Design Manual for Roads and Bridges

Highway Structures & Bridges
Design

CD 368
Design of fibre reinforced polymer bridges and highway structures

(formerly BD 90/05)

Revision 0

Summary
This document contains the requirements for the design of fibre reinforced polymer bridges.

Application by Overseeing Organisations
Any specific requirements for Overseeing Organisations alternative or supplementary to those given in this document are given in National Application Annexes to this document.

Feedback and Enquiries
Users of this document are encouraged to raise any enquiries and/or provide feedback on the content and usage of this document to the dedicated Highways England team. The email address for all enquiries and feedback is: Standards_Enquiries@highwaysengland.co.uk

This is a controlled document.

Contents

Release notes

Version	Date	Details of amendments
0	Feb 2020	CD 368 replaces BD 90/05 and includes additional information taken from the draft Eurocode (JRC report) and recently released CIRIA C779 FRP Bridges: Guidance for Designers. It includes finding from recent research and reflects current best practice. The document has been adjusted to be compatible with the current Eurocodes (there are no references to historic BSi Standards) and re-written to make it compliant with the new Highways England drafting rules.

Foreword

Publishing information

This document is published by Highways England.

This document supersedes BD 90/05, which is withdrawn.

Contractual and legal considerations

This document forms part of the works specification. It does not purport to include all the necessary provisions of a contract. Users are responsible for applying all appropriate documents applicable to their contract.

Introduction

Background

Fibre-reinforced polymer (FRP) structures are to be designed in accordance with the general rules given in BS EN 1990 [Ref 3.N], BS EN 1991 [Ref 4.N] and the associated National Annexes. The additional provisions detailed in this document also apply.

The fundamental requirements in clause 1.1 (2) of BS EN 1990 [Ref 3.N] are applicable. These are considered to have been fulfilled where:

1) the design is based on limit states with the loads and load combinations specified in BS EN 1990 [Ref 3.N] and BS EN 1991 [Ref 4.N];
2) the rules and procedures for resistance, serviceability and durability specified herein have been applied; and
3) it has been demonstrated that the mechanical properties and geometrical tolerances applied in the calculation have been achieved.

FRP bridges can be manufactured from the use of either modular solutions (formed by connecting standard pultrusions) or from utilising bespoke mouldings (and the vacuum infusion process).

FRP bridges can also be constructed using hybrids of both of the composite processing methods listed above. In this instance, recommendations for both pultrusions and infusions can be applicable.

For bridges carrying highway vehicles the use of hybrid construction with steel main beams and an FRP road deck, would generally provide the most cost-effective solution.

In developing an FRP bridge, testing is required to confirm the design assumptions and assumed strengths are achieved.

Complementary standards and design guides

This document includes reference to third party documents. These documents provide design criteria and advice. They also highlight lessons learnt by industry in the deployment of FRP bridges.

The list provided below is a useful source of reference information, design recommendations and rules. They are listed for information to aid the design and manufacturing process.

The documents include:

1) CIRIA C779 [Ref 2.I]: FRP Bridges: Guidance for Designers;
2) BS EN 13706 [Ref 11.N]: Reinforced plastics composites Specifications for pultruded profiles, Parts 1 to 3 (inclusive);
3) EUR 27666 EN [Ref 5.I]: JRC Science for Policy Report: Prospects for the new guidance in the design of FRP, 2016. Report EUR 27666 EN, (pre-standard for reference and 'use with care' health warning);
4) CUR96 [Ref 3.I]:2003 - FRP Composite Structures;
5) Clark 1996 [Ref 6.I] Structural Design of Polymer Composites, Eurocomp Design Guide and Handbook, J.L.Clark, 1996.

Assumptions made in the preparation of this document

The assumptions made in GG 101 [Ref 7.N] apply to this document.

Abbreviations and symbols

Abbreviations

Abbreviation	Definition
3D	Three Dimensional
AIP	Approval in Principle
APL	Additional protection layer
ASTM	American Standard Test Method
BS EN	British Standard European Norm
BM	Bending Moment
CIRIA	Construction Industry Research and Information Association
CSM	Chopped strand mat (usually) or continuous swirl mat (occasionally)
CFRP	Carbon fibre reinforced plastic
FRP	Fibre-reinforced plastic/polymer
GFRP	Glass fibre reinforced plastic
GPa	Giga pascals
HDT	Heat distortion temperature
Hz	Hertz
ILSS	Interlaminar shear strength
ILTS	Interlaminar tensile strength
K	Kilo
MPa	Mega pascals
NDE	Non-Destructive Evaluation
NDI	Non-Destructive Inspection
NDT	Non-Destructive Testing
PAN	Polyacrylonitrile
PET	Polyethylene Terephthalate
PD	Published Document
PMI	Polymethacrylimide
PUR	Polyurethane
PVC	Polyvinyl chloride
NA	National Annex
NDP	National Determined Parameter
RTM	Resin transfer moulding (pressure injection)
SF	Shear Force
SLS	Serviceability Limit State
S-N Curve	Plot of the magnitude of an alternating stress (S) versus the number (N) of cycles to failure for a given material

Abbreviations (continued)

Abbreviation	Definition
UD	Unidirectional fibre reinforcement with continuous fibre glass bundles oriented in one direction. (Common designations: UD roving, UD tape (prepreg), UD non-crimp fabric).
UKAS	United Kingdom Accreditation Service
ULS	Ultimate Limit State
UV	Ultra Violet
VA-RTM	Vacuum injection (Vacuum Assisted Resin Transfer Moulding)

Symbols

Symbol	Definition
T_g	Glass transition temperature

Terms and definitions

Terms and definitions

Term	Definition
Additives	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 UV protection. NOTE: Known also as modifiers.
Adhesion	State in which two surfaces are connected together at the interface by mechanical or chemical forces or interlocking actions.
Adhesive	Substance, can be a polymer based material, which when applied on mating surfaces is capable of bonding the two adherends together. NOTE: An adhesive can be in liquid, film or paste form. There are structural or non-structural types of adhesive products.
Anisotropic	Material having mechanical properties being directionally dependent.
Aspect ratio	In fibre technology it is the ratio of length-to-diameter of a fibre.
Balanced laminate	FRP where the individual layers (or plies) are stacked so that there is a balance maintained of + oriented layers and - oriented layers at the same height from the laminate's mid-plane.
Binder	Agent applied to fibre mat or preforms to bond the fibres prior to laminating or moulding. Is a term used for the matrix that holds the FRP together.
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.
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).
Chopped strand matt	Non-woven mat with short strands cut (approximately 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.
Component	Any element or member made of one of more FRP materials, with or without a core material. NOTE: The FRP component can have metallic features, for example, for a moulded joint.
Composite	A material comprising a polymer resin matrix reinforced by fibres or filaments.

Terms and definitions (continued)

Term	Definition
Connection	For design purposes it is the assembly of the basic components required to represent the transfer of the relevant internal forces and moments.
Continuous roving	Single or multiple strands of parallel filaments coated with sizing and wound into a cylindrical package. NOTE: Rovings can be used to provide continuous reinforcement in woven rovings, filament winding pultrusion, prepregs, or contact moulding components. They can 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. NOTE: Foams, honeycombs, woods (balsa) and cork are core materials.
Coupon	A coupon is a small sample of the material under test that has been prepared in such a way that its failure mechanism will be representative of the larger production pieces.
Crazing	Fine cracks at or under the surface of the matrix material in the finished FRP component. NOTE: Tensile stresses causing crazing can results from shrinkage or machining, flexure, impact shocks, temperature or swelling changes.
Creep	Time dependent part of strain resulting from stress.
Cure	Process of hardening of a thermosetting polymer resin (by cross-linking of the molecular structure), often under the influence of heat energy, (see also 'Post cure').
Cure temperature	Temperature profile to which the FRP is subjected during the curing process.
Cure time	Time needed for liquid polymer resin to reach solid state after the catalyst/hardener has been added, 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.
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), ultraviolet (for photo-degradation), oxygen (for oxidative degradation), or weathering.

Terms and definitions (continued)

Term	Definition
Delamination	Separation of the layers of material in a laminate. NOTE 1: This can be local or can cover a significant area of the component. NOTE 2: This can occur at any time in the cure or subsequent life of the laminate and can arise from a wide variety of causes. NOTE 3: This mode of failure is linked to a relatively low through-thickness tensile strength.
Die (Tool)	Steel mould that is either one or two-sided and is either open or closed, in or upon which FRP material(s) is/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.
E-glass	Low alkali borosilicate glass that is the most widely used in fibres for reinforcing FRPs.
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, 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.
Fabric, woven	Generic reinforcement construction consisting of interlaced yarns or fibres, usually a planar structure. NOTE: The warp direction of the woven fabric is taken to be the longitudinal (or 0o) direction, which is the direction of the principal load action.
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.
Fibre	General term for a material in a filamentary form. NOTE: Often, 'fibre' is used synonymously with 'filament', and it is the more common of the two terms used.
Fibre architecture	Design of a FRP component where the fibre reinforcement is oriented and layered in a particular way to achieve the desire laminate mechanical properties.
Fibre blooming	Exposure of fibres due to erosion of surface veil and top resin layer in composite material.
Fibre content	Quantity of fibre in the FRP material. NOTE: Usually expressed as the percentage volume or weight fraction in the FRP.
FRP	Abbreviation for any fibre reinforced polymer material or fibre reinforced polymer composite, (also referred to as fibre reinforced plastic).

Terms and definitions (continued)

Term	Definition
Filler	Relatively inert substance added to a polymer resin to alter its physical, mechanical, thermal, electrical or other properties or to lower cost. NOTE: The term is often used specifically to mean particulate additives.
Gel	State of a polymer resin, which has set to a jelly-like consistency.
Gel coat	Thin layer of unreinforced quick-setting resin on the outer surface of an FRP component. NOTE: Used in moulding processes to provide an improved surface to the FRP product.
Glass fibre	Reinforcing fibre made by drawing molten glass through bushings. NOTE: There are different types of glass fibres. E-glass is the dominant type of glass fibre.
Glass transition temperature (T_g)	Approximate midpoint 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.
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 reacts with to take part in and promote or control curing reaction.
Heat distortion temperature	The temperature at which a standard beam under controlled heating conditions reaches a prescribed deflection.
Honeycomb	Lightweight cellular core material made from either metallic sheets or non-metallic materials and formed into hexagonal-shaped cells.
Hybrid connection	Connection between two components where the surfaces are held together by combination of adhesive bonding and mechanical fastening. NOTE: Hybrid connection is also known as a combined connection.
Insert	Integral part of the FRP component consisting of metal or other material that can be moulded or bonded into position or pressed into the component after completion.
Interlaminar	Descriptive term pertaining to some feature (e.g. void), event (e.g. 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.
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.
Lamina	Single layer or ply in a laminate of a number of individual layers of fibre reinforcement.

Terms and definitions (continued)

Term	Definition
Laminate	FRP material formed from curing and consolidating one or more laminae, layer or plies of one or more fibre reinforced polymer materials. NOTE: 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.
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 is with additives and/or fillers.
Moulding	Forming of an FRP material in a solid form or prescribed shape and size within a closed or open mould, can be accomplished under pressure and heat. NOTE: Term can be used to denote the finished component.
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	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 the starting constituent.
Orthotropic	Having three mutually perpendicular planes of elastic symmetry, which are coincident with the geometric planes of symmetry.
Peel ply	Sacrificial exterior layer that is removed to create an improved surface for bonding to another component. NOTE: Acts as a protective layer to ensure that the surface remains undamaged and uncontaminated prior to the adhesive bonding process.
Phenolic resin	Family of thermosetting polymer resins made by reacting epichlorohydrin with bisphenol A and sodium hydroxide in dimethyl sulphoxide. NOTE: Phenoxy resins are chemically similar to epoxy resins.
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.

Terms and definitions (continued)

Term	Definition
Polymer	High-molecular weight organic compound composed, natural or synthetic, of molecules characterised by the repetition of one or more types of monomeric units. NOTE: Known also as a plastic.
Polyurethane	Resin produced by reacting a diisocycyanate with an organic compound containing two or more active hydrogen atoms to form a polymer having free isocynate groups. Under 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 (also Voids).
Post cure	Additional elevated temperature cure of the matrix usually without pressure. NOTE: For certain resins, complete cure is attained only by exposure of the matrix to higher temperatures than those of curing.
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.
Prepreg	Factory-made lamina (layer or ply) of a reactive polymer resin matrix and reinforcing fibres (unidirectional, fabrics or mats).
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.
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. NOTE: As an example, unidirectional laminae are often grouped using the four orientations of 0º, 90º and 45º.
Reinforcement	Fibres that are added to a polymer matrix to form an FRP material with the required mechanical properties. NOTE: 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. NOTE: It can exist in solid, semi-solid or liquid state.
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.

Terms and definitions (continued)

Term	Definition
Sandwich construction	FRP structural form comprising lightweight core material to which two high strength FRP faces are adhesively bonded.
Shrinkage	Relative change in dimension between a dimension of the moulded component 24 hours after it has been moulded.
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 fabrics	Textile fabric that also has fibre reinforcement in the out-of-plane direction.
Strand	Assembly of parallel fibres (or filaments), normally an untwisted bundle or assembly of continuous filaments used as a unit.
Stress rupture	Also known as creep rupture. Property whereby the material can fail (rupture) at a sustained stress level considerably less than the short-term ultimate stress.
Surfacing veil	Very thin mat, usually 0.18 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.
Symmetric laminate	Laminate in which each lamina type, angles and composition is exactly mirrored about the mid-plane of the FRP material.
Thermoplastic	Polymer resin that softens each time it is heated and hardens when cooled.
Thermoset	Class of polymers 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 fibers, particularly carbon and graphite fibers, in the FRP industry. Typically designated by a number followed by K, meaning multiplication by 1000 (e.g.12K tow has 12 000 filaments).
UV 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 moulding: pressure 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.
Water absorption	Ratio of mass of water absorbed by FRP to weight of dry (cured) FRP.

Terms and definitions (continued)

Term	Definition
Wet-out	Complete wetting or saturation of the fibre reinforcement by the resin matrix.
Wet lay-up	FRP manufacturing process for making an FRP laminate by applying a liquid resin system whilst or after the reinforcement is put in place.
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.
0º	Orientation of fibres, laminae or component that is aligned to the principal direction of loading.
45º	Orientation that is 45º from the 0º and 90º orientation.
90º	Orientation(s) that is/are perpendicular to the 0º orientation.

1. Scope

Aspects covered

1.1 This document shall be used for the design of FRP bridges.

NOTE The following parts of a highway bridge or structure are included and referenced in this document with guidance given where appropriate:

1) *deck - the part of the bridge deck forming the carriageway and transferring wheel loads to the supporting members. It is assumed that the deck consists of top and bottom flanges, separated by a core of FRP webs or a filler material;*
2) *primary beams/supporting members - the remaining part of the bridge deck, consisting of the main structural members (usually longitudinal beams) that support the deck and transfer loads to piers or abutments. The supporting members can be FRP, steel, concrete, or a combination of these;*
3) *connections and joints – these are usually bonded or bolted and are located at joints, between the spans and also connecting the deck and primary supporting members;*
4) *surfacing system - the surface course, including waterproofing if required, additional protective layers including additional plate for improved load distribution including anti-skid running surface;*
5) *critical interfaces - for example, expansion joints/bearings and connections;*
6) *parapet anchorage - requirements for bridge parapets are given elsewhere: only the anchorage is covered in this document;*
7) *ancillaries - kerbs, foot-ways, drainage, service ducts, anchorage of street furniture (lighting columns, signs, etc.).*

Implementation

1.2 This document shall be implemented forthwith on all schemes involving FRP bridges on the Overseeing Organisations' motorway and all-purpose trunk roads according to the implementation requirements of GG 101 [Ref 7.N].

1.3 This document shall be used for the design of highway bridges and structures and for re-decking of existing bridges using structural members made of FRP materials.

NOTE This document gives guidance and additional requirements for the technical approval of highway structures schemes utilising FRP and also provides information for design including design rules and approvals. The document also presents some materials information and gives guidance on the testing requirements.

1.4 The document is a performance standard, within broad limits on permitted materials and manufacturing processes, it shall be used in conjunction with the 'Complimentary standard and design guides' listed in the Introduction.

1.4.1 The document is intended to be relevant to as wide a range of FRP systems as possible, and should not restrict future developments in materials, manufacturing processes and innovative forms of construction.

1.5 Where variance in the 'Complimentary standard and design guides' exists the values and recommendation made in this document shall prevail.

1.6 In lieu of the release and implementation of any FRP Eurocodes, this document shall be used and testing undertaken to confirm design assumptions and strengths.

1.7 Testing shall be undertaken on all new FRP systems deployed on the network to prove the design assumptions and strengths.

NOTE The testing for modular systems is not required to be replicated, other than workmanship test for any repeated designs.

1.8 The design and testing requirements for FRP bridges varies considerably and the different methods of certification shall be followed in accordance with this document.

NOTE Details of the process of pultrusion and resin infusion can be found in Appendix A.

1.9 Processing methods other than pultrusion and infusion are permitted and specific requirements for these shall be agreed with the Overseeing Organisation.

1.10 Design undertaken using pultrusion shall be classed as 'modular' and designs using resin infusion will be classed as 'bespoke' solutions.

1.10.1 Bespoke solutions may be specifically tailored for individual structures utilising various fibre layups to provide a structure with materials properties designed to meet the individual structures' needs.

1.11 Bespoke designs shall be verified by testing, according to the requirements of this document.

1.12 The testing for bespoke systems (full scale tests and fatigue load tests) shall not be required to be replicated, for any repeated designs where previous test results are available to confirm strengths.

NOTE For repeated design material characterisation (coupon testing) is still required to ensure the design assumptions are realised.

Use of GG 101

1.13 The requirements contained in GG 101 [Ref 7.N] shall be followed in respect of activities covered by this document.

2. Materials

General information

2.1 The materials properties shall be determined by laboratory tests and elaborated from a statistical point of view to give characteristic values in accordance with BS EN 1990 [Ref 3.N].

2.2 The materials selected for use in FRP structures shall be suitable for the proposed manufacturing process.

NOTE 1 The two main components of an FRP composite are the resin and fibre reinforcement. A cured thermosetting resin is often very brittle and the addition of reinforcing fibres improves the composites mechanical properties.

NOTE 2 FRP composites generally have anisotropic properties unlike traditional materials which generally have isotropic properties. The properties of FRP materials depend on the direction being considered and the amount and strength of fibres in that direction.

2.2.1 An FRP composite material may be customised with additional reinforcement in the direction and location of high stresses to allow the creation of a more efficient optimised structures at lighter weights.

2.3 The strength of joints and connections shall be tested to give characteristic properties.

Material properties

Resin

2.4 Resin choice shall be limited to polyester, vinylester and epoxy for structural applications, however, the use of phenolic resin is permitted where fire risk is high.

2.5 The glass transition temperature (T_g) of the resin shall be at least 20°C above the maximum service temperature.

NOTE There is a large variation in strength properties within every resin type. Indicative materials properties are given in Table 2.5N to aid preliminary design choices. For more detailed information refer to the manufacturer's information.

Table 2.5N Indicative resin properties

Material property / resin type	Polyester	Vinylester	Epoxy
Poisson ratio	0.38	0.26	0.39
T_g (degrees C)	60	100	80 – 150
Tensile or compression strength (MPa)	55	75	75
Youngs modulus in tension (MPa)	3550	3350	3100
Strain limit in tension or compression (%)	1.8	2.2	2.5
In plane shear modulus (MPa)	1250	1400	1500
Shear strength (MPa)	50	65	80
Shear strain limit (%)	3.8	3.7	5
Expansion coefficient (10^{-6} K^{-1})	50 - 120	50 - 75	45 – 65

Core materials

2.6 Core materials shall be used to create sandwich-structured composites.

NOTE Sandwiching a low-density, lightweight core material between face sheets increases a laminate's stiffness with little added weight.

2.7 Core materials for use in FRP bridges shall utilise PUR, PMI, PVC, PET or balsa.

2.7.1 Other core materials may be used subject to agreement with the Overseeing Organisation.

NOTE 1 For a sandwich construction, the core functions like the connecting web of an I-beam, separating the face skins at a constant distance, while the skins themselves function as the I-beam flanges.

NOTE 2 Indicative materials properties are given in in Table 2.7.1N2 below to aid preliminary design choices. For more detailed information refer to the manufacturer's information.

Table 2.7.1N2 Indicative core material properties

	Density (kg/m^3)	Compression strength (N/mm^2)	Shear strength (N/mm^2)	Elasticity modulus (N/mm^2)	In-plane shear modulus (N/mm^2)
PUR (polyurethane)	50	0.3 – 0.5	~ 0.2	6 – 10	4 – 5
	100	0.6 – 1.0	0.3 – 0.5	~ 30	~ 10
PVC (polyvinyl chloride)	40	0.5 – 0.8	0.3 – 0.4	20 – 30	~ 10
	80	1.2 – 2.0	0.7 – 1.0	60 – 90	20 – 30
	80	~ 0.9	0.5 – 1.0	~ 50	20
PMI (polymethacrylimide)	30	~ 0.5	~ 0.3	~ 30	~ 15
	70	~ 1.5	~ 1.0	~ 90	~ 30

Fibres and fabrics

2.8 The reinforcing fibres for use in FRP components shall either be glass, basalt, aramid or carbon or a combination of these.

NOTE Fibres are combined to create fabrics and there are various combinations created by different manufacturers. Typical fabrics include unidirectional fabrics, woven fabrics and multiaxial fabrics. Fabrics can also be individually weaved to create bespoke layouts and 3D shapes aptly named 'preforms'.

2.8.1 Hybrid fabrics comprising of 2 or more different fibres may be used in FRP components, subject to the appropriate testing as highlighted in Section 4.

NOTE Indicative materials properties are given in Table 2.8.1N below to aid preliminary design choices. For more detailed information refer to the manufacturer's information.

Table 2.8.1N Indicative fibre properties

		Glass		Carbon		
		E glass	R glass	HS	IM	HM
Tension in fibre direction	Poisson's ratio	0.238	0.2	0.3	0.32	0.35
	Young modulus (MPa)	73100	86000	238000	350000	410000
	Strain limit (%)	3.8	4	1.5	1.3	0.6
	Strength (MPa)	2750	3450	3600	4500	4700
Tension perpendicular to fibre direction	Poisson's ratio	0.238	0.26	0.02	0.01	0.01
	Young modulus (MPa)	73100	86000	15000	10000	13800
	Strain limit (%)	2.4	2.4	0.9	0.7	0.45
	Strength (MPa)	1750	2000	135	70	60
Compression in fibre direction	Strain limit (%)	2.4	2.4	0.9	0.6	0.45
	Strength (MPa)	1750	2000	2140	2100	1850
Shear	Modulus (MPa)	30000	34600	50000	35000	27000
	Strain limit (%)	5.6	5.6	2.4	3	3.8
	Strength (MPa)	1700	1950	1200	1100	1000
Thermal expansion (10-6 K-1)		5 - 0	3	-0.4	-0.6	-0.5

Laminate

2.9 Classical laminate theory shall be used for the design of laminates.

2.10 The resulting mechanical properties of an FRP laminate shall be determined by testing.

2.11 Mechanical testing of the proposed fibre/resin configuration shall be undertaken to prove the theoretical design strengths are achieved specifically for moulded structures.

NOTE 1 Refer to coupon testing in Section 4.

NOTE 2 The mechanical properties are dependent on the chosen resin and reinforcing fibres (material type, layers and orientation) together with the method of manufacture which can have a direct impact on the consolidation of the laminate affecting the achieved fibre volume fraction (FVF).

NOTE 3 Indicative laminate materials properties for varying fibre volume fractions (for unidirectional fibre layups and balanced bi-directional fabrics with polyester resin) are given in Table 2.11N3a and Table 2.11N3b below to aid preliminary design choices.

Table 2.11N3a Indicative UD ply E glass stiffness values

Volume fraction Vf	E_1 (GPa)	E_2 (GPa)	G_{12} (GPa)	v_{12}
40%	30.4	8.9	2.7	0.30
45%	33.8	10.1	3.0	0.29
50%	37.2	11.4	3.4	0.29
55%	40.5	12.9	3.8	0.28
60%	43.9	14.6	4.3	0.27
65%	47.3	16.8	5.0	0.27
70%	50.7	19.4	5.8	0.26

Table 2.11N3b Indicative balanced bi-directional ply E glass stiffness values

Volume fraction Vf	E_1 (GPa)	E_2 (GPa)	G_{12} (GPa)	v_{12}
40%	12.8	12.8	1.9	0.21
45%	14.7	14.7	2.1	0.20
50%	16.8	16.8	2.4	0.20
55%	18.9	18.9	2.6	0.19
60%	21	21.0	2.9	0.19
65%	23.3	23.3	3.3	0.19
70%	25.6	25.6	3.7	0.18

NOTE 4 A simple cost benefit analysis can be undertaken to assess the benefits of improving the fibre volume fraction by improved manufacturing processes versus the provision of additional fibres and the use of thicker sections.

NOTE 5 Increasing the volume fraction percentage can improve the attained strength of the composites however this can come at an increased cost due to more complex composites processing methods.

NOTE 6 In many cases for FRP bridges, utilising a thicker section with a lower cost manufacturing method can be more effective than optimising the material properties with high volume fraction. Thicker sections can also improve the overall damage tolerance hence improving resilience within the materials against external actions.

Material factors

2.12 The appropriate material factors shall be applied to the strength and stiffness.

Equation 2.12 Material Factors

$$\gamma_m = \gamma_{m1} \cdot \gamma_{m2}$$

NOTE 1 $\gamma m1$ *is the partial material factor linked to uncertainties in obtaining the correct material properties,* $\gamma m1$ *is 1.15 in the case of material properties derived from tests, or 1.35 in the case of material properties derived from theoretical models or values available in technical literature.*

NOTE 2 $\gamma m2$ *is the partial material factor due to uncertainties in material properties as a result of the nature of the constituent parts and depends on the production method.*

2.13 For SLS verification, the material partial factor $\gamma m1$ and $\gamma m2$ shall be put equal to 1.0.

2.14 For ULS verification, the material partial factor $\gamma m1$ and $\gamma m2$ shall be obtained from tables 2.14a, b and c.

Table 2.14a Partial Factor $\gamma m2$ for laminates and foam core

Laminate type		$\gamma m2$		
		Strength verification	Local stability	Global stability
Post cured	Variation coefficient $V_x < 0.10$	1.35	1.5	1.35
	Variation coefficient $0.10 <= V_x <= 0.17$	1.6	2.0	1.5
Non post cured	Variation coefficient $V_x <= 0.10$	1.6	1.8	1.6
	Variation coefficient $0.10 <= V_x <= 0.17$	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 2.14b Process derived partial factor $\gamma m1$ for laminates and structures

Quality process and certification		$\gamma m1$
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 2.14c Partial Factor $\gamma m1$ & $\gamma m2$ for adhesives

$\gamma m1$		
Adhesives	Manual application with few controls of the thickness and surface pre-treatment	1.5
	Manual applications with systematic control of the thickness and surface pre-treatment	1.25
	Identified application with defined and repeatable controlled parameters including surface pre-treatment	1.0
$\gamma m2$		
Adhesives	Variation coefficient $V_x <= 0.10$	1.2
	Variation coefficient $0.10 < = V_x <= 0.17$	1.5

NOTE *Uncertainties are allowed for by means of a material factor* γm .

Environmental conversion factors

2.15 The effect of the environment shall be applied using various conversion factors.

2.16 The materials used in FRP bridge construction shall be suitable for the intended service environment, (e.g. temperature range, exposure to moisture, alkalis from concrete, de-icing salts and chemicals).

2.17 General guidance relating to environmental factors is given in BS EN 1990 [Ref 3.N], but site-specific requirements shall also be defined.

2.18 The conversion factor η_c shall be obtained by multiplying the specific conversion factors relevant for all the environmental actions and long term effects affecting the behaviour of the material.

NOTE The effect of environment on the materials is characterised by both the design life and the assumed design values of the material properties over the design life. The data provided does not necessarily need to demonstrate that there can be no reduction in properties over the design life, but that any reductions are consistent with the design assumptions over the design life.

2.18.1 Protective coverings already tested as able to mitigate the environmental degradation and to allow the service life of the structure to remain unaltered, should be used in aggressive environments.

2.18.2 Where the presence of a protective system is able to counteract a specific environmental effect, the value of the corresponding conversion factor may be assumed to be equal to 1.0.

2.19 The total conversion factor, η_c , for the limit states analysis shall be determined from:

Equation 2.19 Environmental conversion factors

$$\eta_c = \eta_{ct}.\eta_{cm}.\eta_{cv}.\eta_{cf}$$

NOTE 1 η_{ct} is the conversion factor for temperature effects for verification of strength, η_{ct} = 0.9; for verification of deformability and stability at a service temperature of $T_d = T_g - 40°C$ then η_{ct} = 1.0 and at a service temperature of $T_g - 40°C < T_d < T_g - 20°C$ then η_{ct} = 0.9.

NOTE 2 η_{cm} is the conversion factor for humidity effects. For UK bridges, in an outdoor climate with temperatures typically below 30°C then for cured laminates η_{cm} = 0.9 and non post cured laminates η_{cm} = 0.8. For temperatures higher than 30°C then for cured laminates η_{cm} = 0.8, (non post cured laminates for temperatures above 30°C are not permitted).

NOTE 3 η_{cv} is the conversion factor for creep effects. The conversions factors for creep related directly to the categories relating to the load duration classes. Dead loads are classed as 'permanent', vertical live loads on bridges which have a medium to high occurrence of heavy goods vehicles are classed as 'long', bridges on local roads with a low HGV occurrence are classed 'medium' and agricultural roads are classed as 'low'.

Table 2.19N3 ηcv conversion factors for time duration tv

Level of proof	Estimated loads	Conversion factors η_{cv} (t_v) according to the tabular value η_{cv20} and the duration of exposure t_v					
tabular value η_{cv20} (20 years)	- - -	0.67	0.5	0.4	0.33	0.29	0.25
Permanent 50 years	permanent	0.65	0.48	0.38	0.31	0.27	0.23
Long - term 10 years	permanent, long	0.69	0.51	0.42	0.35	0.30	0.27
Medium - term 6 months	permanent, long, medium	0.74	0.59	0.49	0.43	0.38	0.34
Short - term 1 week	permanent, long, medium, short	0.80	0.67	0.59	0.53	0.49	0.45
Instantaneous 1 minute	permanent, long, medium, short, very short	1.00	1.00	1.00	1.00	1.00	1.00

NOTE 4 η_{cf} *is the conversion factor for fatigue effects. In the serviceability limit state verification allowance is made for loss of stiffness in the material due to fatigue using a conversion factor for fatigue effects of* η_{cf} *= 0.9.*

Conversion factor combinations

2.20 Conversion factors shall be combined as indicated in Table 2.20.

Table 2.20 Combinations for environmental factors

Aspect being verified							
Influencing factor	Strength (ULS)	Stability (ULS)	Fatigue (ULS)	Creep (SLS)	Momentary deformation (SLS)	Comfort / vibrations (SLS)	Damage (SLS)
Temperature - η_{ct}	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Humidity - η_{cm}	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Creep - η_{cv}	Yes	Yes	No	Yes	No	No	Yes
Fatigue - η_{cf}	No	Yes	No	Yes	Yes	Yes	Yes

3. Design

General recommendations

3.1 The design requirements within this section shall be followed.

NOTE 1 General design advice is given together with information in the form of notes for consideration.

NOTE 2 The design process for FRP bridges manufactured using resin infusion and pultrusion varies considerably. The recommendations and advice are given to highlight the key differences and specific areas for consideration for both processes. For instance, material selection and characterisation is more important for infusions, whilst effective connection design is more appropriate for bridges made with pultrusions.

NOTE 3 In general bridges constructed with glass fibre have high strength and low stiffness compared to traditional construction materials. Therefore, design can be governed by deflection rather than stress and by serviceability limit states rather than ultimate limit states.

3.1.1 For bespoke fabrications the addition of carbon fibre may help improve the stiffness and reduce the anticipated deflections.

NOTE Designs using CFRP can help control deflection however solutions using CFRP can then be governed by ULS stress requirements.

3.1.2 The use of CFRP to control defelction may require the additional bespoke testing (i.e. for fatigue) to ensure the design provides sufficient resilience against the applied actions during its lifetime, where ULS stress requirements govern.

3.2 The configuration of the structure and the interaction between the structural members shall be such as to ensure a robust and stable design.

3.3 In verifying the resistance, the deformability as well as the stability, the characteristic values corresponding to the fractile 5% of the statistical distribution, shall be used.

3.4 In verifying the deformability, the mean values of the modulus of elasticity shall be used.

3.5 FRP materials are generally linear elastic up to failure and do not behave in a ductile manner hence, non-linear analysis methods such as yield-line and moment re-distribution shall not be used.

3.6 Redistribution methods shall not be permitted.

3.6.1 Conventional methods of linear elastic analysis may be used assuming plane sections remain plane, however in the analysis an assessment of the possible increased shear lag effects is required due to the low shear modulus of the constituent materials.

3.7 Local stress concentrations shall be assessed in the design of bearings, movement joints, parapets, kerbs, signs.

NOTE 1 The effect of local stress concentrations is different from that in steel and concrete due to the lower ductility of FRP.

NOTE 2 Modes of failure can also be different to traditional materials, hence damage can accumulate at a microscopic level with very little overall change being apparent.

3.8 The use of structural health monitoring shall be assessed where appropriate concerns are raised over damage tolerance, dynamic performance, accumulation and where there are hidden sections that can be a future concern.

3.9 The temperature and durability data shall be analysed in setting the design values for component properties.

3.10 Due to the lower shear modulus, 'global shear' shall be assessed, (specifically for thin walled FRP sections such as pultrusions) to ensure the relatively low shear strength of the material is acceptable.

3.11 Thermal stress effects shall be assessed to ensure thermal expansion is managed.

3.12 Thermal stress effects shall be regarded as variable stresses and applied with a partial stress factor and a ψ factor. The stress factor and ψ factor are defined in the applicable National Annexes of BS EN 1990 [Ref 3.N] and BS EN 1991 [Ref 4.N].

3.13 Temperature variations shall be assessed in accordance with BS EN 1991 [Ref 4.N].

3.13.1 FRP Bridges may be classed as Type 3 structures in accordance with BS EN 1991 [Ref 4.N].

3.13.2 Alternative values may be taken where supported by information on the thermal characteristic of the material, subject to the agreement of the Overseeing Organisation.

NOTE Within BS EN 1991 [Ref 4.N] Type 2 structures are referred to as composite. This annotation refers to steel / concrete composites and not FRP composites.

3.14 Adjustments shall be made for surfacing thickness as noted in Table NA.1 within the National Annex for BS EN 1991 [Ref 4.N].

3.15 Deflections due to transient effects shall not exceed span/300.

3.16 The structure shall be designed to support loads caused by normal function.

3.16.1 The design of the structure should allow for reasonable probability that it can not collapse or suffer disproportionate damage under the effects of misuse or accident.

3.17 When undertaking the design of an FRP bridge, the following procedure shall be followed:

1) seek advice from materials suppliers, manufacturers and fabricators regarding their preferred materials and manufacturing processes to inform design decisions;
2) establish preferred manufacturing methods and associated information (post cure time and temperature);
3) utilise typical materials properties for preliminary design sizing;
4) establish preferred solution and undertake materials classification process (for infusions) and/or develop outline designs for connections and test accordingly;
5) target zero joints in fully moulded structures or use of prefabricated FRP components with bonded/bolted connections;
6) record details and agree design proposals in consultation with the Overseeing Organisation;
7) design in accordance with available standards and adopt design assisted by testing process for areas of ambiguity/uncertainty;
8) undertake design and analysis including FE analysis utilising agreed material properties with appropriate stiffness matrix used (6x6 or 9x9);
9) appoint competent reviewer for design check ensure they have demonstrable FRP composites expertise;
10) undertake design check, agree outputs and changes required and amend design accordingly.

Pultrusion specific recommendations

3.18 The design and specification of pultrusion for FRP bridges shall be in accordance with BS EN 13706 [Ref 11.N].

3.19 Pultrusions manufactured to BS EN 13706 [Ref 11.N] shall not require individual testing of the structural elements.

3.20 When using pultrusions for the formation of a bridge deck, manufacturers materials information and design guides shall be consulted and relevant controls relating to workmanship of bolted and bonded connections and joints developed.

3.21 Testing shall be undertaken including that of full scale, sub components and structural details.

3.21.1 For pultrusions the design and resulting testing should also assess the application of loads that do not act in the principal fibre directions of the material.

3.22 Where pultrusions are used which do not conform to BS EN 13706 [Ref 11.N] additional coupon testing shall be undertaken to confirm the mechanical properties of the preformed sections in addition to the testing referred to in Section 3.

3.22.1 Additional testing may also involve an assessment of fibre waviness and connection alignment, as addressed in paper on fibre waviness referenced in Section 8, Sebastian 2018 [Ref 1.I].

3.23 Recommendations for testing of bridges made from pultrusion shall be followed in Section 4 of this document.

Infusion specific recommendations

3.24 In the case of preliminary designs for moulded structures, the ply or laminate properties shall be determined from theoretical models or values available in technical literature available from the proposed manufacturer.

3.25 At detailed design the adoption and use of classic laminate theory shall be followed to determine the configuration of individual plies required in the laminate stack(s).

3.26 Testing shall be undertaken to confirm material properties in accordance with Section 4 of this document.

3.27 Areas of uncertainty in the design shall be addressed through the design assisted by testing approach.

Design approval

3.28 The design life of an FRP deck shall be taken as 120 years.

3.28.1 A shorter design life may be permitted where it is otherwise desirable to use a material which is so newly developed that it is not possible to provide reliable evidence for a life of 120 years.

3.29 A shorter design life can be justified where replacement of the FRP deck is possible, however the underlying primary beams shall have a 120 years design life.

3.30 Details of any design life relaxations proposed shall be agreed with the Overseeing Organisation.

3.31 The design and calculation of structures or structural elements shall be supported by tests, as stipulated in Section 4 of this document.

3.32 The design approval process shall include the following considerations:

1) technical approval (AIP process) including construction and maintenance information with design decisions documented and the analysis methods adopted, proposed structural form, manufacturing methods and proposed quality controls;
2) analysis and design of FRP members and components including connections and detailing to required standards and performance specification for the project;
3) verification and validation of materials and component properties by testing;
4) design and check of components and assemblies against defined material properties.

3.33 The additional clauses listed in Appendix A shall be added to the AIP to permit improved clarity of the design input assumptions and approval process.

Design for durability

3.34 To account for durability and environmental factors the design shall:

1) apply environmental factors and material factors;
2) provide sacrificial thickness (designing for environment and for robustness);
3) provide minimum laminate thickness (to be agreed with Overseeing Organisation);
4) apply waterproofing and additional protection layers;
5) utilise coatings as a protection to UV/weathering/moisture uptake.

NOTE To enhance durability for the intended service life of 120 years, FRP bridges can be waterproofed (deck surface below pavement) to prevent water ingress and moisture uptake thereby limiting possible damage to the FRP component from freeze thaw cycles.

3.35 The environmental conditions shall be identified during the design phase in order to evaluate their influence on the durability of the structure, with any eventual measures being included to protect the material or the structural parts.

3.36 It shall be necessary to reduce the mechanical properties of FRP materials by material and environmental conversion factors for strength and stiffness.

3.37 Materials properties shall be reduced by application of adjusted material factors using environmental factors referred to in Section 4.

NOTE Creep and/or stress rupture can reduce the capacity of some fibres and resins under long-term sustained load.

3.38 The robustness and resilience of the surfacing details shall be confirmed through a verification process to be agreed with the Overseeing Organisation.

3.38.1 The surfacing verification process may involve design simulation and/or mechanical testing to demonstrate acceptable long-term behaviour of this interface ensuring the integrity is not compromised due to fatigue or environmental effects.

Ultimate limit state

3.39 The ULS design shall be carried out using either data supplied by the FRP manufacturer for appropriate values of ultimate strength and/or strain limits or data obtained from testing and in accordance with the design loading general rules given in BS EN 1990 [Ref 3.N], BS EN 1991 [Ref 4.N] and the associated National Annexes.

3.40 The testing and/or manufacturer's data shall assess the effects of creep, sustained load, deterioration, ageing, temperature effects and any other effect that can influence the strength and stiffness through the application of environmental factors as highlighted in Section 2.

3.41 The material assumptions made by the design organisation during preliminary/detailed design shall be verified through appropriate testing, (refer to Section 4).

3.42 The ULS design shall be checked as followed:

1) pultrusions: axial tension, axial compression, in-plane flexure, in-plane tension and compression, shear, torsion, through-thickness tension, connection strength;
2) laminates: resistance and stability checks at ply and laminate level;
3) sandwich panels: facing failure, transverse shear failure, flexural crushing of core, local crushing of core, general buckling, shear crimping, face wrinkling and intracell buckling or dimpling.

3.42.1 The list of ULS design checks is not exhaustive and may be extended where required.

Serviceability limit state

3.43 The serviceability limit state design shall undertake a review of the following checks:

1) deformations and deflections;
2) vibrations;
3) damage tolerance.

3.43.1 The SLS requirements may govern the design of FRP components due to the relatively low value of elastic modulus.

Deformations and deflections

3.44 The deflection of the structure or any part of it shall not be such as to adversely affect its appearance or serviceability.

3.45 The deflection of the structure shall be limited to span/300 under live load alone, including shear deformation.

3.46 The deflection limit shall be applied locally and globally, in both longitudinal and transverse directions.

Damping

3.47 When determining the response, a material damping coefficient of 1.0 % and an average value of 1.5 % shall be assumed as a realistic conservative lower limit for calculations.

3.47.1 Higher damping values may be used where these have been substantiated by representative experimental data.

Dynamics and vibrations

3.48 Dynamic analysis shall be carried out to determine the natural frequencies and associated mode shapes of the structure to indicate the susceptibility of the bridge to traffic and pedestrian induced vibrations.

NOTE The lightweight nature of FRP can result in a "lively" bridge.

3.48.1 Excessive vibrations may affect the bond in joints and between surfacing and FRP.

3.48.2 Vibration and sway may cause discomfort to users and/or reduce the function of the structure.

3.49 The deformations and vibration behaviour shall be verified in both the loaded and unloaded situation for vertical, lateral and torsional effects.

3.50 The criteria for assessing the dynamic behaviour of bridges shall follow the procedures outlined in the following Eurocodes (BS EN) and Published Documents (PD):

1) BS EN 1990 [Ref 3.N] as modified by UK National Annex;
2) BS EN 1991 [Ref 4.N] as modified by UK National Annex;
3) PD 6688-2 [Ref 10.N].

NOTE None of the above documents provide limiting horizontal accelerations for deliberate lateral shaking of the bridge.

3.51 Pedestrian comfort criteria shall be assessed in accordance with BS EN 1990 [Ref 3.N], Annex A2 and the National Annex applied with respect to the comfort criteria for pedestrians.

3.51.1 BS EN 1990 [Ref 3.N]/Clause A2.4.3.2 (1) states that comfort criteria should be defined in terms of maximum acceptable acceleration, gives a limit for lateral and torsional vibrations (0.2 ms^{-2}) and makes the value a nationally determined parameter (NDP).

3.51.2 Clause NA.2.3.10 of NA to BS EN 1990 [Ref 3.N] states that the pedestrian comfort criteria should be as given in NA.2.44 of NA to BS EN 1991-2 [Ref 2.N].

NOTE NA.2.44 of NA to BS EN 1991-2 [Ref 2.N] does not specify a maximum acceptable acceleration for horizontal movement under normal use. BS EN 1990 [Ref 3.N] Clause A2.4.3.2 (2) gives the limiting values of fundamental frequency for verification of the comfort criteria (up to 2.5Hz for lateral and torsional modes). This is not a NDP, however NA to BS EN 1991-2 [Ref 2.N] and PD 6688-2 [Ref 10.N] to specify limiting values that are inconsistent with BS EN 1990 [Ref 3.N].

3.52 In the absence of a maximum acceptable acceleration for horizontal movement under normal use being specified by NA.2.44 of NA to BS EN 1991-2 [Ref 2.N], the recommended value given in BS EN 1990 [Ref 3.N]/Clause A2.4.3.2 (1) shall be used (i.e. 0.2 m/s^2), measured at the level of the deck.

3.53 The design is to conform to the requirements of BS EN 1990 [Ref 3.N]/Clause A2.4.3.2 (2) [i.e. a verification of the comfort criteria shall be performed where the fundamental frequency of the deck is less than (1) 5 Hz for vertical vibrations, and (2) 2.5 Hz for horizontal (lateral) and torsional vibrations].

3.54 Where the fundamental frequency of the bridge is less than 3Hz for horizontal (lateral) and torsional vibrations, provision shall be made in the design for the possible installation of dampers in the bridge.

NOTE *Experience with conventional bridges suggests that where the fundamental natural frequency is above 5Hz, then dynamic effects are not significant.*

Fatigue limit state (ULS/SLS)

3.55 The fatigue design shall include the following checks:

1) local effects. Wheel loads on the road surfacing affecting details such as webs, flanges, web-flange connections, plus joints between components, sections of deck and surfacing;
2) global effects. Bending moment and shear forces on components and joints in the FRP decks due to wheels, axles or groups of axles.

3.56 Fatigue effects shall be assessed for stiffness, strength and environmental conditions e.g. moisture ingress.

3.57 The reference fatigue load model shall be taken from BS EN 1991-2 [Ref 2.N].

3.58 The partial load factor for fatigue shall be taken as 1.0.

3.58.1 For the fatigue check for local effects a factor of 1.5 should be applied to allow for the combined effect of twin wheels for wheel loads less than 30kN.

3.59 In the serviceability limit state verification allowance shall be made for loss of stiffness in the material due to fatigue using a conversion factor of:

Equation 3.59 Conversion factor for fatigue (SLS)

$$\eta_{cf} = 0.9$$

3.60 For preliminary design a matrix cracking strain (SLS) limits shall be taken as:

1) 0.002 for polyester;
2) 0.003 for vinylester;
3) 0.004 for epoxy.

3.61 For detailed design, matrix strain limits shall be confirmed by testing where no previous testing information is available.

3.62 For ultimate limit state structures subject to cyclic variations, the fatigue effects resulting from cyclic loading shall be assessed.

NOTE *A cyclic load can be regarded as a constant amplitude load provided that the difference between the maximum and minimum values of the load amplitude does not exceed 10 %. Above that figure, the fatigue load is regarded as a variable amplitude load.*

3.62.1 In the case of a constant amplitude load, the fatigue life should be determined using the S-N line of the same material and of the fatigue load type under consideration, expressed as an R value.

3.62.2 The evaluation of fatigue with a variable amplitude load should be based on Miner's linear damage rule.

3.63 Stress concentrations, such as bolted or bonded attachments shall be reviewed to ensure they are located in areas where they are not subject to excessive dynamic loading, (where possible).

3.64 Where such details are subjected to dynamic loading they shall be included in the fatigue check.

3.65 A bonded unidirectional GFRP additional protective layer (APL) laid normal to the pultrusion direction shall be applied as a measure to reduce peak local stresses and extend the fatigue lives of pultruded decks.

NOTE 1 *The APL also protects the deck from damage during resurfacing.*

NOTE 2 *In estimating the static or fatigue life, finite element analysis can be performed using multiple solid elements through the deck webs, deck flanges, adhesive and overplates. Alternatively the test defined in Section 4 can applied to samples of the overplated deck.*

4. Testing and verification of design

General information

4.1 The wide variety of fibre and matrix types along with the multiple fibre arrangement possibilities makes FRP composites behave in a more complex way than conventional materials and testing shall be undertaken to verify material properties and confirm design adequacy.

NOTE FRP composites are inherently heterogeneous and as a result, they not only have a strong anisotropic behaviour but also predicting failure can be challenging.

4.2 The scope of testing and certification of material properties shall be undertaken following a simplified testing pyramid as suggested in the proceeding sections.

NOTE Historically the solution has been to focus on extensive experimental testing. The testing pyramid can be used to simplify this process.

Testing hierarchy and pyramid approach to material certification

4.3 Testing shall be carried out by an independent laboratory with UKAS accreditation or similar.

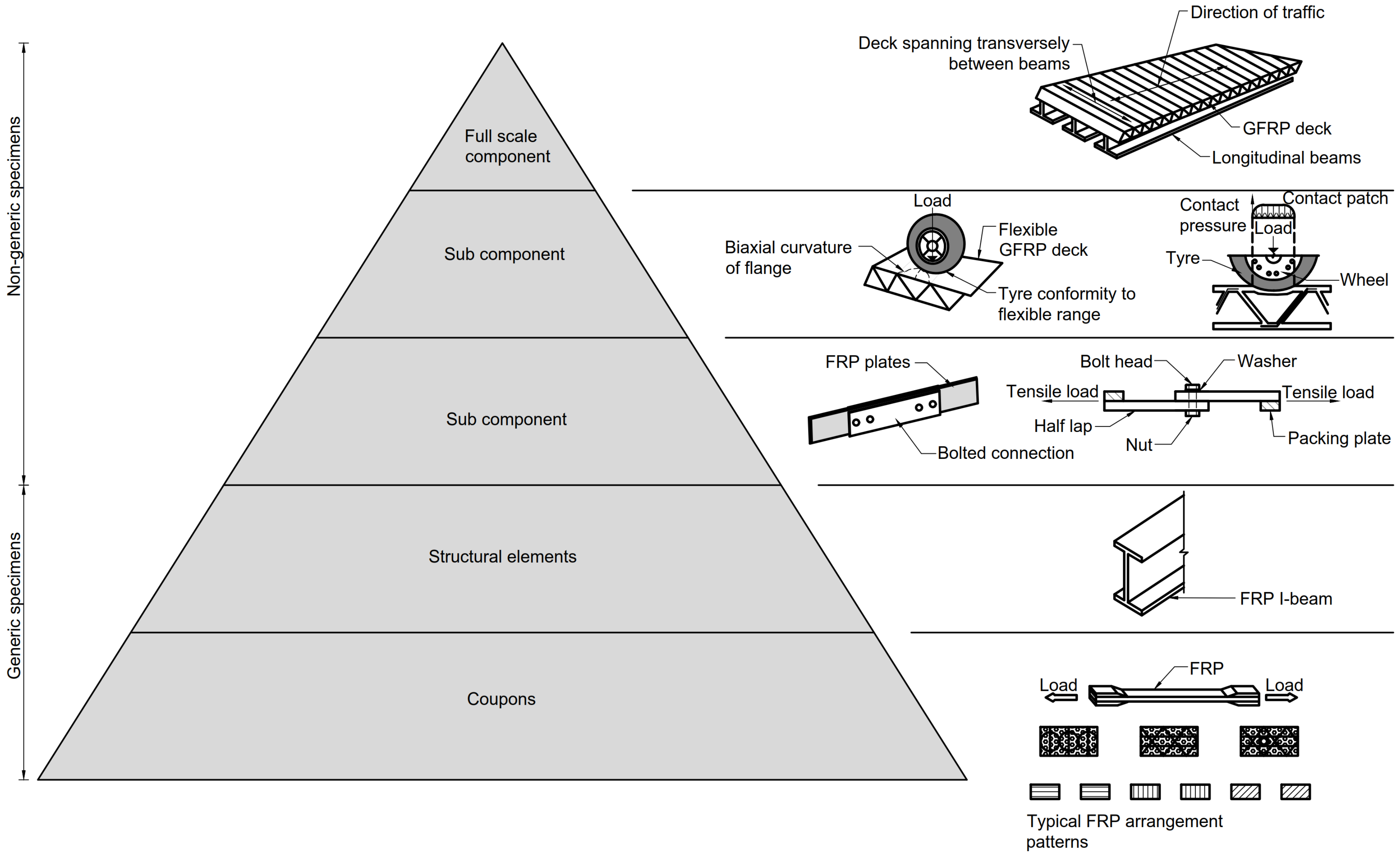
4.4 Tests on full-scale components and sub-assemblies including connections between components shall be undertaken to verify their structural adequacy and confirm the design data and assumptions.

4.5 Static load and fatigue tests shall be carried out for each new design of component or sub-assembly.

4.5.1 Where designs are re-used, (with no changes in the fibre and resin configuration), the design does not need to be retested and existing testing data may be used to verify the solution proposed.

4.6 Where the design or manufacturing process is changed significantly, components and sub-assemblies affected by the change shall be re-tested.

Figure 4.6 Rouchon pyramid of composites materials certification



4.7 Testing shall take the form of laboratory testing from small coupons to full scale static and fatigue tests on built structures.

4.7.1 Virtual testing may also be used to validate observations and calibrate load and analysis models with laboratory performance.

4.8 Testing shall be undertaken on FRP bridges to confirm:

1) material properties (for infusion in particular or pultrusions where the information from the manufacturer is limited);
2) connections methods and strengths (for connecting pultrusions and/or infused sections);
3) static load effects for all structures including foot and road bridges manufactured using both pultrusion and infusion processes;
4) fatigue load effects (from vehicle loading and/or any other critical cyclic load).

NOTE 1 Details of the individual tests required for FRP bridges to address the testing requirements are listed in the 'testing methods' subsection with the testing requirements highlighted for different types of structure.

NOTE 2 The volume of testing to be undertaken during design and manufacturing is to be agreed with the Overseeing Organisation and can be commensurate to the size and complexity of the solution being proposed.

Testing methods

Coupon testing for materials classification and durability

4.9 Coupons shall be tested for bridges manufactured using the resin infusion process and also for pultrusions where the sections do not conform to BS EN 13706 [Ref 11.N] as indicated in Table 4.15.

4.10 Samples of the proposed materials shall be tested to confirm the assumed design properties.

4.11 Tests shall be carried out prior to manufacture to inform the design process by confirming mechanical properties.

4.12 Additional tests (quality control) shall be undertaken during manufacture to confirm the mechanical properties have been achieved in the production.

4.13 The suppliers material properties for pultrusions shall confirm that the requirements of all parts of BS EN 13706 [Ref 11.N] are met.

4.14 Where conformance to the BS EN 13706 [Ref 11.N] (for pultrusions only) is not possible then additional testing shall be undertaken on samples obtained from the pultrusions to establish the relevant material properties.

4.14.1 The size of the test bodies should be adapted to the actual structural dimensions to avoid strong variations of the results.

4.14.2 Additional testing may include an assessment of fibre waviness as addressed in the paper on fibre waviness referenced in Section 8, Sebastian 2018 [Ref 1.I].

4.15 All tests shall be carried out to the standards and methods listed in Tables 4.15 and 4.16.

Table 4.15 Material classification tests

<table>
<tr><th>Property</th><th>ISO test method</th><th>ASTM test method</th></tr>
<tr><td>0º tensile modulus</td><td rowspan="4">ISO 527-4 [Ref 8.N]</td><td rowspan="4">ASTM D638 - 14 [Ref 25.N]</td></tr>
<tr><td>90º tensile modulus</td></tr>
<tr><td>0º tensile strength</td></tr>
<tr><td>90º tensile strength</td></tr>
<tr><td>0º compressive modulus</td><td rowspan="4">EN ISO 14126:1999 [Ref 5.N]</td><td rowspan="4">ASTM D6641 [Ref 22.N]</td></tr>
<tr><td>90º compressive modulus</td></tr>
<tr><td>0º compressive strength</td></tr>
<tr><td>90º compressive strength</td></tr>
<tr><td>0º pin-bearing strength</td><td rowspan="2">BS EN 13706-2 [Ref 12.N]</td><td rowspan="2">ASTM D953 [Ref 23.N]
ASTM D2247-15 [Ref 19.N]</td></tr>
<tr><td>90º pin-bearing strength</td></tr>
<tr><td>0º interlaminar shear strength</td><td rowspan="2">BS EN ISO 14130 [Ref 6.N]</td><td rowspan="2">ASTM D2344 [Ref 24.N]</td></tr>
<tr><td>90º interlaminar shear strength</td></tr>
<tr><td>Major Poisson's ratio</td><td rowspan="2">ISO 527-4 [Ref 8.N]</td><td rowspan="2">ASTM D638 - 14 [Ref 25.N]</td></tr>
<tr><td>Minor Poisson's ratio</td></tr>
</table>

NOTE *In the standards referenced in Table 4.15 there are geometric limitations to address, i.e. for the 0º tensile modulus test the ISO method limits section thickness to 10mm whilst the ASTM method has thickness restrictions of 14mm.*

4.16 Where proposed sections have a thickness greater than the values stipulated in the above test methods, the proposed departures from these test methods shall be highlighted and agreed in the AIP document submission, (refer to Appendix A, section A2).

4.16.1 Durability and weathering tests may be undertaken on coupons to understand the effect of environmental weathering of material properties.

NOTE *Table 4.16.1N highlights the relevant standards and test requirements addressing accelerated weathering.*

Table 4.16.1N Environmental durability test

Test	Reference standard	Test parameters	Test duration (hours)	Retained values (%)
Moisture resistance	ASTM D2247-15 [Ref 19.N] ASTM E104-02 [Ref 17.N]	Relative humidity: >=90% Temperature: 38 +- 2ºC	1000 3000	85 80
Salt water resistance	ASTM D1141-98 [Ref 20.N] ASTM C581 - 15 [Ref 14.N]	immersion at: 23 +-2ºC		
Alkali resistance	ASTM D7705-7705M [Ref 21.N]	immersion in a dilution with pH = 9.5 or larger; temperature 23 +- 2ºC		
Accelerated weathering (UV tests, moisture and heat)	ASTM D4329 [Ref 15.N], ASTM G154 - 16 [Ref 18.N], ASTM D4587 [Ref 16.N], ISO 4892 [Ref 9.N]	A QUV test chamber uses fluorescent lamps to provide a radiation spectrum centered in the ultraviolet wavelengths. Moisture is provided by forced condensation, and temperature is controlled by heaters. The standard sample holders can hold one sample 75 x 300 mm or two samples 75 x 1 50 mm.	Varies	

Static load tests - local wheel loads and maximum design loads

4.17 Static proof load tests shall be carried out assessing the local effects of wheel loads and global effects of maximum design loads on full scale components or partial sections of deck.

4.18 For road bridges the tests for local wheel loads shall consist of a 200 x 200mm patch load placed at 'worst case' locations.

4.19 The patch load shall be represented by a 30mm thick plate faced with a 12mm thick cork pad.

4.20 Static load tests shall also be undertaken with the maximum global design loads applied to the deck using weighed sand bags or by other means to simulate the global load effects.

4.21 The deflection and outer fibre stresses shall be recorded and compared to the theoretical values to verify the design assumptions and manufacturing process suitability.

4.22 The first test deck shall initially be loaded to 1.2 times the serviceability load, with deflection and strain recorded, then unloaded and re-loaded up to failure of the deck.

4.23 The test conditions and the number of tests shall be agreed within the technical approval process.

4.23.1 A minimum of one test per 50m² of deck area should be undertaken.

NOTE *The purpose is to verify the component characteristics and demonstrate that the 'as-built' deck has the load capacities and stiffnesses given in the design data supplied by the FRP designer.*

Maximum design loads on connections

4.24 Tests on materials, samples and processes (e.g. adhesive bonding) shall be undertaken to inform the design process prior to fabrication.

4.25 Tests on materials, samples and processes shall be carried out during fabrication/construction to ensure the quality of the materials and processes used (workmanship) are sufficient to ensure the assumed design strengths are achieved.

Fatigue tests

4.26 A single wheel load test to assess the fatigue strength shall be undertaken on all new roadway deck configurations, in accordance with the paper on wheel load tests referenced in Section 8, Sebastian et al 2017 [Ref 4.I].

4.27 The test shall identify all potential failure locations and determine the position of a single wheel, which produces the most severe effect at each location.

4.28 The component to be tested shall be supported in a manner that is similar to its intended service condition.

4.29 The test load shall be applied by a steel loading plate 200 mm x 200 mm square and at least 30 mm thick, faced with a 12 mm thick cork pad.

4.30 The cork pad shall be intermittently checked for fatigue degradation during the cyclic loading and if necessary replaced.

4.31 The fatigue test load shall be set to induce the required design bending moment or shear force.

4.32 The result of a fatigue test shall be deemed a 'pass' if 10^7 cycles are completed without detectable cracking or failure and the result of the following static test is within two standard deviations of the mean value of the maximum load, BM or SF achieved in the static tests.

4.32.1 Failure of deck may include defects such as the presence of visible cracks which could permit the ingress of moisture resulting in a reduction in the capacity of the member.

4.33 Where a 'pass' result is obtained in the fatigue tests, the value of the test load, BM or SF shall be used as the design fatigue capacity for the location(s).

NOTE The test is not required for repeat installations using the same configuration as structures already tested unless material and processing methods have changed.

Testing matrix

4.34 Tests shall be carried out pre-design, during fabrication and construction to ensure the quality of the materials and processes used (workmanship) are sufficient to ensure the assumed design strengths are achieved.

4.34.1 The matrix in Table 4.34.1 identifies testing which may be required for different forms of construction, subject to agreement of the Overseeing Organisation.

Table 4.34.1 Testing matrix

Bridge form	Full scale component test	Sub component test	Structural details	Structural elements	Coupons
Pultruded profile bridge	Global static load test on completed structure to verify performance.	Local static load tests on sub components such as roadway decking to simulate local effects such as wheel and tyre load.	Connections to be assessed (bonded, bolted and hybrids including steel beam to FRP deck interfaces) and also between pultrusions and other connected furniture (i.e. parapets).	Fatigue tests and tests to failure on structural elements (pultruded sections) required at proof of concept only (repeat tests not required for future structures) permitting the development of fatigue strengths and development of S-N curves to inform future designs.	Refer to BS EN 13706 [Ref 11.N] information if applicable and also refer to manufacturer's data for materials properties. Only test coupons where manufacturer's data is not available or is suspect and/or the profiles do not conform to BS EN 13706 [Ref 11.N]. Environmental durability tests to be undertaken where no manufacture information is available as per recommendations in Table 4.16.1N
Infused bridge	Global static loads tests on completed structures required, (all structures).	Fatigue tests and tests to failure on a representative section of deck/bridge required (proof of concept only - repeat tests not required).	Furniture connections to be assessed, (i.e. parapets).	Fatigue tests and tests to failure on a representative section of deck/bridge required (proof of concept only - repeat tests not required).	Undertake coupon testing for material classification including 'environmental durability tests' if there is no previous information available (for similar materials) as per recommendations in Table 4.16.1N.

Table 4.34.1 Testing matrix (continued)

Bridge form	Full scale component test	Sub component test	Structural details	Structural elements	Coupons
Steel beam and pultruded deck	Not required.	Global static laboratory load test on representative deck sample only required.	Connections to be tested (bonded, bolted and hybrids) between pultrusions and also for connected furniture (i.e. parapets).	Laboratory fatigue tests and tests to failure on a representative section of deck only required (if no previous tests have been undertaken). Proof of concept only - repeat tests not required.	Use manufacturer's data for materials classification and only test coupons where manufacturers data is not available or is suspect. Environmental durability tests to be undertaken where no manufacture information is available as per recommendations in Table 4.16.1N.
Steel beams and infused deck	Not required.	Global static laboratory load tests representative deck sample only required.	Furniture connections to be assessed, (i.e. parapets).	Laboratory fatigue tests and tests to failure on a representative section of deck/bridge required (proof of concept only - repeat tests not required).	Undertake coupon testing for material classification including 'environmental durability tests' if no previous information is available as per recommendations in Table 4.16.1N.
Other	Previous laboratory load tests on representative samples can be relied upon subject to the agreement of the Overseeing Organisation				

Design assisted by testing

4.35 Design assisted by testing shall be undertaken where uncertainty in the design exists to ensure long-term durability and robustness principles are adopted to target environmental effects.

4.36 Where required, the process for 'design assisted/supported by testing' given in Annex D of BS EN 1990 [Ref 3.N] shall be followed.

NOTE 'Design assisted by testing' aims to introduce new innovations into the sector including the use of new fibres such as Basalt, Flax plus Hybrid Fabrics and 3D fabrics.

5. Durability and detailing

Design for durability

Service environment

5.1 The resistance of the FRP material to the expected extreme in-service environmental conditions shall be verified by appropriate testing and/or back-up data.

NOTE The expected extreme in-service environmental conditions include water, alkalis, chlorides, ultra-violet light, chemicals (vehicle oil and fuel) and de-icing salts amongst others.

5.2 Information relating to resistance of the FRP materials with respects to the service environment suitability and conditions shall be provided within the AIP documentation, (refer to Appendix A).

Resistance to impact damage

5.3 Information shall be provided with the AIP documentation on the resilience and resistance of the relevant FRP components to impact damage including the design approach adopted and materials used to provide effective damage tolerance.

NOTE FRP can be susceptible to impact damage from vehicle accidents or falling loads.

Detailing

5.4 The performance of details such as connections, joints, protection methods and coatings of all FRP bridges shall be sufficient for the life cycle of the structure.

NOTE Detailing of FRP composite structures is one of the most important aspects in ensuring the long-term performance and durability.

5.5 For moulded structures using the resin infusion process, the fibre layups/orientation including stacking requirements and detailing at interfaces (corners and near connections) are key areas where quality controls shall be agreed with the Overseeing Organisation to cover the manufacturing process.

5.5.1 Typical quality controls may include the specification of non crimp fabrics and/or the use of additional reinforcement fibres at areas of high stress.

5.6 Connections shall be either bonded, bolted or a combination of both.

NOTE 1 For pultruded elements, the primary consideration relates to the design and detailing of the connections and interfaces.

NOTE 2 It is critical that the details of connections and interfaces are carefully worked up, designed and tested to ensure that they do not compromise the integrity of the overall structure.

5.7 The detailing of FRP members and connections the following aspects shall include:

1) protection of the end of the FRP units such as the use of grouted infill;
2) levelling of main beams for effective connection between main beams and roadway/decking units (dimension tolerance);
3) deck end connections and bearing use (fixed, free ends, tackling uplift);
4) parapet connections and the parapet replacement process in the event of an impact event;
5) application and configuration of the surfacing details including the use of additional protections layers and bond promoters.

5.8 In the design and detailing of connection and interfaces the analysis and detailing shall demonstrate there is sufficient longitudinal shear strength without causing local damage to the FRP components.

NOTE The longitudinal bond is of particular importance in specifying the surfacing. Insufficient bond strength can result in damage occurring to the FRP deck through cyclic actions.

Waterproofing

5.9 Waterproofing shall be provided to:

1) prevent water ingress/seepage through joints, thereby limiting environmental degradation (via mechanisms such as freeze/thaw);
2) promote bond with conventional surfacing.

5.10 The use of an additional protection layer (APL) formed with pultruded plates bonded to the upper surfaces of the deck shall be provided to:

1) act as a sacrificial layer, promoting bond between the FRP deck and surfacing (a gritted finish can also be provided);
2) provide additional distribution permitting reduction in high localised stresses from wheel loads;
3) protect the deck during future resurfacing operations.

NOTE 1 Whilst FRP as a material has good water resisting qualities with a very low water absorption rate, the management of water over the structure still is an important feature, especially for structures comprising bonded and bolted sections where ingress in and through joints is possible.

NOTE 2 Most waterproofing systems can bond well to the FRP sections and provide an effective bond to conventional surfacing materials thereby reducing the risk of bond failure between the surfacing and FRP deck.

Surfacing

5.11 Evidence regarding the surfacing and its interface with the FRP deck system shall be provided (laboratory test data, computer simulations and analysis outputs) to support the suitability of the proposed surfacing system.

NOTE Historic failures have resulted from fatigue failure from localised wheel loads. To overcome this the use of APLs is suggested to reduce the localised induced effects. Further information is included in the publication from CIRIA C779 [Ref 2.I].

5.12 Conventional surfacing solutions shall be used on all road overbridges with an allowance for APL to protect the FRP during future resurfacing and provide sufficient dispersal of high localised wheel loads through the pavement and into the FRP Deck.

NOTE The use of APLs such as bonding additional GFRP plates is recommended to:

1) improve load distribution;
2) act as an additional protection layer;
3) help improve bond.

5.13 The APL shall be a contrasting colour to help identification during future maintenance operations such as resurfacing.

5.14 For road bridges the surfacing shall be in accordance with CS 228 [Ref 13.N] and CD 236 [Ref 26.N], and in keeping with the existing pavement located either side of the bridge.

5.14.1 For footbridges thin surfacing materials (resin based solutions incorporating fine aggregate materials) may be used subject to testing.

5.15 The bond between roadway and surfacing shall be sufficient to prevent failure of the bond in service.

5.16 A tensile bond strength 1 N/mm² and a longitudinal shear strength greater than the shear strength of the surfacing shall be achieved.

5.17 The effects of differential thermal movement between surface course and FRP roadway shall be assessed.

5.18 Localised strains within the surfacing due to wheel loading and the resulting local deflection of the FRP deck shall be designed to avoid fatigue failure of the surfacing material and/or interface bond.

5.19 The temperature at which the surfacing material is laid shall be assessed to ensure that the FRP deck is not adversely affected.

5.20 Testing shall be undertaken to confirm the suitability of any surfacing proposals.

5.21 The testing shall review the lay temperatures and glass transition temperature effects in their proposals.

5.22 Bond tests shall also be undertaken to confirm suitability of the proposed systems with the FRP deck.

5.23 The use of non-contributory protection, APL, shall be used to protect the FRP deck.

NOTE The use of APLs can reduce the concerns about exceeding the glass transition temperatures through the application of hot laid bituminous surfacing and use of sacrificial layers (APLs) which help protect the main structural FRP deck.

5.24 The minimum recommended thickness of an APL shall be 10mm excluding bond lines.

NOTE The APL thickness can be fabricated using plates bonded together.

Parapets

5.25 The forces from parapet impact shall not result in irreparable damage to the FRP deck.

5.26 A combination of analysis, simulations and tests shall be used to model these effects.

5.26.1 Where an FRP deck is to be installed onto existing steel or concrete beams, the parapets may be attached directly to the beams provided that the beams have been assessed as capable of carrying the additional loads.

5.27 For high containment parapets, full-scale quasi-static testing shall be undertaken on the FRP deck-parapet connection.

Movement joints

5.28 The movement joints shall:

1) prevent leakage between deck end and abutment;
2) provide a smooth running surface over the gap and allow the level of the surface course adjacent to the deck and on the deck to be set equal, so that dynamic magnification of wheel loading is minimised;
3) bridge the gap at the ends of the deck/abutment interface.

5.29 The ends of any moulded FRP road bridge deck shall also be manufactured adopting stiff end plates to avoid issues relating to vehicle 'hammering' as a result of longitudinal loads at the deck ends.

5.30 Likewise the ends of the deck for modular construction using pultrusions shall be filled with a stiff material such as grout/resin to avoid similar issues from longitudinal deck loads.

Fire

5.31 The risk of fire damage shall be minimised through appropriate measures.

NOTE FRP structures pose no threat over and above that to be found in traditional bridges.

5.31.1 The use of fire retardant additives in the resin may be considered for critical structural components whose loss would result in disproportionate effects, as well as the use of fire protection plates with fire-retardant materials such as phenolic FRP plates, or the use of fire retardant coatings.

NOTE Actions for bridges are included in BS EN 1991-2 [Ref 2.N], however actions due to fire are not required for bridges unless enclosures are provided; hence the requirements of BS EN 1991-1 [Ref 1.N] govern as opposed to BS EN 1991-2 [Ref 2.N] where enclosures are provided.

5.32 Where utilising fire-retardant fillers in the resin, additional testing shall be undertaken to ensure the use of the filler is not compromising the strength and durability of the material.

5.33 FRP decks shall utilise long unidirectional fibres which maintain strength much longer than chopped fibres.

NOTE Due to the low thermal conductivity of FRP, fire damage where it occurs is likely to be localised.

Finishes

5.34 Surface finishes shall be applied to improve the long-term appearance, improve durability and aid performance of FRP bridges and other composite products.

5.35 The surface finish shall be free from defects and be smooth in appearance with a suitable surface finish applied to provide UV protection, additional corrosion resistance and aesthetics.

5.35.1 FRP composites may accept a wide range of surface finishes, including paints, gel coats, surface veils and adhesives.

NOTE Other surface finishes include aliphatic isocyanates, polyurethanes, polyesters, acrylics and epoxies. In some cases, fine sand can be added for additional protection and improved surface roughness where bonding operations require improved bond characteristics.

5.36 The FRP elements shall be protected from UV radiation.

5.36.1 Surface finishes may be applied to block UV radiation which can cause degradation of polymers and reduce the strength of the resin and in some cases even of the fibre reinforcement:

1) gel coats - a common surface finish for FRP composites is gel coat, a specifically formulated polyester resin that is applied to the mould surface prior to laminate build-up. Gel coats are used to improve weathering, filter out ultraviolet radiation, add flame resistance, provide a thermal barrier, improve chemical resistance, improve abrasion resistance, and provide a moisture barrier;
2) paints (including top coats and lacquers) - various paint systems are available for use with a palette of colours possible.

5.36.2 Other methods of finishes may include:

1) pigments - resins can be coloured through the addition of pigments. Pigments improve UV resistance however they are not as effective as surface coatings which provide a physical barrier;
2) surface veils with UV inhibitors - in some composite designs, a surface veil is used to provide an improved corrosion or weather barrier to the product. A surface veil is a fabric made from nylon or polyester that acts as a very thin sponge that can absorb resin to 90% of its volume. This helps to retain an extra layer of protective resin on the surface of the product;
3) use of UV resistant resin and/or the use of UV absorbers and additives.

NOTE 1 Gel coats are used to improve the product appearance and a unique benefit of gel coats is that they are supplied in many colours by the incorporation of pigments per the specification of the engineer.

NOTE 2 Surface veils are used to improve the surface appearance and ensure the presence of a corrosion resistance barrier for typical composites products such as pipes, tanks and other chemical process equipment. Other benefits include increased resistance to abrasion, UV and other weathering forces.

NOTE 3 The application of a surface protection coating is advisable. Alternatively, UV absorbers can be specified.

NOTE 4 Surface finishes are used for both aesthetics and protection, and they can be specified and applied in a number of forms. Some notable characteristics include:

1) can be applied to the internal surfaces of the mould or be applied (painted/sprayed) as post-manufacture coatings;
2) bond promoters can be used to improve the bond between FRP composites materials and coatings;
3) veils can be used in conjunction with gel coats to provide reinforcement to the resin;
4) for applications where toughness is needed, urethane paints can be used.

6. Execution of FRP bridges

Fabrication

General

6.1 Manufacturing of the bridge shall be undertaken offsite in a controlled environment.

6.2 All cut surfaces (including drilled holes) shall be sealed with resin to protect against weathering.

Adhesive bonding

6.3 Adhesives shall be structural (such as epoxy), compatible with the materials to be joined and suitable for the intended service environment.

6.4 Surface preparation shall be undertaken in accordance with the manufacturer's information and surface treatments used to help promote bond and improve the adhesion characteristic of joints within FRP components.

6.5 Additional testing shall be carried out where site bonding is undertaken to ensure the design strengths are achieved.

6.6 Where site bonding activities are required a covered 'tented' area with appropriate environmental controls shall be provided to permit the outstanding assembly to be undertaken in a controlled environment with controls on temperature and humidity in place.

6.6.1 Site bonding is permitted, although it should be avoided where alternative solutions are possible to ensure fabrication quality control is maximised.

7. Normative references

The following documents, in whole or in part, are normative references for this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

Ref 1.N	BSI. BS EN 1991-1, 'Eurocode 1- Actions on Structures'
Ref 2.N	BSI. BS EN 1991-2, 'Eurocode 1. Actions on structures. Traffic loads on bridges'
Ref 3.N	BSI. BS EN 1990, 'Eurocode: Basis of structural design'
Ref 4.N	BSI. BS EN 1991, 'Eurocode 1: Actions on structures'
Ref 5.N	ISO. Technical Committee: ISO/TC 61/SC 13 Composites and reinforcement fibres. EN ISO 14126:1999, 'Fibre-reinforced plastic composites -- Determination of compressive properties in the in-plane direction'
Ref 6.N	BSI. BS EN ISO 14130, 'Fibre-reinforced plastic composites. Determination of apparent interlaminar shear strength by short-beam method'
Ref 7.N	Highways England. GG 101, 'Introduction to the Design Manual for Roads and Bridges'
Ref 8.N	ISO. Technical Committee: ISO/TC 61/SC 13 Composites and reinforcement fibres . ISO 527-4, 'Plastics -- Determination of tensile properties -- Part 4: Test conditions for isotropic and orthotropic fibre-reinforced plastic composites'
Ref 9.N	ISO. Technical Committee: ISO/TC 61/SC 6 . ISO 4892, 'Plastics – Methods of exposure to laboratory light sources'
Ref 10.N	BSI. PD 6688-2, 'Recommendations for the design of structures to BS EN 1991-2'
Ref 11.N	BS EN 13706, 'Reinforced plastics composites. Specifications for pultruded profiles. Method of test and general requirements'
Ref 12.N	BSI. BS EN 13706-2, 'Reinforced plastics composites. Specifications for pultruded profiles. Method of test and general requirements'
Ref 13.N	Highways England. CS 228, 'Skidding resistance'
Ref 14.N	ASTM. ASTM C581 Subcommittee: D20.23. ASTM C581 - 15 , 'Standard Practice for Determining Chemical Resistance of Thermosetting Resins Used in Glass-Fiber-Reinforced Structures Intended for Liquid Service'
Ref 15.N	ASTM. ASTM D4329 Subcommittee: D20.50. ASTM D4329, 'Standard Practice for Fluorescent Ultraviolet (UV) Lamp Apparatus Exposure of Plastics'
Ref 16.N	ASTM. ASTM D4587 Subcommittee: D01.27. ASTM D4587, 'Standard Practice for Fluorescent UV-Condensation Exposures of Paint and Related Coatings'
Ref 17.N	ASTM. ASTM E104 Subcommittee: D22.11. ASTM E104-02, 'Standard Practice for Maintaining Constant Relative Humidity by Means of Aqueous Solutions'
Ref 18.N	ASTM. ASTM G154 Subcommittee: G03.03. ASTM G154 - 16 , 'Standard Practice for Operating Fluorescent Ultraviolet (UV) Lamp Apparatus for Exposure of Nonmetallic Materials'
Ref 19.N	ASTM. ASTM D2247 Subcommittee: D01.27. ASTM D2247-15, 'Standard Practice for Testing Water Resistance of Coatings in 100 % Relative Humidity'
Ref 20.N	ASTM. ASTM D1141 Subcommittee: D19.02. ASTM D1141-98, 'Standard Practice for the Preparation of Substitute Ocean Water'

Ref 21.N	ASTM. ASTM D7705 / D7705M Subcommittee: D30.10. ASTM D7705-7705M, 'Standard Test Method for Alkali Resistance of Fiber Reinforced Polymer (FRP) Matrix Composite Bars used in Concrete Construction'
Ref 22.N	ASTM. ASTM D6641 / D6641M Subcommittee: D30.04. ASTM D6641, 'Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials Using a Combined Loading Compression (CLC) Test Fixture'
Ref 23.N	ASTM. ASTM D953 Subcommittee: D20.18. ASTM D953 , 'Standard Test Method for Pin-Bearing Strength of Plastics'
Ref 24.N	ASTM. ASTM D2344 / D2344M Subcommittee: D30.04. ASTM D2344, 'Standard Test Method for Short-Beam Strength of Polymer Matrix Composite Materials and Their Laminates'
Ref 25.N	ASTM. ASTM D638 Subcommittee: D20.10. ASTM D638 - 14 , 'Standard Test Method for Tensile Properties of Plastics'
Ref 26.N	Highways England. CD 236, 'Surface course materials for construction'

8. Informative references

The following documents are informative references for this document and provide supporting information.

Ref 1.I	Sebastian W M. 2018. Sebastian 2018, 'Fibre waviness in pultruded bridge deck profiles : Geometric characterisation and consequences on ultimate behaviour, Composites Part B: Engineering, Vol. 146, 270-280'
Ref 2.I	CIRIA. J T Mottram and J G Henderson. CIRIA C779, 'FRP Bridges:Guidance for Designers'
Ref 3.I	CUR96, 'FRP Composites Structures'
Ref 4.I	Sebastian W M, Ralph M, Poulton M, Goacher J. 2017. Sebastian et al 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, 100-122'
Ref 5.I	JRC Science and Policy Report. EUR 27666 EN, 'Prospect for the new guidance in the design of FRP'
Ref 6.I	J.L.Clark. Clark 1996, 'Structural Design of Polymer Composites, Eurocomp Design Guide and Handbook 1996'

Appendix A. Approval in principle for FRP bridges

A1 General information

There are a number of additional aspects that need to be agreed in the development of FRP bridge designs over and above those provided in the standard AIP template.

Hence, a number of additional clauses are listed below to add to the AIP template for use in the design approval of FRP bridge. The inclusion of these details can improve the level of detail therein aiding the design and approval process with increased clarity of requirements.

A2 AIP additions for FRP bridges

The following additional clauses are to be added to the AIP submission as highlighted below:

1) Construction/Structural Details: Minimum proposed laminate thicknesses to be stated and connection methods;
2) Parapet Fixings: Methods of attachment of parapets and options for replacement to be stated;
3) Surfacing Details: Surfacing proposals to be highlighted together with strategy for maintenance and replacement;
4) Hidden Areas: Inspection of hidden areas to be provided, proposed mitigation where access is not available, (i.e. additional redundancy);
5) Durability and Resilience: Measures to be identified such as coatings and additional protection measures, sacrificial laminate thickness and additional redundancy. In addition to this any resistance of the materials to the intended service environment to be highlighted in this section;
6) Constituent Materials: Details of resins, fibres, core materials, adhesives including the use of any additives and surfacing agents;
7) Materials Processing: Proposed composite processing methods to be highlighted including initial cure temperature, post cure time and temperatures;
8) Design Properties: Assumed post manufacture design properties;
9) Consultation with Manufacturers: Details of any manufacturer discussions to be listed here including any specific requirements;
10) Proposed Testing: To include details of testing proposals including static load, fatigue testing, full scale testing, connections, component and sub-component tests, coupons, tests to destruction and accelerated weathering tests;
11) Testing Standards: Standards used and to be followed for testing including amendments and departures from these standards;
12) Proposed Software: Details of software to be used including revisions;
13) Stiffness Matrix: Adopted stiffness matrix size for use in all modelling to be quantified.

A3 Composites processing Information

A3.1 Pultrusion

Pultrusion is a process used to create an FRP component such as a beam by drawing resin-coated fibres through a heated die. As opposed to extrusion, which pushes the material, pultrusion works by pulling the material. Typical characteristics defining pultrusion are their higher material strengths in the longitudinal direction and a lower strength in transverse direction due to the limited transverse fibres. Designs using pultrusions therefore require a much greater focus on how connections are made and designed. The detailing and subsequent testing of these connections is a key design consideration to ensure an efficient and effective design is promoted. Workmanship is also a key aspect of connection strength and efficiency requiring attention.

A3.2 Infusion

Resin Infusion is a process by which vacuum draws resin into a dry fibre laminate in a one (or sometimes two) sided mould. For single sided moulds, a rigid or flexible film membrane is placed over the top and sealed around the mould periphery with a vacuum used to pull resin through the fibre layups. Resin infusion permits bespoke fibre layups to be installed permitting the customisation of the properties of the FRP component which is not possible for pultrusions. This permits areas of high stress to receive additional reinforcement in the orientation required. Most moulded bridges are 'infused' in a single operation with no joints thereby negating the issues of connection design and testing common with the use of pultrusions. However, classifying and understanding the material properties through design, simulation and testing is one of the key focus areas to be addressed in designing bespoke moulded components.