
**VOLUME 1 HIGHWAY STRUCTURES:
APPROVAL PROCEDURES
AND GENERAL DESIGN**

SECTION 3 GENERAL DESIGN

PART 17

BD 90/05

**DESIGN OF FRP BRIDGES AND
HIGHWAY STRUCTURES**

SUMMARY

This Departmental Standard gives the requirements for the design of highway bridge and structures using Fibre Reinforced Polymer materials.

INSTRUCTIONS FOR USE

This is a new document to be incorporated into the Manual.

1. Remove Contents pages for Volume 1.
2. Insert New Contents pages for Volume 1 dated May 2005.
3. Insert BD 90/05 into Volume 1, Section 3, Part 17.
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**THE DEPARTMENT FOR REGIONAL DEVELOPMENT
NORTHERN IRELAND**

Design of FRP Bridges and Highway Structures

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REGISTRATION OF AMENDMENTS

Amend No	Page No	Signature & Date of incorporation of amendments	Amend No	Page No	Signature & Date of incorporation of amendments

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1. INTRODUCTION

Background

1.1 Highway structures built with steel and concrete are designed by Engineers using Design Codes and Product Standards which set limits on the manufacturing process and specify approval tests to ensure that the finished product meets the required material properties. Fibre Reinforced Polymer (FRP) products for use in highway structures are not currently supported by Product Standards. There are many standards for FRP materials, but few are directly applicable to highway structures. In addition, suppliers' data sheets and design guides, similar to those provided by steel and concrete producers, are just beginning to appear.

1.2 Limit State principles as set out in BS 5400: Part 1, with suitable amendments, can be used to design highway structures in which main members are made from FRP materials. This Standard gives guidance and additional/amended requirements for the technical approval of highway structures schemes utilising FRP. As far as possible, it is a performance standard, within broad limits on permitted materials and manufacturing processes. It is intended to be relevant to as wide a range of FRP systems as possible, and not to restrict future developments in materials, manufacturing processes and innovative forms of construction.

Applications

1.3 In the early stages, FRP decks are likely to be used in combination with conventional materials. FRP may provide an effective solution in cases where the advantages of light weight, rapid construction and corrosion resistance outweigh the additional material cost. These could include design of new bridges, replacement of under-strength decks in existing bridges, and provision of running surfaces over soft ground.

1.4 Examples of potential applications are:

- a) a new or replacement bridge with an FRP roadway supported by FRP, steel or concrete main members (i.e. longitudinal beams). This may be particularly beneficial in road widening and at congested sites where an FRP deck could be assembled and then lifted into place rapidly with a mobile crane, minimising installation and traffic delay costs;
- b) replacing a concrete deck with an FRP roadway. This would free up additional live load capacity in an under-strength bridge;
- c) sites with restrictions or difficult ground conditions where an FRP bridge would minimise substructure works and costs;
- d) locations where conditions are particularly severe, for example, in marine environments or where application of de-icing salt is high.

Scope

1.5 This standard presents the requirements for the design of highway bridges and structures and for re-decking existing bridges using structural members made of FRP materials. It is intended to enable bridge designers with knowledge of FRP materials, but without specialist expertise or facilities for analysis at the material science level, to design an FRP bridge or highway structure using standard components validated and supplied by others.

1.6 'Bespoke' solutions are also permitted in which FRP materials are designed specifically for an individual structure. In this case, the bridge designer would have to have specialist expertise to design FRP structures at material science level and verify their structural adequacy by testing according to the requirements of this Standard.

1.7 The following parts of a highway bridge or structure are included in this Standard:

- a) **Roadway.** The part of the bridge deck forming the carriageway and transferring wheel loads to the supporting members. It is assumed that the roadway would consist of top and bottom flanges, separated by a core of FRP webs or a filler material; Figure 2 shows some typical examples;
- b) **Supporting members.** The remaining part of the bridge deck, consisting of the main structural members (usually longitudinal beams) that support the roadway and transfer loads to piers or abutments. Note: the supporting members may be FRP, steel, concrete, or a combination of these;

- c) **Connections** between the roadway and supporting members;
- d) **Surfacing system.** The surface course, including waterproofing if required, and anti-skid running surface;
- e) **Joints.** Structural joints between sections of roadway or supporting members;
- f) **Parapet anchorage.** Requirements for bridge parapets are given elsewhere: only the anchorage is covered in this standard;
- g) **Ancillaries:** kerbs, footways, drainage, service ducts, anchorage of street furniture (lighting columns, signs, etc).

Roles and Responsibilities

1.8 The design and approval process is summarised in Figure 1. The process may be divided into:

- a) Analysis and design of FRP components at material science level, specification and procurement;
- b) Verification and validation of component properties by full-scale tests;
- c) Supply of components and supporting design information;
- d) Design and check of a bridge deck or highway structure using components with defined properties;
- e) Technical approval, construction and maintenance of the structure.

1.9 The roles and responsibilities are separated and defined so that FRP bridge design is accessible to engineers without specialist expertise. They are as follows.

The **FRP designer** is an experienced engineer with specialist knowledge of FRP materials and design methods as well as experience relevant to structural design. The FRP designer is responsible to the Bridge designer for:

- a) Design of FRP components at a material science level;
- b) Production of a specification and advice on the procurement of components from an FRP manufacturer or supplier;
- c) Verification of the structural properties of the components in relation to the specification and provision of design data.

The **Bridge designer** is an experienced chartered engineer with knowledge of the properties of FRP materials relevant to structural design but no specialist expertise at the material science level. The bridge designer may rely on the use of standard components, the properties of which are supplied by the FRP designer. The bridge designer has overall responsibility for the structural adequacy of the bridge or highway structure.

The **Supplier** is usually a specialist FRP producer. The Supplier's role is to produce components, sub-assemblies and ancillary items, together with quality control test data and certification to meet the specifications provided by the FRP designer.

The **Contractor** is employed to, through liaising with the FRP designer, procure FRP components from an FRP manufacturer or supplier and shall assemble FRP components and other materials supplied to site and to build the bridge or highway structure, and shall therefore be experienced in assembling FRP components or sub-contract this activity to a specialist. The Contractor's responsibilities include storage and handling of materials and provision of a method statement for all critical processes. In other respects, the contractor's responsibilities are similar to those for a conventional bridge or highway structure. They shall be clearly defined in the contract.

1.10 It is anticipated that the FRP design and the bridge design shall be carried out by the same company or Group, or by separate companies with a formal contractual agreement. Whatever arrangement is in place, the design team shall either include an engineer with sufficient experience of designing FRP structures, or have access to specialist advice.

1.11 It shall be necessary to carry out an independent check (Category II or Category III) of the design. The Overseeing Organisation shall decide what level of checking is required on a case-by-case basis.

1.12 Construction of an FRP bridge deck requires specialist expertise and training. Careful attention shall be paid to the selection of a contractor able to demonstrate (a) relevant experience and (b) a workforce with appropriate training and skills.

Implementation

1.13 This Standard shall be used for the design of FRP highway structures and components.

Feedback

1.14 Feedback on the use of this Standard shall be provided in accordance with HD34, the Implementation and Use of the Standard Improvement System. (DMRB 5.3.1)

Abbreviations

1.15 The following abbreviations are used in this standard:

BS 5400: Part *x* means BS 5400: Part *x* as implemented by the relevant HA standard (BD).

Definitions

Adhesive:	A polymeric material capable of bonding two materials together.
Aramid fibre:	A high strength, long-chain, aromatic polyamide synthetic fibre.
Bond:	The adhesion of one surface to another using a high strength adhesive or other bonding agent.
Carbon fibre:	High strength, high modulus fibres produced from organic materials such as rayon, polyacrylonitrile (PAN) or pitch. The term is often used interchangeably with “graphite”.
Composite:	Or advanced composite. Alternative term for FRP, i.e. fibres plus resin to produce specific performance properties.
Fabric:	Fibres woven into a fabric. Fibres can be aligned in any direction, with 0°, 45° and 90° being the most common.

FRP:	Fibre reinforced polymer comprising high strength fibres in a resin matrix.
FRP properties:	Properties of the completed laminate or structural section, or part section such as web or flange.
Glass fibre:	A fibre spun from an inorganic product of fusion that has cooled to a rigid condition without crystallising.
Hand layup:	A process in which resin and reinforcement are applied manually either to a mould or to a working surface in a number of successive layers.
Laminate:	A composite material consisting of one or more layers of fibres impregnated in a resin system and cured.
Prepreg:	Fibres, fabrics or mats impregnated with resin and attached to a backing paper or plastic release film in flat form that can be stored for later use in moulds or for hand lay-up.
Pultrusion:	A semi-continuous factory method for manufacturing FRP laminates of constant section in long lengths. Sections currently available include plates, rods, I, T, angle sections etc and special profiles.
Resin:	A polymer which may exist in solid, semi-solid or liquid state. A resin matrix is used to impregnate the fibres and bind filaments, fibres and layers of fibre together.
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.
Voids:	Air bubbles trapped in the resin or between the FRP and parent substrate.
Wet layup:	A method of installing FRP by hand. The laminates are produced by impregnating layers of fibres or mats by applying a liquid resin system to them as they are laid up.

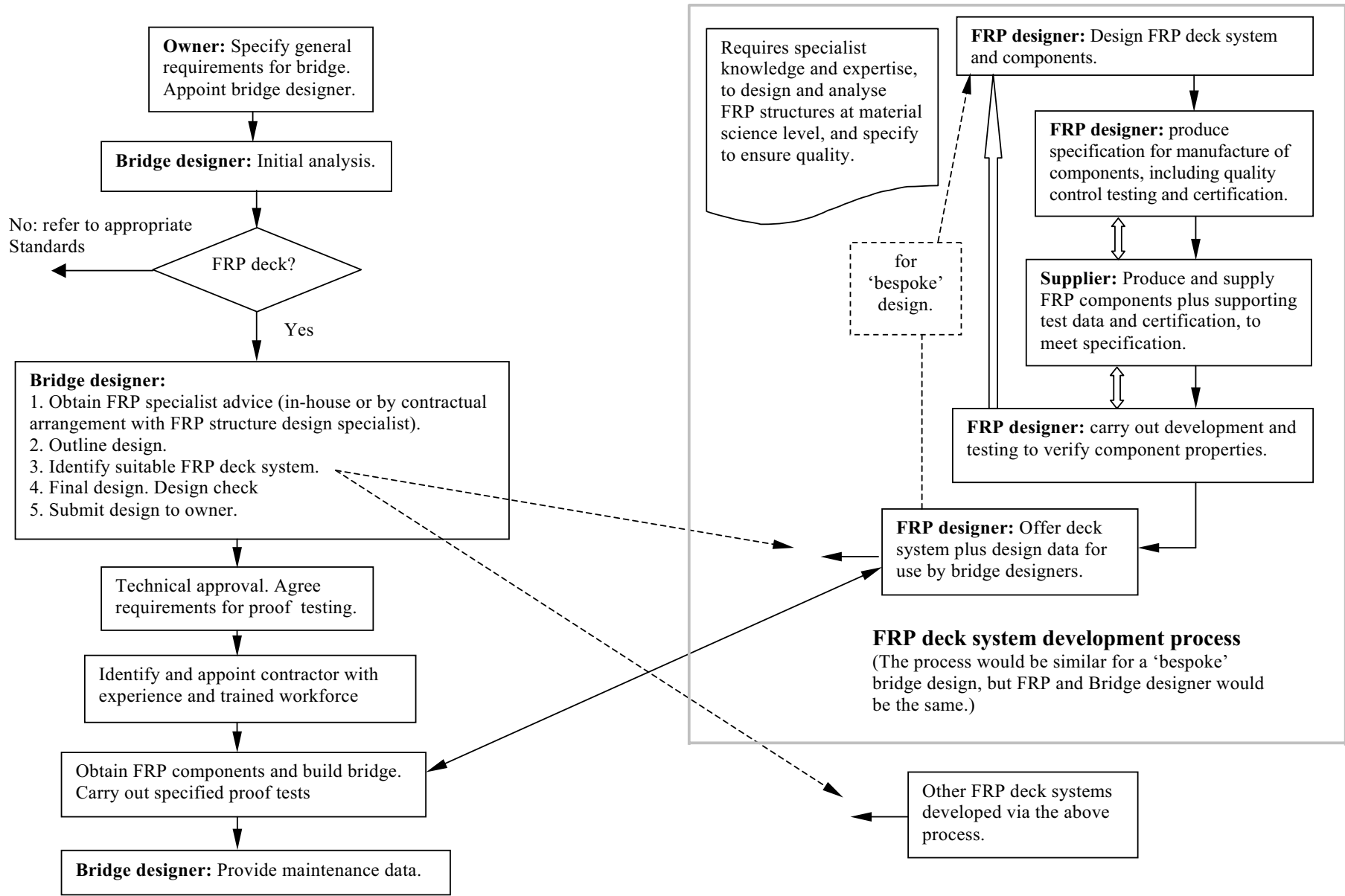


Figure 1 Summary of FRP bridge deck procurement process

2. COMPONENTS AND SUB-ASSEMBLIES

General

2.1 FRP bridge decks or highway structures covered by this standard may be made up of closed or open sections bonded and/or bolted together, or by sections of deck produced as a single piece. These components or sub-assemblies are likely to be transported to site for final assembly and erection, so that site joints and ancillary components will be required.

2.2 Figure 2 shows sketches of typical forms of FRP bridge systems. These are examples only, to illustrate a few of the possible types of FRP components which may be used in bridge decks.

Materials

2.3 The requirements for materials used in FRP bridge decks are consistency and a level of defects which does not compromise the specified component properties during the design life of the deck.

2.4 The materials used must be suitable for the intended service environment, e.g. temperature range, exposure to moisture, alkalis from concrete, de-icing salts, chemicals etc. General guidance is given in BS 5400, but site-specific requirements shall be defined by the bridge designer. It is the responsibility of the Supplier to provide assurance supported by test data that the components supplied will resist the specified environmental effects having regard to the design life, to the satisfaction of the designer. Note; specific tests or generic test data for the relevant materials may be offered as evidence of compliance.

2.5 Materials shall comply with the following categories:

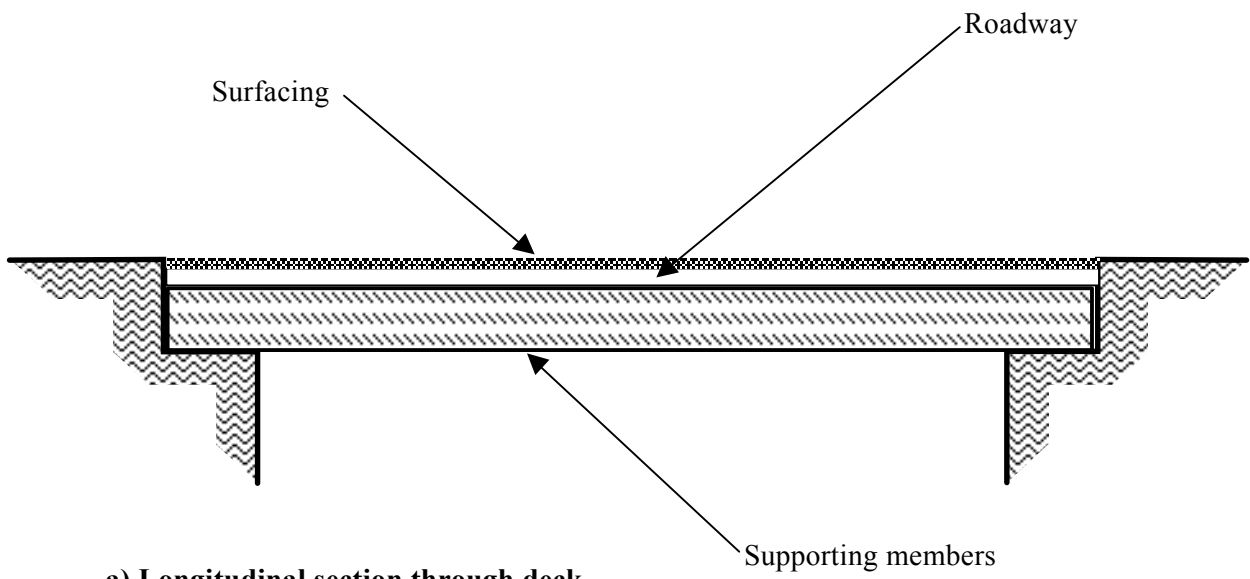
- a) Components/sections shall be manufactured by an established process. Examples of processes currently known to be suitable are pultrusion, filament winding, resin infusion, resin transfer moulding, pre-preg moulding and hand lay-up.
- b) Fibres used in structural components shall be glass, aramid or carbon. Within these categories, the type of fibre must be suitable for its intended service environment. New fibres may be permitted in future by means of amendments.

- c) Resin shall be polyester, vinyl ester or epoxy. Within these categories, the resin must be suitable for its intended service environment. Careful formulation of the resin is required to achieve all of the required properties and ensure long-term durability and robustness against environmental and other load effects, which may occur over its service life.
- d) Adhesives shall be structural (such as epoxy) and compatible with the materials to be joined and suitable for the intended service environment.

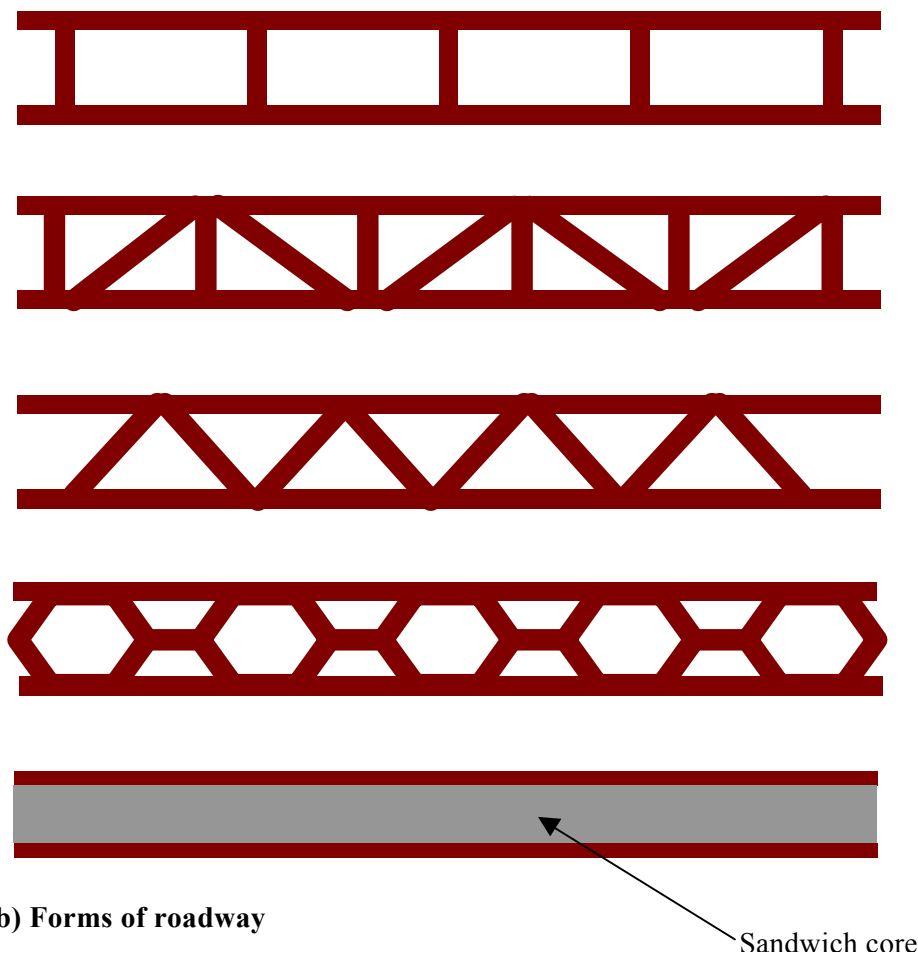
Verification of Properties

2.6 Tests shall be carried out on FRP materials and components which are intended for use in bridges and highway structures designed to this Standard. The following tests shall be carried out:

- a) Tests on constituent materials and small samples of FRP laminates (coupons). These are to ensure that the materials supplied by the FRP supplier meet the specification provided. Specification and interpretation of these tests are outside the scope of this Standard. The FRP designer shall specify suitable tests to ensure that the components provided by the supplier comply with the specification for manufacture.
- b) Tests on full-scale components and sub-assemblies including connections between components, to verify their structural adequacy and support the design data produced by the FRP designer. These tests shall be carried out for each new design of component or sub-assembly. If the design or manufacturing process is changed significantly, components and sub-assemblies affected by the change shall be re-tested. (Note: these tests are carried out once for each FRP deck system, not for each bridge on which the system is used. A 'bespoke' design must be tested each time it is used.) The FRP designer shall have these tests carried out by an independent laboratory and have UKAS accreditation. As an alternative to UKAS accreditation, an independent inspector shall be appointed to oversee the tests. Copies of the results shall be passed to the bridge designer, the Overseeing Organisation and the owner's representative. The tests shall comply with Annex A of this Standard.



a) Longitudinal section through deck



b) Forms of roadway

Sandwich core

Figures 2. Typical cross-sections of FRP roadway

- c) Tests on materials, samples and processes (e.g. adhesive bonding) during construction to ensure the quality of the materials and processes used to build the bridge or highway structure. These tests shall be agreed between the bridge designer and FRP designer. They shall be included in the contract and relevant method statements and be subject to the agreement of the Overseeing Organisation.
- d) Static proof load tests on components or sections of deck supplied for a particular bridge. The tests shall consist of a 200 x 200mm patch load placed at a typical 'worst case' location on the component. The purpose is to verify the material and FRP component connection characteristics, and demonstrate that the 'as-built' deck has the load capacities and stiffnesses given in the design data supplied by the FRP designer. The test conditions and the number of tests shall be agreed between the bridge designer and the Overseeing Organisation in consultation with the FRP designer. A minimum of one test per 50m² of deck area will generally be required. 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. Subsequent tests shall be carried out to 1.2 times the serviceability load.
- 2.8 Resistance to local loading at locations offered for such loading by the FRP designer or supplier, e.g. pull-out of bolts, grout plugs, shear keys, etc, and reductions in component properties and limitations on the placing of holes shall be included.
- 2.9 The temperature range over which the specified properties are achieved shall be stated. The temperature range shall exceed the full range of service temperatures for a UK highway bridge, as specified in BD 37 (DMRB 1.3.14).
- 2.10 Durability data, including chemical and UV resistance, uptake of moisture, resistance to freeze/thaw and de-icing salts, mechanical impact of the FRP/resins being used in the structural member shall be provided by the FRP designer. (Note: Durability data may be supported by specific tests or by previously existing test data).
- 2.11 The bridge designer shall ensure that the temperature and durability data are taken into account in setting the design values for component properties. The partial factors shall not be relied upon to take account of known degradation of material properties (Note: the partial factors take account of variability and unknown effects).

Provision of Design Data

2.7 Design data shall be made available by the FRP designer in a form suitable for use by a bridge designer who is not an FRP specialist. The data shall be 'design values' which are the lower 95% confidence limit of the test data. Properties of any connections, anchorages and other ancillary components offered by the FRP designer shall be included. The data provided shall include:

- a) load capacities, e.g. bending moment and shear, of components for global and local loading;
- b) stiffness, e.g. load-deflection curves;
- c) reduction in strength and stiffness under long term loading;
- d) fatigue strength for each component or critical detail.

3. OVERVIEW OF DESIGN

Design Philosophy

3.1 The philosophy to be adopted in the design of FRP bridge or highway structures and components is as stated in BS 5400: Part 1. The objective is to verify structural adequacy at the defined ultimate and serviceability limit states. However, the material characteristics of FRP are fundamentally different from those of steel or concrete and this needs to be taken into account in the design procedure. This section is intended to give general design advice on the structural use of FRP in bridges and how it differs from that of the more traditional construction materials.

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. The structure shall be designed to support loads caused by normal function, but there should be a reasonable probability that it will not collapse or suffer disproportionate damage under the effects of misuse or accident (Clause 3.4 of BS 5400: Part 1).

3.3 In general, currently available FRP materials and components used for bridge decks or highway structures have high strength and low stiffness compared to steel. Therefore design may be governed by deflection rather than stress and by Serviceability rather than Ultimate limit states, to a greater extent than for conventional designs.

3.4 The ratio of maximum design stress to ultimate stress will be smaller for FRP than for steel. For example BS 5400: Part 4 places a Serviceability limit of $0.75f_y$ on steel reinforcement for dead load and/or live load stresses. The limit on FRP is lower for several reasons:

- a) FRP materials are brittle in the sense of being linear elastic to failure: this does not necessarily mean that the structure will fail in a brittle manner but it does suggest that re-distribution of load may not occur to the same extent as in steel and reinforced or pre-stressed concrete structures. However, cracking and excessive local deformations may occur before failure and some limited load capacity may remain after failure.
- b) Creep and/or stress rupture reduce the capacity of some fibres and resins under long-term sustained load.

- c) FRP materials are relatively new in the service environment found on highway bridges, so there is greater uncertainty over their long-term behaviour.

It shall be necessary to reduce the mechanical properties by gamma (material) factors for strength and stiffness, which are given in section 4.5.

3.5 If the FRP roadway is designed to act compositely with the supporting members then the designer must ensure through appropriate analysis and detailing that the connections provide sufficient longitudinal shear strength without causing local damage to the FRP components. It shall also be necessary to provide data to show the long-term behaviour of the connections are not compromised due to fatigue or environmental loading.

Material Characteristics

3.6 The bridge designer should be aware of the differences between FRP and other, more familiar, construction materials. Some of these differences affect the behaviour of the finished structure, while others affect construction. The main differences are:

- a) Light weight, permitting different handling, assembly and transport methods.
- b) FRP materials are generally linear elastic up to failure and do not behave in a ductile manner, like steel. Non-linear analysis methods such as yield-line and moment re-distribution shall not be used.
- c) The properties of FRP materials depend on the direction being considered and are a function of the amount and strength of fibres in that direction. Those which are mainly uni-directional will have very low transverse properties.
- d) The effect of local stress concentrations is different from that in steel and concrete due to the lower ductility of FRP. Hence, the effect of attachments, joints, holes, etc, will be different. The bridge designer should consider these effects in relation to the applied loading.

- e) Special attention shall be paid to the design of bearings, movement joints, parapets, kerbs, signs and lighting, provision for services, etc. in order to limit local stress concentrations.
- f) Special attention shall be paid to loads that do not act in the principal fibre directions of the material.
- g) The lower modulus of some FRP materials compared to steel results in larger displacements and dynamic effects. In addition, buckling capacity is more likely to be critical than in steel structures.
- h) Serviceability loading may be limited by deflection rather than stress, so working stress levels relative to ultimate, are likely to be lower than for steel.
- i) Modes of failure may be different. Damage can accumulate at a microscopic level with very little overall change being apparent.
- 3.7 Table 1 presents indicative values of material properties: strength, modulus, density and strain to failure of fibres and resins. Values of material properties of the FRP (fibres and resins combined) used in the design shall be specified by the FRP Designer and verified to a 95% confidence limit.

Fibre Type	Tensile Strength (MPa)	Elastic Modulus (GPa)	Elongation (%) at Failure	Density (kg/m ³)
Carbon: High Strength	3500 - 4800	220 - 240	1.6 - 2.0	1740 - 2200
Carbon: High Modulus	2700 - 4000	300 - 350	0.9 - 1.14	1740 - 2200
Carbon: Ultra High Modulus	2100 - 2500	540 - 640	0.39 - 0.4	1740 - 2200
Aramid: Low Modulus	3500 - 4100	70 - 80	5.0 - 5.1	1390 - 1470
Aramid: High Modulus	3500 - 4000	115 - 130	3.0 - 3.1	1390 - 1470
Glass: E	2000 - 3000	70	2.9 - 4.3	2460 - 2580
Glass: S	3500 - 4800	85 - 90	4.1 - 5.3	2460 - 2580
Resin Type	Tensile Strength (MPa)	Elastic Modulus (GPa)	Elongation (%) at Failure	Density (kg/m ³)
Isophthalic Polyester	50 - 75	3.1 - 4.6	1.6 - 2.5	1110 - 1250
Epoxy	60 - 85	2.6 - 3.8	1.5 - 8.0	1110 - 1200
Phenolic	60 - 80	3.0 - 4.0	1.0 - 1.8	1000 - 1250
FRP Laminate Fibre/Resin Type and Orientation	Tensile Strength (MPa)	Elastic Modulus (GPa)	Elongation (%) at Failure	Density (kg/m ³)
Carbon FRP (high strength), uni-directional orientation Epoxy resin	2500	150	1.6 - 2.0	1600
Aramid FRP (low modulus), uni-directional orientation, Epoxy resin	2100	40	5.0 - 5.1	1400
Aramid FRP (high modulus), uni-directional orientation, Epoxy resin	2100	70	3.0 - 3.1	1400
Glass FRP (E-glass), uni-directional orientation, polyester resin	1200	40	2.9 - 4.3	1800
Glass FRP (E-glass), 0/90° symmetrical, polyester resin	350	20	1.8	1800
Glass FRP (E-glass), +45/-45° symmetrical, polyester resin	280	15	2.0	1800

Table 1: Typical properties of Dry fibres, Resins and FRP Laminates

3.8 In general, a stress limit approach to design shall be adequate in most cases, but a more sophisticated approach is also permitted. High local stresses may occur at specific locations, eg. under wheel loads and close to bearings, so testing is considered necessary. The tests are intended to cover both global and local wheel loading.

Analysis

3.9 Conventional methods of linear elastic analysis may be used assuming plane sections remain plane. No redistribution is permitted.

3.10 BS 5400: Part 1 states the general principles to be adopted in the calculation of load effects and member resistance and these should be followed for FRP bridges and components. However the use of plastic methods of analysis is not permitted.

3.11 The effect of local stress concentrations needs careful consideration, e.g. at connections and adjacent to bearings. The bridge designer shall seek specialist advice from the FRP designer in this area.

4. DESIGN REQUIREMENTS

4.1 This section relates to the design of a bridge using FRP components, carried out by the Bridge designer. Design of FRP components is outside the scope of this Standard.

Loading

4.2 The design loading to be used for FRP bridges for serviceability and ultimate limit states are as given in BD 37 (DMRB 1.3.14).

Design Life

4.3 The design life of an FRP deck shall normally be 120 years as given in BS 5400: Part 1, Section 6 (and elsewhere). The provisions of that section regarding inspection, repair and maintenance shall be taken into account in the design.

4.4 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 and where the following conditions are met:

- a) The main structural members shall have a design life of 120 years;
- b) Where FRP main beams are used, higher material factors for ULS and SLS shall be used as given in Tables 2 and 3. Provision shall also be made for inspection and rapid replacement without undue disruption to users, should the design life not be achieved;
- c) Other parts have a life of at least 30 years and provision is made for inspection and rapid replacement without undue disruption to users;
- d) Failure of a single affected part or component does not endanger the stability of the structure;
- e) A design life of less than 120 years may be justified under the provisions of BS 5400 or other Standard, for example for re-decking an existing bridge or highway structure.

Ultimate Limit States

4.5 The general requirements for the ultimate limit states are as specified in BS 5400: Part 1, Clause 3.2. The design should be carried out using data supplied by the FRP designer for appropriate values of ultimate strength and/or strain limits. These should take account of creep, sustained load, deterioration, ageing, temperature effects and any other effect that might influence the strength and stiffness.

Serviceability Limit States

4.6 The general requirements for the serviceability limit states to be considered are as specified in BS 5400: Part 1, Clause 3.2.

Deflection

4.7 Serviceability requirements may govern the design of FRP components due to the relatively low value of elastic modulus. The deflection of the structure or any part of it shall not be such as to adversely affect its appearance or serviceability. This can be achieved by limiting the deflection of FRP components under live load to $\text{span}/300$, including shear deformation. The deflection limit shall be applied locally and globally, in both longitudinal and transverse directions.

4.8 Where the FRP components are supported on steel or concrete main beams, the global deflection of the main beams under live load shall be limited to $\text{span}/250$. The global and local deflection under live load of the FRP components shall be limited to $\text{span}/300$ as per 4.7 above.

Vibration

4.9 The lightweight nature of FRP may result in a “lively” bridge. Excessive vibrations may cause user discomfort and affect the bond in joints and between surfacing and FRP. Dynamic analysis shall be carried out to determine the natural frequencies of the structure to indicate the susceptibility of the bridge to traffic induced vibrations. Experience with conventional bridges suggests that if the fundamental natural frequency is above 5Hz, then dynamic effects are not significant.

4.10 Vibrations due to wind shall be considered in accordance with BD 49 (DMRB 1.3.3).

4.11 For footbridges and the structural components of bridges whose prime function is to carry pedestrian loading, the requirements of BD 37 (DMRB 1.3.14), Appendix B shall be applied.

Fatigue Limit State

4.12 This Standard covers fatigue due to traffic loading. If other effects such as wind loading or vibration are significant, they shall be taken into account in the fatigue assessment.

4.13 As far as possible, details which introduce stress concentrations, such as bolted or bonded attachments should be located where they are not subject to dynamic loading. Where such details are subjected to dynamic loading they shall be included in the fatigue check. The FRP designer shall provide data for any 'standard details' offered by him for use in areas subject to dynamic loading.

4.14 Unless otherwise agreed with the Overseeing Organisation, design traffic loading for fatigue shall be taken from BS 5400 Part 10, table 11. A single wheel may be represented by a uniformly distributed load on a square contact area 200mm x 200mm. Note. The fatigue checks required by this Standard are based on all dynamic loads being lower than the fatigue damage threshold, so the number of vehicles is not relevant.

4.15 Consideration shall be given to the risk of high local dynamic stresses at locations remote from wheel loads, e.g. in an FRP section close to a bearing. These stresses may arise from secondary effects such as out of plane bending, or unintended restraint.

4.16 A full fatigue assessment is outside the scope of this Standard. Checks shall be carried out for the following:

- a) **Local effects.** Wheel loads on the roadway affecting details such as webs, flanges, web-flange connections, plus joints between components or sections of deck.
- b) **Global effects.** Bending moment and shear forces on components and joints in the roadway and supporting decks due to wheels, axles or groups of axles.

4.17 Where a bridge or highway structure with an FRP deck is designed for less than 45 units of HB loading, the axle loads of vehicle types 18GT, 9TT, 7GT, 7A and 5A-H may be reduced as follows for the global effects check:

For 37.5 units HB divide axle weight by 1.3.

For 25 units HB divide axle weight by 1.7.

4.18 The partial factor for fatigue, γ_{fatm} shall be taken as 1.0.

Fatigue check (i) local effects

4.19 The requirements of this Standard will be met if:

local wheel load capacity, $W_{fatm} \cdot \gamma_{fatm} \geq$ design wheel load, $W_{fatd} \cdot \gamma_{fatd}$

where W_{fatm} is the wheel load corresponding to a constant amplitude endurance of 10^7 cycles (L_0) on the design S-N curve. The value of W_{fatm} shall be provided by the FRP designer on the basis of tests, see annex A.

For bridges designed to BS 5400, W_{fatd} is equal to 30kN, and γ_{fatd} is equal to 1.5.

(Note. the highest single wheel load in BS 5400 Part 10 Table 11 for vehicles <40t GVW is 30kN. A factor of 1.5 is applied to allow for the combined effect of twin wheels and for wheel loads >30kN due to vehicle types 5A-H to 18GT-H.)

Fatigue check (ii) global effects

4.20 The requirements of this Standard will be met if:

Bending moment fatigue capacity, $BM_{fatm} \cdot \gamma_{fatm} \geq$ Maximum bending moment due to dynamic loading, $BM_{fatd} \cdot \gamma_{fatd}$

and

Shear force fatigue capacity, $SF_{fatm} \cdot \gamma_{fatm} \geq$ Maximum shear force due to dynamic loading, $SF_{fatd} \cdot \gamma_{fatd}$

4.21 Values of BM_{fatm} and SF_{fatm} for each component and joint between components shall be provided by the FRP designer on the basis of tests, see Annex A.

Partial Safety Factors for Load

4.22 The partial safety factors for load shall be taken from BD 37/01.

Partial Safety Factors for Material

by the FRP designer. These factors shall be multiplied by a further factor of 1.1 for automated processes such as pultrusion, and 1.3 for semi-automated or hand techniques, such as resin transfer moulding, pre-preg moulding or hand lay-up. These safety factors take into account effects such as creep, stress rupture, moisture uptake, temperature variation, and general degradation.

Ultimate Limit States

4.23 Table 2 gives material factors that shall be applied to each relevant component capacity supplied

		FRP Deck		FRP main beams	
Material	Loading type	Transient	Permanent	Transient	Permanent
Glass FRP		1.7	3.0	3.0	4.5
Aramid FRP		1.7	3.0	3.0	4.5
Carbon FRP		1.5	2.0	2.5	4.5

Table 2: Material Factors to be applied at ULS

Serviceability Limit States

4.24 Table 3 gives material factors that shall be applied to each relevant component property supplied by the FRP designer. These factors shall be multiplied by a further factor of 1.1 for automated processes and 1.3 for semi-automated or hand techniques as per 4.23 above.

Material		FRP Deck		FRP main beams	
Material	Loading type	Transient	Permanent	Transient	Permanent
Glass FRP		1.2	1.5	1.8	2.5
Aramid FRP		1.2	1.5	1.8	2.5
Carbon FRP		1.1	1.25	1.5	2.3

Table 3: Material Factors to be applied at SLS

4.25 The material factors in Table 2 shall be applied to strength. The material factors in Table 3 shall be applied to modulus and strength.

5. GENERAL REQUIREMENTS

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. This includes resistance to water, alkalis, chlorides, ultra-violet light, chemicals (vehicle oil and fuel) and de-icing salts.

Resistance to Impact Damage

5.2 FRP can be susceptible to impact damage from vehicle accidents or falling loads. The FRP designer shall provide information on the resistance of the relevant FRP components to impact damage. Structural FRP components shall have a minimum headroom above the carriageway of 5.5m.

Detailing

5.3 Proper detailing of connections is one of the most important aspects in ensuring the long-term performance of any FRP bridge structure. Most connections shall be either bonded, bolted or a combination of both. It is therefore critical that these details are carefully worked up and designed to ensure that they do not compromise the integrity of the overall structure. In particular careful consideration shall be given to protection of the end of the FRP units, levelling of main beams for effective connection between main beams and roadway units, deck end connections, parapet connections and application of the running surface.

5.4 Where bolted connections are used, the effect of high stress concentrations should be considered. Please refer to Clauses 2.7 and 2.8.

Surfacing

5.5 The surfacing shall be considered part of the FRP deck system. The FRP designer may offer a surfacing system as part of an FRP deck. In this case, test data shall be provided to demonstrate the durability of the surfacing.

5.6 Care is needed to select materials which fulfil all of the service conditions. If the surfacing is to be specified by the Bridge designer, particular attention shall be given to the requirements listed in Clauses 5.7 to 5.13 below, and tests carried out where necessary to demonstrate the durability of the materials selected.

5.7 The surface shall provide skid resistance compatible with the pavement on either side of the bridge.

5.8 Although a conventional waterproofing layer is not required to protect the deck, the design shall incorporate adequate drainage to avoid excessive moisture take-up. The effects of differential thermal movement between surface course and FRP roadway shall be considered and a 'buffer' layer provided if necessary.

5.9 The designer shall ensure that strains in the surface course due to wheel loading and resulting local deflection of the roadway are not so high as to cause fatigue failure of the surfacing material.

5.10 The bond between roadway and surfacing shall be sufficient to prevent failure of the bond in service. A tensile bond strength $\geq 1\text{N/mm}^2$ and a shear strength greater than the shear strength of the surfacing shall be considered sufficient.

5.11 Provision shall be made for the surface course to be replaced at the end of its life. A method statement for replacement shall be included in the maintenance manual. (See also Clause 6.6)

5.12 The method of installation shall be such as to ensure a smooth transition between deck and adjacent pavement.

5.13 The temperature at which the surfacing material is laid shall be considered to ensure that the roadway is not adversely affected.

Parapets

5.14 Vehicle parapets and combined pedestrian/vehicle parapets (referred to below as parapets) must meet the requirements of the Interim Requirements for Road Restraint Systems (IRRRS) and BS EN 1317 Parts 1 & 2. Careful consideration must be given to the

way in which forces from the parapet are transferred to the bridge and its supports

5.15 Where an FRP deck is to be installed onto existing steel or concrete beams, parapets may be attached directly to the beams subject to the agreement of the Overseeing Organisation, and provided that the beams have been assessed as capable of carrying the additional loads resulting from attaching the parapets.

Movement Joints

5.16 Depending on the properties of the materials used, conventional movement joints may not be required at the ends of the deck. However, a gap will be present between deck ends and abutments and some form of movement joint is necessary.

5.17 The movement joints shall:

- a) prevent leakage between deck end and abutment;
- b) 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.

5.18 The continuity requirements of BD 57 (DMRB 1.3.7) can be relaxed provided that extra precautions are taken at the joint. These precautions may include extra rebar cover, drainage falls, coating of the rebar or use of stainless steel or FRP rebar, coating of the concrete in the vicinity of the movement joint, etc.

Resistance to Fire

5.19 There are currently no requirements for fire resistance of bridges in BS 5400. FRP structures pose no particular threat over and above that to be found in traditional bridges. However, the use of fire retardant additives in the resin shall be considered for critical structural components whose loss would result in disproportionate effects. Neither the fibre reinforcement nor the fillers currently used in the resin support combustion.

5.20 The high fibre content of structural components likely to be used in bridge and highway structure applications offer good fire resistance. Components with long unidirectional fibres maintain strength much longer than chopped fibres. Because of the low thermal conductivity of FRP, fire damage if it occurs is likely to be localised.

Surface Finish

5.21 Care shall be taken to ensure that the colour and texture of visible FRP surfaces are consistent.

6. CONSTRUCTION AND MAINTENANCE

6.1 Construction of an FRP deck shall be carried out by a suitable specialist contractor employing operatives trained in the techniques to be used. Special attention shall be paid to the provision of method statements, to a programme of inspection at each stage of the construction process and to provision of suppliers' certificates and samples for quality control testing.

6.2 FRP components can be less robust than traditional materials and may be damaged by careless handling. It is therefore important to select a contractor able to specify and adhere to procedures for lifting, storage, transportation and installation.

6.3 It is a requirement that a covered area with appropriate environmental control, ie temperature, humidity, etc be set up for the assembly of FRP components into sections of deck or a complete deck, where site bonding is required.

6.4 The following information shall be provided by the FRP designer to aid construction, maintenance and repair:

- a) requirements for transportation, handling and storage. These should be sufficient to prevent damage and deterioration of properties;
- b) guidance on methods of cutting and drilling, including protective treatment to cut surfaces;
- c) method of repairing local damage during construction and criteria for assessing the structural adequacy of damaged parts;
- d) guidance on assembly methods which will produce a structure in which the specified properties will be achieved;
- e) data to enable repairs to be carried out to FRP components during the life of the bridge, including sufficient details of the materials to enable compatible repair materials to be independently sourced;
- f) sufficient data to enable a replacement surfacing system to be specified and independently sourced, including details of the system installed at the time of construction, plus chemical and mechanical characteristics of the FRP material at the surface of the deck;

g) guidance on inspection and the significance of defects.

6.5 Manufacturers' advice shall be sought in relation to the safe storage of adhesives on site, and other associated items such as surface primers.

6.6 The bridge designer shall provide sufficient information and data to the bridge owner or his agent to enable the bridge to be maintained in a serviceable condition throughout its design life. The information shall be sufficient to allow materials for repair and replacement to be sourced independently of the FRP designer or supplier of the deck. The information provided shall include method statements and material/loading data for the following:

- a) removal of the surfacing system;
- b) installation of a replacement surfacing system;
- c) replacement of a section of the roadway;
- d) replacement of movement joints;
- e) replacement of bearings;
- f) reinstatement of a parapet following vehicle impact (where standard anchorage details are offered by the FRP designer or supplier);
- g) de-commissioning and recycling.

6.7 The bridge designer shall provide Health and Safety data sheets detailing precautions to be taken when handling and working FRP materials including details for safe disposal of FRP and adhesives.

7. REFERENCES

7.1 Design Manual For Roads and Bridges

HD 34 Implementation and Use of the Standards Improvement System (DMRB 5.3.1)

IAN 44/02 (Rev1) Introducing Interim Requirements for Road Restraint Systems (IRRRS)

BD 37 Loads for Highway Bridges (DMRB 1.3.14)

BD 49 Design Rules for Aerodynamic Effects on Bridges (DMRB 1.3.3)

BD 57 Design for Durability (DMRB 1.3.7)

7.2 BSI Publications

BS5400: Part 1 Code of Practice for Steel, Concrete and Composite Bridges. General Statement

BS EN 1317-1-1998 Road Restraint Systems: Terminology and General Criteria for Test Methods

BS EN 1317-2-1998 Road Restraint Systems: Impact Tests acceptance and tests methods for safety barriers

7.3 Other Publications

The following background information will be of assistance to designers:

Clarke, J L (1996). *Structural design of polymer composites. EUROCOMP Design code and handbook*. The European Structural Polymeric Composites Group, edited by J L Clarke, E and FN Spon, London.

Cripps, A (2002). *Fibre-reinforced polymer composites in construction*. CIRIA C564, Construction Industry Research and Information Centre, Department of Trade and Industry.

Hollaway, L C and P R Head (2001). *Advanced polymer composites and polymers in the civil infrastructure*. Elsevier Science, London.

Hutchinson, A R (1997) CIRIA Project Report 46, *Joining of fibre-reinforced polymer composite materials*, CIRIA, UK.

CIRIA (2000), *The use of FRP in construction*, CIRIA, UK.

8. ENQUIRIES

All technical enquiries or comments on this Standard should be sent in writing as appropriate to:

Chief Highway Engineer
The Highways Agency
123 Buckingham Palace Road
London
SW1W 9HA

G CLARKE
Chief Highway Engineer

Chief Road Engineer
Scottish Executive
Victoria Quay
Edinburgh
EH6 6QQ

J HOWISON
Chief Road Engineer

Chief Highway Engineer
Transport Wales
Welsh Assembly Government
Cathays Parks
Cardiff
CF10 3NQ

M J A PARKER
Chief Highway Engineer
Transport Wales

Director of Engineering
The Department for Regional Development
Roads Service
Clarence Court
10-18 Adelaide Street
Belfast BT2 8GB

G W ALLISTER
Director of Engineering

ANNEX A VERIFICATION OF DESIGN PROPERTIES

A. Verification of Properties for Roadway Panels

1. The properties provided by the FRP designer shall be supported by experimental evidence.
2. Production of components and sub-assemblies shall be carried out to a quality assurance plan approved by the FRP designer and which includes sampling and testing to appropriate Standards.
3. The FRP designer shall ensure that the contractor carries out static tests on completed components or sub-assemblies. Connections between components shall be included in the tests. Test configurations and loads applied shall be generally similar to highway bridge deck loading. A sufficient number of each test shall be carried out to enable the characteristic (95%) value to be determined. Tests shall be carried out to confirm the strength and modulus of the components. The majority of tests shall be carried out to the serviceability load multiplied by a factor of 1.2. The tests shall be for at least one simply supported condition and one 2-span continuous support condition. At least one test shall be carried out to failure per support condition, after having been loaded to 1.2 times the serviceability load.
4. Where a recommended design for attachments, e.g. of FRP deck components to supporting members, parapets or street furniture, is provided by the FRP designer, the design shall be verified by testing and/or data provided by the supplier. Alternatively, the bridge designer may design attachments and have them verified by testing.

B. Test Requirements for Static and Fatigue Loads

1. Tests shall be carried out by the FRP designer to verify the static and fatigue strength of the deck. These tests are required for each new deck system (or 'bespoke' bridge design) and following significant modifications to an existing system. The tests shall include:
 - (a) all potential fatigue failure locations;
 - (b) all joints and connections;
 - (c) any proposed method of repair, or replacement of components provided by the FRP designer.

2. The tests shall be submitted to the Overseeing Organisation for approval.

3. The tests shall be carried out on full-scale sections of the component taken from a normal production batch.

Local Effects

4. Identify all potential failure locations and determine the position of a single wheel, which will produce the most severe effect at each location, i.e. the positions corresponding to the peak and trough values of an influence line for strain, due to the passage of a single wheel.
5. The test is to reproduce the effect of a single wheel passing over the potential failure location. The wheel load may be represented by a steel loading pad 200mm x 200mm square faced with ≥ 6 mm thick rubber. For some locations the most severe effect will be produced by two adjacent pads loading alternately, e.g. if the passage of a wheel produces both tensile and compressive strains. Where possible, several locations may be covered by one load position. The fatigue test load shall be set to the required value of local wheel load capacity, W_{fatm} .

Global Effects

6. The component to be tested shall be supported in a manner that is similar to its intended service condition. The test load shall be applied by a loading pad designed to minimise local effects, e.g. a 300mm x 100mm pad faced with ≥ 6 mm thick rubber. The fatigue test load shall be set to induce the required design bending moment, BM_{fatm} or shear force, SF_{fatm} .

Test Procedure

7. Carry out five static tests to failure using 200mm x 200mm load pads. The design ultimate static capacity is the characteristic (95%) value of the average maximum load, BM or SF achieved.
8. Carry out three fatigue tests. Each test shall be run to failure or 10^7 cycles. At the end of the fatigue test each specimen shall be subjected to a static test to failure under the same conditions as the static tests, see Clause 7.

9. The result of a fatigue test shall be deemed a 'pass' if 10^7 cycles are completed without 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.

10. If a 'pass' result is obtained in all three fatigue tests, the value of the test load, BM or SF may be used as the design fatigue capacity for the location(s) or component tested.

C. Proof Tests

1. Tests shall be carried out on sections of deck, by an independent laboratory. The purpose of the tests is to verify that the properties used by the Bridge designer are achieved on site, taking into account both component properties and the methods and materials used in assembly.

2. The size and number of sections to be tested shall be determined by the Overseeing Organisation as part of the technical approval, e.g. one test per 50m^2 of FRP deck area, in consultation with the bridge designer, the FRP designer and the contractor.

3. The tests shall be specified to enable a direct comparison to be made with the capacities provided by the FRP designer for strength and modulus.

Where a complete FRP bridge is being assembled (ie FRP main beams and deck), the tests shall include the main structural members, the roadway and the connections. In other words, a load test on the installed bridge shall be required, in addition to tests on sections of the roadway assembled on site.