″ N and 2° 54′ 47.54″ W)
4	Calder Viaduct, 2009*	Near to Sellafield, Cumbria
5	Church Road Bridge, 2014	(51° 32′ 06.79″ N and 2° 28′ 49.45″ W)
6	Dawlish Footbridge, 2011	(50° 34′ 49.82″ N and 3° 27′ 52.53″ W)
7	Halgavor Bridge, 2000–01	(50° 27′ 00.49″ N and 4° 42′ 50.02″ W)
8	Launder Aqueduct, 2009*	(51° 57′ 14.99″ N and 1° 14′ 50.92″ W)
9	Mapledurham Bridge, 2016	(51° 29′ 12.92″ N and 1° 02′ 28.92″ W)
10	Moss Canal Bridge, 2011	(53° 36′ 30.91″ N and 2° 08′ 16.86″ W)
11	Mount Pleasant Bridge, 2006*	(53° 54′ 20.42″ N and 2° 45′ 08.33″ W) close-by
12	Parsons Footbridge, 1994–5	(52° 23′ 46.17″ N and 3° 50′ 24.70″ W)
13	Purfleet Footbridge, 2013	(52° 45′ 13.18″ N and 0° 23′ 38.73″ W)
14	River Chor Aqueduct, 2014*	(53° 39′ 51.98″ N and 2° 37′ 42.70″ W)
15	River Leri Footbridge, 2009	(52° 31′ 00.43″ N and 4° 02′ 24.74″ W)
16	Rubha Glas Viaduct, 2011*	Near to Loch Lomond, Scotland
17	Sedlescombe Footbridge, 2015	(50° 55′ 51.65″ N and 0° 32′ 09.59″ W)
18	St. Austell Footbridge, 2007	(50° 20′ 18.86″ N and 4° 46′ 59.70″ W)
19	Standen Hey Bridge, 2007	(53° 51′ 02.15″ N and 2° 24′ 34.11″ W)
20	Thornaby Footbridge, 2014	(54° 33′ 31.54″ N and 1° 18′ 10.01″ W)
21	West Mill Bridge, 2002	(51° 36′ 59.68″ N and 1° 40′ 00.42″ W)
22	Wilcott Bridge, Nescliffe, 2002	(52° 45′ 54.89″ N and 2° 55′ 04.68″ W)
23	Pont y Ddraig Lift Bridge, Rhyl, 2013	(53° 18′ 53.52″ N and 3° 30′ 28.34″ W)

UK Composites: **https://compositesuk.co.uk/composite-materials/applications/construction**

A2 Approval in Principle

The purpose of the AIP document is described in the Highways England standard Highways Agency (2012), and the standards of other infrastructure owners or technical approval authorities (eg Network Rail). A brief description of the AIP process is that it allows the proposed structural form, materials and design methods to be proposed by the designer and agreed with the technical approval authority at an early stage, and provides evidence that relevant aspects and design standards or guidance have been considered by the designer. The AIP document gives the designer an opportunity to formally show how the client brief will be satisfied at an early stage in the design process.

Every FRP bridge currently requires a "departure from standard" for specification/installation, as these aspects are not covered by generic model documentation and will generally be bespoke. In addition, a Category 3 check of the design will usually be required due to the novelty and immaturity of using structural FRP shapes and systems, although a Category 2 check may be considered appropriate depending on the scale, complexity and risks associated with the bridge project and design method proposed.

For an unusual structural material (such as FRP), the AIP document is the opportunity to clearly define the mechanical properties and practical composite manufacturing processes, assumed at an early stage in the design process.

It is proposed that the following information, beyond that usually required for conventional structural materials, is recorded as a minimum in the AIP document and follows guidance by Atkins (2011) as appropriate:

1. Basic structural form and types of fibre, resin matrix, core and adhesive bonding materials to be used in the FRP structure.
2. Relevant physical and mechanical properties for the above materials (in particular considering the anisotropic nature of FRPs). This may comprise actual material properties based on test records or a typical range of characteristic or design properties based on experience and with reference to design guidance documentation.
3. For a moulded FRP material, the individual fibre and resin constituent properties, and the design method to be used to determine mechanical properties of the FRP with reference to design guidance documentation. It is recommended that a typical range of mechanical properties for laminates to be used in the structural design are provided as a general guide on expected laminate properties.
4. Test methods and standards that have been or will be used to confirm the mechanical properties.
5. Proposed methods for composite manufacturing and fabrication, with reference to material and production standards or guidance documents.
6. Structural analysis method to be used to verify that the proposed FRP structure will meet the requirements of stated design standards or guidance documents. This may typically comprise linear elastic analysis using a 3D finite element model, although a simpler form of analysis may be appropriate for less complex FRP structures.
7. Design method used to confirm that the structural member capacity will meet the limit state requirements of stated design standards or guidance documents. For ULS design this may comprise the failure theory to be used (eg maximum strain, as proposed in **Section 5.2.3**) or an alternative method, such as design-by-testing, as introduced in **Section 5.1.12**.
8. Design method used to confirm that joint and connection resistances will meet the requirements of stated design standards or guidance documents. This should include confirmation of whether bolted and/or bonded (or other) methods of connection are to be used and whether any FRP damage will be allowed before ULS.

9 Approach used to confirm that the FRP structure meets the robustness requirements of BS EN 1990 and UK National Annex.

10 Evidence of the adequacy of the FRP material and structural form with respect to accidental or deliberate damage, or how such adequacy will be proven, eg by testing. This may include previous test records for chemical or fire resistance, case studies of previous structural applications in similar environments or that have experienced or shown resistance to accidental or deliberate damage, or design approaches used to reduce the risk or consequence of damage.

11 Evidence of the adequacy of the materials with respect to durability, or how such adequacy will be proven (eg by accelerated ageing testing), with reference to design standards or guidance documents. As discussed in this design guide, although FRP materials are generally recognised as providing a higher level of durability, it is currently difficult to confirm a design life of 100 years with certainty. In addition to test results or field evidence, alternative approaches such as an engineered design solution to allow easy replacement of FRP components may be included.

Where practical, it is recommended that the information in the AIP document is supported by reference to standards or guidance documentation widely recognised within the industry and inclusion of supporting evidence. The specific information and guidance presented in **Chapters 4 to 7** for FRP bridge engineering will greatly assist the designer in writing an AIP document and associated departures from standard as appropriate.

CIRIA members

ABG Geosynthetics Ltd
AECOM Ltd
AMC Environmental Ltd
Arcadis Consulting (UK) Ltd
ARL Training Services Ltd
Arup Group Ltd
Atkins Consultants Ltd
Balfour Beatty Group
BAM Nuttall Ltd
Barratt Developments plc
Black & Veatch Ltd
BSG Ecology
Buro Happold Engineers Ltd
BWB Consulting Ltd
City University
Costain Ltd
COWI UK Ltd
Dynasafe BACTEC Ltd
Environment Agency
ESRI UK Ltd
Farrow Walsh Consulting Ltd
Galliford Try Plc
Gatwick Airport Ltd
Geotechnical Consulting Group
Golder Associates (UK) Ltd
Highways England Company Ltd
High Speed Two (HS2) Ltd
HR Wallingford Ltd
Hydro Water Management Solutions Ltd
Imperial College London
Institution of Civil Engineers
Jacobs
J Murphy & Sons Ltd
Kier Group plc
Laing O'Rourke Civil Engineering Ltd
London Underground Ltd
Loughborough University
Maccaferri Ltd
Marshalls Plc
Ministry of Justice
Mistras Group Ltd
Morgan Sindall Construction and Infrastructure Ltd
Mott MacDonald Group Ltd
Multiplex Construction Europe Ltd
Network Rail
Northumbrian Water Ltd
O'Keefe Construction
Polypipe
Rail Safety and Standards Board
Royal HaskoningDHV Ltd
RSK Group Plc
Sir Robert McAlpine Ltd
SLR Consulting Ltd
Southern Water Services Ltd
Stantec
Stuart Michael Associates
T&S Environmental Ltd
Temple Group Ltd
Thames Water Utilities Ltd
TOPCON (Great Britain) Ltd
Transport Scotland
UK Green Building Council
United Utilities Plc
University College London
University of Reading
University of Southampton
Wessex Archaeology
WYG Environmental

October 2018

This guide is for the design, procurement, execution, monitoring and inspection of new bridges where components are made using fibre-reinforced polymeric (FRP) composite material. Over the past 25 years there has been an increasing exploitation for structural strengthening and for all-FRP or hybrid-FRP structures, including for bridges and iconic architectural pieces.

It has been a natural progression to consider FRPs in the construction of new bridges, where appropriate to do so, and on a project-by-project basis. Progress in the uptake of FRPs for bridge engineering has been partly restricted by the lack of suitable design standards and guidance for the use of these materials to enable technically efficient and economic design. The structural material of FRP was not covered by the first generation of Eurocodes that were adopted in the UK in 2010.

This first edition is intended to assist in the design of FRP bridges and has the support of all the leading consultants, suppliers, clients, contractors and universities involved in this sector of the construction industry in the UK.

Network Rail

highways england

ciria

C779

9 780860 177944