Design Manual for Roads and Bridges

Highway Structures & Bridges
Design

CD 371
Strengthening highway structures using fibre-reinforced polymers and externally bonded steel plates

(formerly BD 85/08, BD 84/02)

Revision 0

Summary
The use of this document enables existing concrete and steel highway structures to be strengthened using fibre-reinforced polymers (FRPs) or externally bonded steel plates, thereby reducing risk and maintaining a safe and operational network.

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	Mar 2020	CD 371 replaces BD 85/08 and BD 84/02. The full document has been re-written to make it compliant with the new Highways England drafting rules.The document has been aligned with Eurocodes and current best practice and incorporates updated provisions from the withdrawn BA 30/94.Specification content has been removed, to be incorporated in the Specification for Highway Works.

Foreword

Publishing information

This document is published by Highways England.

This document supersedes BD 85/08 and BD 84/02, which are withdrawn.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

This document has been developed to enable the use of Eurocode principles for basis of design when strengthening structures with fibre-reinforced polymers and incorporate updates in technology.

It includes reference to methods in third party documents, particularly:

1) CS TR55 [Ref 3.I];
2) CIRIA C595 [Ref 9.I].

The document also incorporates updated provisions from the withdrawn BA 30/94.

The opportunity has been taken to incorporate requirements for strengthening structures with steel plate bonding and to align the requirements with those for fibre-reinforced polymers where appropriate.

Assumptions made in the preparation of the document

The assumptions made in GG 101 [Ref 6.N] apply to this document.

Abbreviations

Abbreviations

Abbreviation	Definition
FRP	Fibre-Reinforced Polymer (or Plastic) comprising high strength fibres in a resin matrix.
NSM FRP	Near-Surface-Mounted Fibre-Reinforced Polymer, where the FRP is installed into grooves that have been cut into the concrete.
SLS	Serviceability Limit State
ULS	Ultimate Limit State

Terms and definitions

Terms

Term	Definition
Aramid fibre	A synthetic fibre consisting of a long-chain aromatic polyamide in which at least 85% of the amide linkages are attached directly to two aromatic rings.
Carbon fibre	Fibre produced from organic materials such as rayon, polyacrylonitrile or pitch. NOTE: The term is often used interchangeably with 'graphite'.
Composite (or advanced composite)	Alternative term for FRP, i.e. fibres plus resin.
Cure	To irreversibly change the properties of a thermosetting resin by chemical reaction, i.e. condensation, ring-closure, or addition. NOTE: Cure can be accomplished by the addition of curing agents, with or without catalyst, and with or without heat.
Fabric	Fibres woven into a fabric. NOTE: Fibres can be aligned in any direction, with 0°, 45° and 90° being the most common.
Galvanic corrosion (or bimetallic corrosion)	Corrosion where two conducting materials with different electropotentials are in contact.
Glass fibre	A fibre spun from an inorganic product of fusion that has cooled to a rigid condition without crystallising.
Laminate	FRP composite in the form of a plate. NOTE: Pultruded sections are often referred to as laminates, but the term is not specific to any method of production.
Prepreg	Fibres impregnated with resin and attached to a backing paper or plastic release film.
Primer	A low viscosity epoxy resin applied to the concrete to provide a good bond (normally stronger than the surface concrete) and a suitable surface for the FRP.
Pultrusion	A factory method of manufacturing FRP laminates in long lengths. NOTE: Sections currently available include plates, rods and profiles.
Putty	A filler, usually an epoxy resin in the form of a paste, used to fill holes and surface defects in a concrete surface.
Resin	A resin which is used to impregnate the fibres and bind filaments, fibres and layers of fibre together.
Stress rupture (also known as creep rupture)	Failure under sustained loads at a stress level considerably lower than the short term strength.
Thermoset	A resin that cannot be melted and recycled because the polymer chains form a three-dimensional network.
Voids	Air bubbles trapped in the resin or between the FRP and concrete/steel substrate.
Wet lay up	A method of installing FRP by hand. NOTE: The dry FRP (fabric or tow sheet) is impregnated with resin immediately prior to application.

1. Scope

Aspects covered

1.1 This document shall be used for the design of the strengthening of concrete and steel highway structures using fibre-reinforced polymers (FRPs), including:

1) flexural and shear strengthening of concrete bridge decks;
2) flexural, shear and axial strengthening of concrete bridge supports; and
3) flexural strengthening of steel bridges.

NOTE 1 The viability of FRP strengthening of reinforced concrete structures has been demonstrated through experimental studies and numerous practical applications in the UK and elsewhere. Experience of the application of FRPs to steel structures is more limited in highway structures and less experimental verification exists.

NOTE 2 This document does not provide specific requirements for the strengthening of cast iron and wrought iron structures. Relevant guidance is provided in CIRIA C595 [Ref 9.I]. The assessment of cast iron and wrought iron structures is covered by CS 454 [Ref 2.I].

NOTE 3 This document does not provide specific requirements for the strengthening of structures for fatigue.

1.2 This document shall be used for the design of the strengthening of concrete structures with externally bonded steel plates.

Implementation

1.3 This document shall be implemented forthwith on all schemes involving strengthening on the Overseeing Organisations' motorway and all-purpose trunk roads according to the implementation requirements of GG 101 [Ref 6.N].

Use of GG 101

1.4 The requirements contained in GG 101 [Ref 6.N] shall be followed in respect of activities covered by this document.

2. Applicability

2.1 The suitability of the structure for strengthening using FRPs or externally bonded steel plates shall be assessed, and a viable strengthening methodology developed.

2.2 The assessment of suitability shall include:

1) whether the strengthened structure would be robust in an accidental damage scenario;
2) whether it is possible to achieve sufficient integrity of the interface between the strengthening materials and the structure;
3) whether the structure is over-reinforced;
4) whether the strengthening would be effective and durable;
5) the feasibility of sustained loading or prestress in FRP strengthening;
6) an options report and economic evaluation including alternative methods of strengthening.

NOTE The requirements for each item listed can be found in the relevant sub-section.

Robustness against accidental damage

2.3 Structures that are to be strengthened shall be sufficiently robust that the accidental damage or removal of strengthening materials not protected from accidental damage or removal does not cause collapse of the structure.

2.3.1 A structure may be strengthened using externally bonded FRPs or steel plates if it has sufficient robustness that its ultimate limit state resistance after removal of the strengthening can be shown to be at least sufficient to resist the effects of the frequent combination of actions without any partial factors applied.

NOTE 1 The frequent combination of actions is defined in BS EN 1990 [Ref 3.N].

NOTE 2 Verification of the unstrengthened structure using the frequent combination of actions is equivalent to the verification of the structure following removal of the strengthening in the accidental design situation.

2.3.2 Strengthening techniques where FRPs are embedded in a concrete structure, including the use of near-surface-mounted (NSM) bars or deep embedment bars, may be considered to be protected from accidental damage or removal, unless a specific risk of damage has been identified.

2.3.3 Where a specific risk has been identified relating to the possible damage of embedded FRP, the approach to verifying robustness may be the same as for externally bonded strengthening.

2.4 Where FRPs are applied to the top surface of slabs or beams and buried by the road surfacing, the FRP shall be protected from being damaged during installation and removal of surfacing.

NOTE NSM FRP bars are embedded in concrete which can provide protection to the FRP from the risk of damage.

2.4.1 Where externally-bonded FRP laminates are used, protection from damage by hot surfacing during installation may be provided by specifying FRP and adhesive materials which can tolerate high temperatures or by providing a protective layer of mortar on top of the laminates.

2.4.2 Where externally-bonded FRP laminates are used, protection from removal of surfacing may include studs with a thickness greater than that of the FRP laminates, bolted to the structure adjacent to FRP laminates.

2.4.3 Where NSM FRP bars are used, protection from damage by hot surfacing during installation may be provided by specifying an adhesive which can tolerate high temperatures.

Integrity of the interface with the structure

2.5 The interface between the structure and externally bonded FRPs or steel plates shall be capable of sustaining the stresses necessary for tension to be developed in the FRP or steel plates.

NOTE *The effectiveness of externally bonded strengthening is highly dependent on the integrity of the bond with the surface of the structure and also on the integrity of the surface material itself.*

2.6 FRPs or steel plates shall not be bonded to a surface with a concave profile, unless justified through a rigorous analysis or experimental results.

NOTE *If strengthening materials carrying tension are bonded to a concrete surface with a concave profile, the likelihood of separation failure increases.*

2.7 Externally bonded FRPs or steel plates shall not be bonded to uneven surfaces where the gap under a 1m long straight edge exceeds 5mm.

2.7.1 Externally bonded FRPs or steel plates may be used where the gap under a 1m straight edge is up to 5mm provided the depth of adhesive is varied to achieve the required straightness after installation.

2.8 The acceptable gap under a 1m long straight edge held to the surface of FRPs or steel plates following installation shall be no greater than 3mm.

2.9 NSM FRP bars and deep embedment FRP bars shall be installed straight, without being bent.

2.10 When considering the suitability of a structure for strengthening with FRPs or steel plates, investigations shall be carried out to ensure that the risk of corrosion in the existing member is low and to determine the soundness of the structure, including any repaired areas.

NOTE *For concrete structures, CS 462 [Ref 7.I] gives advice on special inspections and guidance on suitable tests.*

2.11 The surface to be strengthened shall be dry, sound and undamaged prior to installation.

2.11.1 Where needed, remedial measures to achieve a dry, sound and undamaged surface should include:

1) the stoppage of leaks and drying out of the whole depth of the member to be strengthened;
2) removal of damaged material on the surface to be strengthened down to a sound base.

2.12 For concrete structures, the integrity of the surface concrete and its method of preparation shall be demonstrated by a series of pull-off tests.

2.13 The requirements for the pull-off testing shall be set out in the specification.

2.14 Externally bonded FRPs or steel plates shall not be used for strengthening concrete structures when the characteristic concrete tensile strength of the surface to be strengthened is less than 1.5 MPa.

2.14.1 The characteristic value of the concrete tensile strength may be taken as 70% of the mean of the test results but not greater than the minimum test result.

Over-reinforced sections

2.15 When strengthening concrete structures, the sections to be strengthened shall not be over-reinforced, either before or after strengthening.

NOTE *Over-reinforced sections are those where the ultimate limit state resistance is reached without yielding of the steel reinforcement, for example a beam that has so much flexural reinforcement that flexural failure could occur in a brittle mode without yielding of the steel.*

Effectiveness and durability of the strengthening

2.16 Before undertaking a design, where uncertainties exist concerning the effectiveness of an FRP system or steel plate bonding for a particular application, experimental testing on representative specimens shall be undertaken to prove the technique is effective.

NOTE *Examples where testing might be required include the use of a material with significantly different properties to those used in previous studies or applications, the use of a new approach or system, or bonding onto an irregular, curved or deteriorated surface.*

2.17 Where testing is proposed to prove a strengthening technique, the requirements for, and the extent of, the testing shall be agreed with the Overseeing Organisation.

2.18 Information and test results to demonstrate the long-term performance and durability of all components of the strengthening system shall be sought from manufacturers and suppliers.

2.19 Steel plates shall be protected from corrosion.

NOTE Specification requirements for the protection of steelwork against corrosion are given in MCHW Series 1900 [Ref 7.N].

2.20 Protective coatings and seals shall be specified in accordance with the recommendations from manufacturers and suppliers to ensure the strengthening system is durable.

2.20.1 Protective coatings and seals may be required:

1) to protect adhesives from water ingress and moisture;
2) to protect FRP components from ultraviolet radiation;
3) to reduce solar gain and consequence temperature rise of the FRP components;
4) for protection against vandalism or accidental removal of the strengthening system;
5) for fire protection of the strengthening systems in situations where fire resistance is required.

FRP with sustained loading effects

2.21 Guidance shall be sought from specialist designers and materials suppliers when a strengthening scheme includes the use of FRP subjected to significant, sustained loading effects.

NOTE 1 The efficiency of FRP strengthening can be increased by prestressing the FRP, or alternatively by jacking up a structure during the installation of the FRP. These approaches provide strengthening for permanent loads as well as variable loads, and enable a greater proportion of the FRP strength to be used.

NOTE 2 Excessive sustained stress in FRP can result in creep rupture. Requirements for the avoidance of creep rupture are provided in section 3.

NOTE 3 For further guidance, see CS TR55 [Ref 3.I].

Options report and economic evaluation

2.22 An options report and economic evaluation shall be carried out to compare the proposed strengthening technique with other methods for strengthening the structure in object.

2.23 Factors at options report stage shall include safety, cost, risks, performance history of the proposed techniques, construction methods, environmental factors, remaining life, inspection and maintenance.

3. Basis of design

Design life

3.1 The strengthening system shall be designed for a minimum design life of 30 years, unless otherwise agreed with the Overseeing Organisation.

Limit states

Ultimate limit states

3.2 The design shall include verifications at the ultimate limit state.

NOTE Requirements and advice regarding specific verifications at the ultimate limit state are provided in the respective sections of this document.

Fatigue

3.3 The strengthening system shall have sufficient fatigue resistance to achieve the design life.

3.3.1 The fatigue resistance of FRP strengthening components may be deemed to be satisfied.

3.3.2 The fatigue resistance of adhesives may be deemed to be satisfied where:

1) the structure being strengthened is concrete; or
2) the design stresses in the adhesive at the FRP ends due to traffic loading are less than 20% of the design adhesive strength.

NOTE The stresses at the ends of FRP bonded to steel structures are often dominated by thermal effects, which occur at a relatively low frequency and are unlikely to cause fatigue problems.

3.3.3 The fatigue resistance of strengthening steel plates may be verified using the relevant parts of BS EN 1993 [Ref 6.I].

3.3.4 The fatigue resistance of the existing structure to be strengthened may be deemed to be satisfied where:

1) the structure has previously been assessed and there are no concerns relating to fatigue;
2) the stress range in the fatigue-sensitive components of the existing structure is not expected to increase in the strengthened configuration with the new loading regime.

NOTE Requirements and advice regarding the need for fatigue assessment calculations are provided in CS 454 [Ref 2.I] and the associated assessment documents.

3.4 Where the fatigue resistance has not been deemed to be satisfied, the need and methodology for fatigue verifications shall be agreed with the Overseeing Organisation.

Serviceability limit states

3.5 The strengthened structure shall satisfy the relevant design serviceability criteria for new structures, unless otherwise agreed with the Overseeing Organisation.

3.5.1 Serviceability verifications of the existing structural components may be deemed to be satisfied where:

1) the structure has been performing satisfactorily in service without exceeding the relevant serviceability criteria;
2) the future loading carried by the structure is not expected to increase; and
3) the addition of the strengthening will not increase the stress in the existing structural components.

3.6 The sustained stress in the FRP shall be limited at the serviceability limit state to avoid creep rupture.

3.6.1 The creep rupture criteria in CS TR55 [Ref 3.I] should be applied.

Design actions

3.7 The actions and partial factors shall be taken from the relevant parts of BS EN 1991 [Ref 4.N] and BS EN 1990 [Ref 3.N] respectively.

NOTE The actions for strengthening bridge supports for impact are contained in BS EN 1991-1-7 [Ref 1.N].

Structural analysis

3.8 The structural analysis methodology shall be selected considering the possibility of low ductility of strengthened elements.

NOTE 1 Strengthened elements that have resistance governed by criteria relating to FRP fracture or separation of the strengthening materials can exhibit failure modes that are brittle.

NOTE 2 Strengthening concrete bridge supports with FRPs can increase ductility through the provision of confinement.

3.9 Structural analysis methods that rely on redistribution of load effects shall not be used unless it can be robustly demonstrated that such redistribution would occur prior to failure.

3.9.1 Moments may be redistributed from an unstrengthened region into a strengthened region, where it can be demonstrated that there is sufficient rotation capacity in the unstrengthened region.

3.10 The existing stresses in the structure at the time of strengthening shall be taken into account in the design.

3.10.1 When there is uncertainty in the magnitude of the existing stresses, and when the design is sensitive to the magnitude of the existing stresses, tests should be undertaken to quantify the existing stresses in the structure.

NOTE 1 Stresses in the structure can arise from permanent actions (including support settlement) and variable actions (including traffic and thermal actions).

NOTE 2 The strengthening design of statically indeterminate structures can be sensitive to the stress in the structure at installation.

3.11 The redistribution of stresses due to creep in concrete following installation shall be considered where the design is sensitive to such effects and where further creep is expected.

NOTE Creep in prestressed concrete structures can cause compression to be developed in the strengthening materials.

Partial factors for material properties

3.12 Design values of material properties shall be determined using representative values of material properties and partial factors that are consistent with the target reliability for the strengthened structure.

3.12.1 Characteristic values or worst credible values of material properties should be used.

NOTE A characteristic value is defined as the value below which not more than 5% of all possible test results can be expected to fall.

3.12.2 Worst credible values should be derived for concrete structures in accordance with CS 455 [Ref 10.I].

3.12.3 The partial factors for concrete, reinforcement and prestressing steel at the ultimate limit state should be taken from Table 3.12.3.

Table 3.12.3 Partial factors for concrete, reinforcement and prestressing steel at the ULS.

Design situations	Material property	Concrete	Reinforcement and prestressing steel
Persistent and transient	Characteristic strength	1.5	1.15 (can be reduced to 1.05 for grade 460 steel)
	Worst credible strength	1.2	1.10 (can be reduced to 1.05 for grade 460 steel or if measured steel depths are used)
Accidental	Characteristic or worst credible strength	1.2	1.0

3.12.4 The partial factors for structural steel in the existing structure at the ultimate limit state should be taken from BS EN 1993-2 [Ref 2.N].

3.12.5 The partial factors for FRP stiffness and ultimate strain at the ultimate limit state should be taken from Table 3.12.5a for all design situations, and multiplied by the additional partial factor for the method of manufacture as given in Table 3.12.5b.

Table 3.12.5a Partial factors for FRP at the ULS

Material	Partial factor to be used with characteristic stiffness	Partial factor to be used with characteristic ultimate strain
Carbon FRP	1.1	1.25
Aramid FRP	1.1	1.35
AR glass FRP	1.6	1.85
E-glass FRP	1.8	1.95
Basalt FRP	1.8	1.95

Table 3.12.5b Additional partial factors for FRP method of manufacture

Type of System	Additional partial factor
Plates	
Pultruded	1.05
Prepreg	1.05
Preformed	1.1
Sheet or tapes	
Machine-controlled application	1.05
Vacuum infusion	1.1
Wet lay-up	1.2
Prefabricated (factory-made) shells	
Filament winding	1.05
Resin transfer moulding	1.1
Hand lay-up	1.2
Hand-held spray application	1.5

NOTE *The values of the partial factors are taken from CS TR55 [Ref 3.I]. For further guidance on the application of the partial factors, refer to CS TR55 [Ref 3.I].*

3.12.6 The partial factor for adhesive strength at the ultimate limit state should be taken as 4.0 or greater, unless otherwise agreed with the Overseeing Organisation.

NOTE Guidance on the derivation of partial factors can be found in ISE Adhesives [Ref 1.I] and CIRIA C595 [Ref 9.I].

3.12.7 The partial safety factors for the material properties of steel plates for strengthening should be taken from BS EN 1993-2 [Ref 2.N].

3.12.8 At the serviceability limit state, all material partial factors should be taken as 1.0.

Design verification

3.13 The strengthened structure shall be designed to have sufficient design resistance for the effects of all design actions.

3.14 The design resistance shall be determined in accordance with the relevant sections of this document.

NOTE Strengthening for one mode of failure can make another mode of failure critical.

4. Materials

General

4.1 Values for all material properties assumed in the design shall be listed within the specification.

4.2 Key material properties shall be noted on all drawings, specifications and relevant documents.

Fibre reinforced polymers (FRPs)

4.3 Consistent properties for the FRPs shall be used in the design, specification and installation.

4.4 Guidance shall be sought from specialist designers and materials suppliers regarding the values for material properties of specific FRP systems.

Adhesive and fixings

4.5 Guidance shall be obtained from specialist designers and materials suppliers regarding the specification of an adhesive that:

1) has the required mechanical properties;
2) is appropriate for the application;
3) is compatible with the components to be bonded;
4) has sufficient durability in the environmental conditions;
5) can be installed at the required speed of installation.

NOTE Particular environmental conditions affecting the durability of adhesives include high temperatures or submersion in water.

4.6 The specification shall include any constraints affecting the curing of the adhesive during installation.

NOTE If excessive vibrations are expected these can be limited by managing the traffic during installation.

4.7 Where mechanical fixings or anchorages are proposed, the effectiveness, reliability and durability of the proposed system shall be demonstrated through testing.

NOTE Guidance is given in CS TR55 [Ref 3.I] where some of the potential solutions are discussed.

4.8 Where a fixing system is proposed that includes bolts through holes in the FRP, the design shall include the verification of local stress concentrations and potential failure modes in the FRP.

Steel plates

4.9 Material properties for steel plates shall be obtained from BS EN 1993-2 [Ref 2.N] and BS EN 10025 [Ref 5.N].

4.9.1 The grade of steel plates should be S275 in accordance with BS EN 10025 [Ref 5.N].

NOTE The use of high yield steel does not generally provide benefits as the modulus of elasticity is the same as mild steel.

4.10 Stainless steels shall not be specified unless it can be demonstrated that the adhesive bond to the stainless steel has sufficient long-term performance.

NOTE There is little published information on the effect of the composition of stainless steel on the adhesive bond strength, particularly with respect to long-term performance.

4.11 The methodology for the preparation, installation and protection of the steel plates shall be set out in the specification.

Existing structure

4.12 Representative values of the material properties of the existing structure shall be determined and used in the design calculations.

NOTE Guidance on the assessment of material properties is given in CS 454 [Ref 2.I].

4.12.1 For existing concrete structures, worst credible strengths should be derived in accordance with CS 455 [Ref 10.I].

4.13 The methodology for the preparation of the surface, including any repairs, shall be set out in the specification.

5. Strengthening concrete bridge decks with FRPs

Strengthening for flexure at the ultimate limit state

5.1 Where strengthening for flexure in concrete beams and slabs is required, an effective form of flexural strengthening shall be selected that complies with the requirements of this document.

5.1.1 Flexural strengthening methodologies using FRPs should be based on either:

1) externally bonded FRP laminates, attached to the concrete surface; or
2) near-surface-mounted (NSM) FRP bars installed into grooves that have been cut into the cover concrete.

5.2 The resistance to all failure modes that could govern the flexural resistance shall be verified, including failure modes where there is a loss of composite action between the FRP and the concrete, and failure modes where composite action is maintained.

5.3 Sufficient anchorage shall be provided beyond the point at which the FRP is required to be effective.

5.4 The force developed in the FRP anchorage shall not exceed the resistance of the anchorage.

5.4.1 The FRP anchorage should be designed in accordance with CS TR55 [Ref 3.I].

NOTE The anchorage resistance can be improved, if required, by increasing the width of the bonded interface without increasing the area of FRP.

5.4.2 A minimum anchorage length of 500mm should be provided when the FRP is terminated within a span.

5.5 Where the FRP anchorage is located in a region where the concrete is expected to be cracked at ULS, a detailed analysis of the anchorage shall be carried out.

5.6 The design resistance corresponding to the separation of the FRP from the concrete shall be determined.

5.7 The following failure modes, which relate to a loss of composite action, shall be verified:

1) FRP separation induced by surface irregularity;
2) FRP separation induced by shear cracking;
3) FRP separation induced by longitudinal shear stress in the yield zone;
4) FRP separation induced by longitudinal shear stress near the ends of FRP; and
5) FRP separation due to insufficient anchorage length.

5.7.1 The methods and criteria of CS TR55 [Ref 3.I] should be used to verify the failure modes relating to a loss of composite action.

5.7.2 The strain in the FRP should be limited to 0.008 to limit the risk of separation failure.

5.7.3 The use of additional fixings to prevent loss of composite action may be considered with externally bonded multi-directional FRP laminates if the effectiveness of the proposed system is verified by testing and agreed with the Overseeing Organisation.

5.8 Where it is necessary to extend the FRP into an area in compression, the possibility of buckling and a loss of composite action shall be considered.

5.9 The strengthened section shall be designed to have sufficient flexural resistance based on composite action being maintained.

5.10 The flexural resistance of the strengthened section shall be determined based on the following principles and assumptions:

1) plane sections remain plane;
2) there is perfect bond;
3) the strains in the section at the time of strengthening are taken into account;

4) zero tensile strength in the concrete at ULS;
5) the stress in the concrete compression zone is determined based on a constitutive model for flexural design;
6) the strain in the concrete in the compression zone is limited to avoid crushing failure;
7) the stress in the reinforcement and prestressing is determined based on constitutive models for design;
8) the FRP is linear elastic in tension based on the design value of the elastic modulus;
9) the strain in the FRP is limited to avoid tensile failure and separation of the FRP; and
10) additional longitudinal tensile forces associated with shear effects are included in the design.

NOTE Guidance on the flexural design of FRP-strengthened sections is provided in CS TR55 [Ref 3.I].

5.10.1 The design constitutive models for the concrete, reinforcement and prestressing should be taken from BS EN 1992 [Ref 5.I].

5.11 Pultruded FRP plates that are stacked to form a multi-layer laminate shall be limited to a thickness of no more than two plates when stacked in-situ.

5.12 Stacks of more than two pultruded FRP plates formed in factory conditions by the manufacturer shall only be used if their effectiveness has been verified by testing.

NOTE 1 Guidance on stacked pultruded FRP plates is provided in CS TR55 [Ref 3.I].

NOTE 2 Multi-layer laminates can be avoided where there is space to position the plates side by side.

Strengthening for shear at the ultimate limit state

5.13 Where strengthening for shear is required, an effective and robust form of shear strengthening shall be selected that complies with the requirements of this document.

5.13.1 Shear strengthening methodologies using FRP may be based on either:

1) externally bonded FRPs attached to the concrete surface (for example, FRP fabric wrapped around beams);
2) deep embedment FRP bars, installed by resin fixing into holes drilled into slabs or beams; or
3) near-surface-mounted (NSM) FRP reinforcement, installed into grooves that have been cut into the cover concrete in the webs of beams.

5.14 The anchorage of the FRP shall be detailed in the design.

5.14.1 Shear strengthening should be undertaken by wrapping FRP completely around a beam where this is possible.

5.14.2 When externally bonded FRPs are not wrapped completely around a beam, additional FRP anchorage systems should be considered, based on specialist advice.

5.14.3 Where additional FRP anchorage systems are used, the effectiveness should be demonstrated based on testing.

5.15 All failure modes that could govern the shear resistance shall be verified, including failure modes limited by rupture of the FRP, separation of the FRP from the concrete, and crushing of the concrete.

5.15.1 The significance of failure modes governed by separation of the FRP is reduced when a beam is fully encased in FRP, however separation should still be verified.

5.15.2 The shear resistance of sections strenghtened with FRPs should be determined in accordance with CS TR55 [Ref 3.I].

5.16 The spacing of bars or strips of FRP for shear strengthening shall be limited to prevent shear failures occurring between the FRP bars or strips.

5.16.1 The spacing of FRP bars or strips should not exceed the criteria given in CS TR55 [Ref 3.I].

5.17 Longitudinal reinforcement and FRP shall be provided to resist the tensile forces that arise from the combined effects of shear and flexure.

5.17.1 Tensile forces due to combined shear and flexure should be verified according to CS TR55 [Ref 3.I].

6. Strengthening concrete bridge supports with FRPs

General

6.1 When strengthening concrete bridge supports is required, an effective form of strengthening shall be selected that complies with the requirements of this document.

6.1.1 Strengthening methodologies for concrete bridge supports using FRPs should be based on wrapping the support in FRP fabric with fibres that are oriented in the hoop (horizontal) direction, and, if required, in the axial (vertical) direction, bonded to the surface of the bridge support.

6.1.2 The outer layers of fibres should run in the hoop direction, to provide:

1) shear reinforcement; and
2) confinement effects.

NOTE 1 Enhancement of the concrete strength and ductility by confinement using FRPs is particularly effective for strengthening circular bridge supports.

NOTE 2 The effectiveness of the FRP confinement for non-circular sections depends on the geometry of the section and can be zero for rectangular sections. CS TR55 [Ref 3.I] provides guidance.

NOTE 3 For all sections, the stress that can be developed in the hoop FRP at failure is considerably lower than the tensile strength of the FRP. CS TR55 [Ref 3.I] provides guidance.

6.2 A minimum of two layers of FRP hoop fibres shall be provided.

6.3 FRPs in the hoop direction shall be installed with an effective overlap so that the FRPs act as a continuous hoop.

6.3.1 The length of the overlap should be determined in order to provide a full-strength anchorage and shall be no less than 200mm.

6.4 Where axial and hoop FRP are applied to a column, hoop FRP shall be placed over axial FRP.

6.5 FRPs in the axial direction shall be anchored effectively.

6.5.1 Anchorage lengths should be determined in accordance with CS TR55 [Ref 3.I].

6.6 Where strengthening is required to a bridge support below ground level or at the connection to the base, a concrete collar shall be provided.

6.6.1 Concrete collars should extend from the base to ground level or above.

6.7 Where flexural strengthening is required at the top connection to the crosshead or deck, a concrete or steel collar shall be provided.

6.8 The axial FRP shall be anchored effectively into the collar.

6.9 Collars and their connections into the structure or base shall be designed to resist the effects of the actions.

6.10 The design shall be carried out to avoid stress concentrations on fibres where they emerge from collars.

6.11 Appropriate details, including the provision of drips and sealants, shall be provided to prevent the ingress of water into the interface between the FRP and the concrete.

Strengthening for flexure and axial effects at the ultimate limit state

6.12 The flexural and axial resistance of bridge supports strengthened with FRPs shall be based on the following assumptions:

1) plane sections remain plane;
2) there is perfect bond;
3) the strains in the section at the time of strengthening are taken into account;

4) zero tensile strength in the concrete at ULS;
5) the stress in the concrete compression zone is determined based on a constitutive model for flexural design;
6) confined concrete properties only apply where sufficient effective confinement can be provided by the hoop FRP;
7) the strain in the concrete in the compression zone is limited to avoid crushing failure;
8) the stress in the reinforcement is determined based on constitutive models for design;
9) the FRP is linear elastic in tension based on the design value of the elastic modulus;
10) the strain in the FRP is limited to avoid tensile failure and separation of the FRP;
11) the compressive strength of axial FRP is taken to be zero; and
12) additional longitudinal tensile forces associated with shear effects are included in the design.

NOTE 1 Guidance on the flexural and axial resistance of circular and non-circular bridge supports strengthened with FRP is provided in CS TR55 [Ref 3.I].

NOTE 2 CS TR55 [Ref 3.I] provides models for determining the degree of confinement that is possible in circular and non-circular sections.

6.13 No enhancement of concrete properties due to confinement from the hoop FRP shall be included when the aspect ratio of the cross section of the bridge support is greater than 3:2, or when the combination of axial force and bending is such that the existing axial steel reinforcement yields in tension at ULS.

Strengthening for shear at the ultimate limit state

6.14 All failure modes that could govern the shear resistance shall be considered, including failure modes limited by FRP rupture, concrete crushing and separation of FRP from the concrete.

NOTE FRP separation failures are less significant for circular sections than for non-circular sections, due to the confining effect on the bond.

6.14.1 For circular sections, separation of the FRP may be deemed to be prevented if the strain in the hoop FRP is limited to 0.004.

6.14.2 The shear resistance of FRP strengthened bridge supports should be determined in accordance with CS TR55 [Ref 3.I].

7. Strengthening steel structures with FRPs

7.1 When strengthening steel structures is required, an effective form of strengthening shall be selected that complies with the requirements of this document.

7.1.1 Flexural strengthening methodologies using FRPs should be based on the application of externally bonded FRPs attached to the steel surface.

NOTE This document does not cover the shear strengthening of steel structures using FRPs.

7.2 The flexural resistance and stiffness of a steel section strengthened with FRPs shall be evaluated based on the following:

1) plane sections are assumed to remain plane (except for the anchorage regions and in the analysis of the adhesive layer);
2) the stresses in the structure when the FRP is installed are accounted for;
3) differential thermal expansion of the FRP and metallic elements are taken into account; and
4) FRP is assumed to be linear elastic until failure at the design tensile strain.

7.2.1 The strengthening design of steel structures using FRPs should be carried out using CIRIA C595 [Ref 9.I] in conjunction with this document.

7.3 Where it is necessary to extend the FRP into an area in compression, the resistance to buckling and a loss of composite action shall be verified.

7.4 Resistance to all failure modes that could govern the resistance shall be verified, including failure modes where there is a loss of composite action between the FRP and the steel, and failure modes where composite action is maintained.

7.5 Resistance to the following modes of failure shall be verified:

1) FRP rupture;
2) rupture of the metallic element;
3) global or local buckling of the element; and
4) rupture or bond failure of the adhesive.

NOTE Guidance on the verification of failure modes of steel structures strengthened with FRP is provided in CIRIA C595 [Ref 9.I].

7.6 Sufficient anchorage shall be provided beyond the point at which the FRP is required to be effective.

7.6.1 The anchorage should be designed using CIRIA C595 [Ref 9.I].

7.7 The force developed in the anchorage shall not exceed the resistance of the anchorage.

7.8 The design of FRP-strengthened steel structures shall include a detailed analysis of the local stresses in the adhesive layer, including shear and tensile (peeling) stresses and taking account of any lack of straightness in the FRP and yielding of the substrate.

NOTE 1 The behaviour of FRP-strengthened steel structures differs markedly from FRP-strengthened concrete structures. For example, for concrete structures the adhesive strength generally greatly exceeds the strength of the surface concrete, so the design is typically governed by the behaviour of the surface concrete. However, for steel structures the behaviour of the adhesive itself can govern the capacity of the strengthened member, and requires detailed consideration in the design.

NOTE 2 Peak local stresses typically occur in the adhesive near the ends of the FRP and at discontinuities or changes in thickness, due to variable actions including traffic loading and differential thermal expansion.

NOTE 3 The stresses in the adhesive cannot be analysed making the assumption that plane sections remain plane.

7.8.1 The analysis of the adhesive layer should be carried out using the methods of CIRIA C595 [Ref 9.I].

7.8.2 Stresses in the adhesive may be reduced by increasing the width of the FRPs and by tapering the FRPs near the end of the strengthening.

NOTE As the width of pre-manufactured FRP laminates is increased, the difficulty of expelling the air under the laminate during installation also increases, particularly for laminates wider than 300mm.

7.9 Thermal effects shall be included in the design, including differential thermal expansion between the FRP and the steel.

NOTE The coefficient of thermal expansion of FRP can differ significantly from that of steel elements. As a result differential thermal expansion can lead to significant stress concentrations at the ends of externally bonded FRP laminates and at any other geometric discontinuities.

7.10 The thermal effects shall be evaluated considering the timing of the operation and the range of effective bridge temperatures likely to be encountered.

7.10.1 Thermal actions should be taken from BS EN 1991-1-5 [Ref 4.I].

7.11 When FRP strengthening is proposed to enhance the fatigue life, shear capacity, bearing capacity or buckling resistance of metallic elements or to enhance the capacity of connections, the design approach shall be agreed with the Overseeing Organisation based on specialist guidance and proved by testing.

7.12 Cracked steel structures shall not be strengthened using FRP.

7.13 When a carbon fibre based system is used to strengthen a steel structure, an insulating layer shall be used between the carbon fibre and steel substrate to electrically isolate the FRP and prevent galvanic corrosion.

7.14 The effectiveness of the isolation system used between the carbon fibre and steel substrate to electrically isolate the FRP and prevent galvanic corrosion shall be verified by testing.

8. Strengthening concrete structures with externally bonded steel plates

General

8.1 When strengthening of concrete structures is required, an effective strengthening methodology shall be selected that complies with the requirements of this document.

8.1.1 Flexural strengthening methodologies for concrete structures using steel plates should be based on the application of steel plates bonded to the concrete surface to enhance the flexural resistance.

NOTE This document does not cover the strengthening for shear using steel plates.

8.2 The resistance to all failure modes that could govern the flexural resistance shall be verified, including failure modes where there is a loss of composite action between the steel plates and the concrete, and failure modes where composite action is maintained.

Design for anchorage and separation

8.3 Sufficient anchorage shall be provided beyond the point at which the steel plates are required to be effective.

8.3.1 The effective anchorage length should not be less than 1.2 times the plate width, plus 100mm.

8.3.2 Where the width to thickness ratio of the plate is less than 60, the effective anchorage length should not be less than 1.5 times the plate width, plus 100mm.

8.3.3 Bolts should be provided within the anchorage length.

8.3.4 Bolts within the anchorage length should be designed to resist 3 times the ultimate limit state longitudinal shear stress and be adequately anchored into the concrete substrate.

8.4 The longitudinal shear stress at the interface shall be limited to avoid failure of the concrete or the adhesive, using the same methods as for FRP-strengthened concrete structures in section 5.

8.5 Separation initiated by shear cracking shall be avoided using the same methods as for FRP-strengthened concrete structures in section 5.

8.6 Where it is necessary to extend the plates into an area in compression, the possibility of buckling and a loss of composite action shall be included in the design.

8.6.1 Buckling restraint provided by the bonded interface should be ignored.

8.6.2 Bolts may be used to resist buckling.

8.6.3 The spacing of bolts to resist plate buckling should be determined by calculation, considering imperfections and ignoring any restraint from adhesive.

8.6.4 The spacing of bolts to resist plate buckling should not exceed 300mm.

Flexural resistance at the ultimate limit state

8.7 The strengthened section shall be designed to have sufficient flexural resistance based on composite action being maintained.

8.8 The flexural resistance of the strengthened section shall be determined based on the following principles and assumptions:

1) plane sections remain plane;
2) perfect bond is assumed;
3) the strains in the section at the time of strengthening are taken into account;
4) zero tension in the concrete at ULS;

5) the stress in the concrete compression zone is determined based on a constitutive model for flexural design;
6) the strain in the concrete in the compression zone is limited to avoid crushing failure;
7) the stress in the reinforcement and prestressing is determined based on constitutive models for design;
8) the stress in the steel plate is limited to the design yield strength;
9) the loss of section which may occur during grit blasting is taken into account in the design; and
10) additional longitudinal tensile forces associated with shear effects are included in the design.

8.8.1 The design models for the concrete, reinforcement and prestressing should be taken from BS EN 1992 [Ref 5.I].

8.8.2 The steel plate should be designed in accordance with BS EN 1993 [Ref 6.I].

8.9 The strengthened section shall not be over-reinforced at the ultimate limit state.

NOTE Over-reinforced sections are those where the ultimate limit resistance is reached without yielding of the steel reinforcement.

Geometry of the plates

8.10 The width to thickness ratio of the plates shall not be less than 50.

8.11 The plate thickness shall not be less than 4mm.

NOTE The minimum plate thickness is required to avoid distortions during grit blasting and handling on site.

8.12 The transverse clear distance between the plates shall not be greater than twice the overall depth of the member less 100mm.

9. Installation, inspection and maintenance

Installation

9.1 The specification shall provide detailed requirements for the surface preparation of the structure, the application of the adhesive or resin, and the installation of the strengthening materials.

NOTE 1 The effectiveness of FRP strengthening and steel plate bonding is highly dependent upon the quality of installation.

NOTE 2 Further guidance is provided in CS TR55 [Ref 3.I] and CS TR57 [Ref 8.I] for concrete structures.

NOTE 3 The guidance in CS TR57 [Ref 8.I] refers to FRP strengthening but can also be relevant for steel plate bonding.

Inspection and maintenance

9.2 A comprehensive manual of procedures for inspection and maintenance of the strengthened structure shall be prepared including:

1) procedures for long-term monitoring and testing;
2) all relevant technical literature relating to the products used;
3) installation records, drawings, test findings and photographs of critical details. procedures for minor repairs;
4) accurate drawings indicating the as-built location of all FRP components and steel plates, including those buried by surfacing;
5) inspection methods to enable the identification of areas of debonding of externally bonded FRP laminates and steel plates; and
6) requirements for the inspection of the strengthening system before and after the passage of a significant abnormal load.

NOTE Debonding of FRPs and steel plates buried by surfacing can be indicated by local break-up or reflective cracking of the surface at the strengthening location.

10. 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 1991-1-7, 'Eurocode 1 - Actions on structures - Part 1-7 General actions - Accidental actions'
Ref 2.N	BSI. BS EN 1993-2, 'Eurocode 3. Design of steel structures Part 2: Steel 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	BSI. BS EN 10025, 'Hot rolled products of structural steels'
Ref 6.N	Highways England. GG 101, 'Introduction to the Design Manual for Roads and Bridges'
Ref 7.N	Highways England. MCHW Series 1900, 'Manual of Contract Documents for Highway Works, Volume 1 Specification of Highways Works, Series 1900, Protection of Steelwork against Corrosion'

11. Informative references

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

Ref 1.I	Institution of Structural Engineers. ISE Adhesives, 'A guide to the use of structural adhesives'
Ref 2.I	Highways England. CS 454, 'Assessment of highway bridges and structures'
Ref 3.I	Concrete Society. CS TR55, 'Design guidance for strengthening concrete structures using fibre composite materials'
Ref 4.I	BSI. BS EN 1991-1-5, 'Eurocode 1: Actions on structures. Part 1-5: General actions – Thermal actions'
Ref 5.I	BSI. BS EN 1992, 'Eurocode 2. Design of concrete structures'
Ref 6.I	BSI. BS EN 1993 , 'Eurocode 3: Design of steel structures'
Ref 7.I	Highways England. CS 462, 'Repair and management of deteriorated concrete highway structures'
Ref 8.I	Concrete Society. CS TR57, 'Strengthening concrete structures with fibre composite materials - acceptance, inspection and monitoring'
Ref 9.I	CIRIA. CIRIA C595, 'Strengthening Metallic Structures Using Externally Bonded FRP'
Ref 10.I	Highways England. CS 455, 'The assessment of concrete highway bridges and structures'