SUMMARY

This Standard covers the strengthening of concrete and metallic highway bridges, on trunk roads including motorways, using externally bonded fibre reinforced polymer (FRP). This Standard does not cover the use of prestressed plates or other systems in which the FRP is subjected to sustained long-term loading. This Standard does not cover the strengthening of prestressed concrete structures, although many of the issues and limit states described will also be relevant to the design of FRP strengthening schemes for such structures. Design guidelines are provided for flexural and shear strengthening of reinforced concrete bridge decks. Design guidelines for strengthening metallic bridge decks are limited to flexural strengthening. In addition, general guidance is provided on suitable strengthening techniques.

INSTRUCTIONS FOR USE


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Strengthening Highway Structures Using Externally Bonded Fibre Reinforced Polymer

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November 2008
PART 18

BD 85/08

STRENGTHENING HIGHWAY STRUCTURES USING EXTERNALLY BONDED FIBRE REINFORCED POLYMER

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Annex A Flow Chart for FRP Strengthening Design
1. INTRODUCTION

General

1.1 This Standard covers the strengthening of concrete and metallic highway structures using externally bonded fibre reinforced polymer (FRP). The viability of the technique when applied to reinforced concrete has been demonstrated through experimental studies and numerous practical applications in the UK and elsewhere. Experience of its application to metallic structures is more limited and less experimental verification exists.

1.2 This Standard focuses on the use of FRP for strengthening both reinforced concrete and metallic beams and reinforced concrete slabs. Design guidelines are provided for flexural and shear strengthening of reinforced concrete structures. Design guidelines for strengthening metallic structures are limited to flexural strengthening. In addition general guidance is provided on suitable strengthening techniques and their specification.

1.3 This Standard does not cover the use of prestressed plates or other systems in which the FRP is subjected to sustained long-term loading. However, some general guidance on such techniques is provided in Clauses 2.17 to 2.19.

1.4 This Standard does not cover the strengthening of prestressed concrete structures, although many of the issues and limit states described in Chapters 3 and 4 will also be relevant to the design of FRP strengthening schemes for such structures.

Implementation

1.5 This Standard shall be used forthwith on all schemes involving strengthening of highway bridge decks on trunk roads, including motorways. In Northern Ireland this Standard shall be used forthwith on all schemes involving strengthening of highway bridge decks on all roads. The use of FRP for the strengthening of bridge supports is dealt with in BD 84/02 (DMRB 1.3.16).

Definitions

1.6 The following definitions and terminology relating to FRP are used in this document:

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: Fibres produced from organic materials such as rayon, polyacrylonitrile or pitch. 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. Cure may be accomplished by the addition of curing agents, with or without catalyst, and with or without heat.

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 (or Plastic) comprising high strength fibres in a resin matrix.

Galvanic corrosion: Also called 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. Pultruded sections are often referred to as laminates, but the term is not specific to any method of production.
NSM FRP: Near-surface mounted (NSM), where FRP is installed into grooves that have been cut into the concrete.

Pre preg: 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. 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 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 stress level considerably less than the ultimate stress under sustained loading.

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. The dry FRP (fabric or tow sheet) is impregnated with resin immediately prior to application.

Notation

1.7 The following notation is used in this document:

- \( \alpha \): Angle between the principal fibres of the FRP and the vertical
- \( \gamma_{ma} \): Material partial safety factor for adhesive
- \( \gamma_{mc} \): Material partial safety factor for concrete
- \( \gamma_{mfc} \): Material partial safety factor for FRP strain capacity
- \( \gamma_{ms} \): Material partial safety factor for steel reinforcement
- \( \varepsilon_{fps} \): Effective strain in the FRP for shear strengthening
- \( \varepsilon_{fpu} \): Characteristic ultimate strain capacity of FRP
- \( \lambda \): Parameter used to determine longitudinal shear at point where reinforcement yields
- \( \sigma_{frp1} \): Stress in FRP at location 1
- \( \sigma_{frp2} \): Stress in FRP at location 2
- \( \sigma_{at} \): Maximum tensile principal stress in the adhesive
- \( \tau_{f} \): Longitudinal shear stress at the FRP-concrete interface
- \( \omega_{f} \): Parameter used to determine longitudinal shear at point where reinforcement yields
- \( \omega_{s} \): Parameter used to determine longitudinal shear at point where reinforcement yields
- \( A_{frpm} \): Cross-sectional area of the FRP laminate for flexural strengthening (mm
- \( A_{frps} \): Cross-sectional area of FRP (mm
- \( A_{s} \): Cross-sectional area of tensile steel reinforcement (mm
- \( b \): Cross-sectional area of tensile steel reinforcement (mm
- \( b_{frp} \): Width of the FRP laminate (mm) measured perpendicular to the direction of the fibres (see Figure 1.1). For continuous FRP sheet, \( s_{frp} \) is taken as 1.0 and \( b_{frp} \) is taken as \( \cos \alpha \)
- \( d \): Effective depth to the centroid of the tensile steel reinforcement (mm)
Characteristic tensile modulus of the steel reinforcement (MPa)

Characteristic tensile modulus of the FRP laminate (MPa)

Characteristic or worst credible strength of the concrete (MPa)

Characteristic tensile strength of the concrete (MPa)

Characteristic or worst credible strength of the tensile steel reinforcement (MPa)

Characteristic strength of the adhesive

Maximum anchorage capacity of FRP (N)

FRP anchorage capacity (N)

Force in FRP (N)

Total depth of the section (mm)

Parameter used to determine maximum anchorage capacity of FRP

Anchorage length required to develop $F_{ck,max}$ (mm)

Anchorage length (mm)

Longitudinal spacing of the FRP laminates used for shear strengthening (see Figure 1.1). For continuous FRP sheet, $s_{fp}$ is taken as 1.0 and $b_{fp}$ is taken as $\cos \alpha$

Thickness of the FRP laminate (mm)

Shear force due to ultimate loads (N)

Contribution from the concrete to the shear capacity (N)

Contribution from the FRP to the shear capacity (N)

Contribution from the steel to the shear capacity (N)

Ultimate shear capacity of FRP strengthened section (N)
Figure 1.1  Notation for Shear Strengthening of Concrete Elements

\[ A_{frps} = 2b_{frp} t_{frp} \]

- $d$:
- $h$:
- $s_{frp}$:
- $b_{frp}$:
- $\alpha$:

FRP Laminates on both sides
2. APPLICATION

General

2.1 FRP can be used to increase the load capacity of structural elements as described in this Standard. A structure shall only be considered suitable for strengthening using this technique if it can be shown to be at least capable of supporting nominal dead load plus nominal superimposed dead load plus nominal assessment live load, as specified by BD 21 (DMRB 3.4) with all partial safety factors, including those applied to material strengths, set to unity.

2.2 General guidance on the use of FRP to strengthen concrete structures is given in the Concrete Society Technical Reports No. 55[1] and No. 57[4]. General guidance on the use of FRP to strengthen metallic structures is given in CIRIA Report, C595 Strengthening metallic structures using externally bonded fibre-reinforced polymers[5] and ICE design and practice guide FRP composites – Life extension and strengthening of metallic structures[6].

2.3 For a particular structure, an economic evaluation shall be carried out in order to compare this technique with other methods of strengthening. This evaluation shall include a risk assessment, taking into account the performance history of the proposed techniques. Factors to be considered are safety, cost, construction methods, environmental considerations, remaining life and inspection and maintenance capability.

2.4 FRP systems are available in many forms including fabrics applied using a wet lay-up process, and factory produced FRP plates installed using adhesives. All FRP systems are acceptable provided they comply with the requirements of this Standard and have been shown to be appropriate for the application for which they are being considered.

2.5 Where uncertainties exist concerning the effectiveness of an FRP system for a particular application, appropriate experimental testing on representative specimens shall be undertaken to prove the technique. Examples where this 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. The requirements for, and the extent of, the testing shall be agreed with the Overseeing Organisation.

2.6 The durability of all components of the FRP strengthening system shall be considered when selecting an appropriate strengthening approach. Information and test results to demonstrate the long-term performance of the system shall be sought from manufacturers and suppliers (see also Chapter 6).

2.7 A flow chart is included in Annex A setting out the steps to be taken in assessing the suitability of a structure for strengthening using FRP, together with references to relevant documents and clauses.

Suitability of Structure

2.8 The effectiveness of externally bonded FRP is highly dependent on the integrity of the bond between the FRP and the surface of the structure and also on the integrity of the surface material itself. This interface must be capable of sustaining the stresses necessary for tension to be developed in the FRP. For surface profile requirements for concrete, see Clause 4.25.

2.9 When considering the suitability of a structure for the application of externally bonded FRP, 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. For concrete structures, BA 35, The inspection and repair of concrete highway structures (DMRB 3.3.2) gives advice on special inspections and guidance.
2.10 Externally bonded FRP shall only be applied to dry surfaces. Remedial measures shall be taken if surfaces are damp, and leakages stopped. Any damaged material shall be removed down to a sound base.

2.11 For concrete structures, expansive rust products arising from reinforcement corrosion may disrupt the concrete and eventually cause de-bonding of the FRP. Therefore, unless repairs have been carried out, bonding shall only be considered where half-cell potential measurements are numerically greater than -250mV with respect to a copper/copper sulphate electrode.

2.12 For concrete structures, the integrity of the surface concrete and its associated method of preparation shall be demonstrated by a series of pull-off tests, for which the failure plane should occur within the concrete. Such tests shall be carried out in accordance with PR EN 1542. A minimum of five tests shall be undertaken at representative locations on each element to which the FRP is to be bonded. 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. FRP strengthening shall not be used when the characteristic concrete tensile strength is less than 1.5 N/mm².

2.13 Wrought iron structures may be prone to delamination. For this reason, wrought iron structures shall not be strengthened with FRP without the specific approval of the Overseeing Organisation. Guidance shall be sought from specialist designers in such cases.

2.14 Where FRP is bonded to soffits above carriageways, the available headroom shall be checked to ensure that impact from high vehicles is not likely, making allowance for the presence of fixings if used. FRP should not be installed on bridge soffits where there is evidence of frequent damage from vehicle impact.

2.15 The ease of inspection of the installed system shall be considered in devising the strengthening scheme and a recommended inspection regime (see Chapter 7).

2.16 Special consideration shall be taken where strengthening is required to the top surfaces of slabs and beams and subsequently buried by the road surfacing. In such cases it can be impractical to provide inspection facilities for the plates. Special care should be taken during bridge inspections to identify any areas of plates which may have de-bonded as indicated by local break-up or reflective cracking of the surface in the location of the plates. Accurate drawings indicating the location of all plates shall be available for such inspections (see Clause 7.1). The use of Near Surface Mounted (NSM) FRP should be considered in top slab strengthening applications. See Clause 4.2.

2.17 The efficiency of externally bonded FRP strengthening can be increased by prestressing the FRP, or alternatively by jacking up a structure during the installation of the FRP. Such approaches can enable a greater proportion of the ultimate strength of the FRP to be utilised. Only a limited amount of testing of such systems is currently available.

2.18 When FRP is subjected to sustained long-term loading, failure of the FRP can occur through creep rupture at a load level significantly below its ultimate short-term strength. Creep rupture can be prevented by limiting the magnitude of any sustained loading.

2.19 Guidance shall be sought from specialist designers and materials suppliers when a strengthening scheme includes the use of externally bonded FRP subjected to sustained loading. The design of such schemes is not covered by the guidelines given in this Standard, although many of the issues and limit states described are relevant to their design.
3. DESIGN

General

3.1 The design guidelines set out in this Standard are based upon experimental findings and current best practice in the design of FRP strengthening schemes. They are applicable to the design of strengthening schemes using both pultruded laminates and fabric systems. Before undertaking a design, the requirements of Clause 2.5 should be carefully considered.

3.2 Structural elements strengthened with FRP can have significantly reduced ductility when compared with conventional structural elements of the same strength. The ductility of FRP strengthened elements can be particularly low when their ultimate capacity is governed by failure modes involving fracture of the FRP or a loss of composite action between the FRP and the surface to which it is bonded. The implications of such limited ductility of FRP strengthened elements shall be carefully considered, especially in relation to the structural analysis upon which the design is based.

3.3 The FRP strengthening system should be designed for a minimum service life of 30 years.

3.4 The stresses in the structure when the FRP is installed shall be taken into account in the design. Such stresses may arise from permanent and live loads, support settlement or thermal effects. Particular care is required in establishing permanent stresses in statically indeterminate structures and for brittle metallic structures for which the strengthening design will be particularly sensitive to the stress in the structure when the FRP is installed. In such cases, it may be necessary to undertake tests to establish the permanent stresses in the structure with confidence. If excessive vibrations are expected the designer should consider excluding traffic from the bridge while the FRP is installed.

Properties of FRP

3.5 Characteristic values of the elastic modulus, strain to failure and ultimate stress of the FRP material shall be used in design. A characteristic value is defined as the value below which not more than 5% of all possible test results may be expected to fall.

3.6 Care shall be taken to ensure that consistent properties for the FRP are used in the design and installation. These should be noted on all drawings and relevant documents.

Properties of Concrete and Reinforcement

3.7 Characteristic values of steel reinforcement and concrete strengths may be used. Alternatively, worst credible values may be derived from test data where they exist, in accordance with BD 44 (DMRB 3.4.14). Where design values are not known or are uncertain, tests shall be undertaken to enable appropriate values to be derived. Guidance on the assessment of material properties is given in BD 21 (DMRB 3.4.3).

Properties of Metallic Elements

3.8 The material strengths of metallic elements may be obtained using BD 21 (DMRB 3.4.3). Additional guidance is included in the CIRIA report C595[5].
Partial safety factors

3.9 The partial safety factors for FRP for the ultimate limit state shall be taken from Table 3.1 or Table 3.2. These safety factors shall be applied to the characteristic values of the material properties. The values given in Table 3.1 may be used for Combination 4 loading in accordance with BD 37 (DMRB 1.3.14). The values in Table 3.2 shall be used in all other cases.

3.10 For the serviceability limit state, the value of the partial safety factors for FRP shall be taken as 1.0.

3.11 For the ultimate limit state, the partial safety factors for material strength shall be as specified in BD 44 (DMRB 3.4.14) for concrete elements, and BD 21 (DMRB 3.4.3) for steel elements.

3.12 For the serviceability limit state, the partial safety factors shall be taken as specified in BS 5400: Part 4 for concrete elements, and BS 5400: Part 3 for steel elements.

3.13 Strengthened cast iron elements shall be analysed on a permissible stress basis, as described in BD 21 (DMRB 4.3), with the partial factors for FRP taken from Table 3.1 or 3.2. The values given in Table 3.1 may be used for Combination 4 loading in accordance with BD 37 (DMRB 1.3.14). The values in Table 3.2 shall be used in all other cases.

3.14 The partial factor for the adhesive at ultimate limit state should be taken as $\gamma_{\text{mfe}} = 5$, unless a project-specific value is determined and agreed with the Overseeing Organisation. Adhesive properties are affected by environment and time related factors in addition to material variability. Guidance on the evaluation of project-specific partial factors is included in C595[5].

### Table 3.1 Values of partial factors for FRP materials for the ultimate limit state for Combination 4 loadings in accordance with BD 37

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<th>Material</th>
<th>$\gamma_{\text{mfe}}$</th>
<th>$\gamma_{\text{mf}}$</th>
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<tr>
<td>Carbon</td>
<td>1.15</td>
<td>1.15</td>
</tr>
<tr>
<td>Aramid</td>
<td>1.20</td>
<td>1.20</td>
</tr>
<tr>
<td>Glass</td>
<td>1.50</td>
<td>1.50</td>
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### Table 3.2 Values of partial factors for FRP materials for the ultimate limit state, excluding Combination 4 loading in accordance with BD 37

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<th>$\gamma_{\text{mfe}}$</th>
<th>$\gamma_{\text{mf}}$</th>
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<td>Wet lay up</td>
<td>Laminate</td>
<td>Wet lay up</td>
</tr>
<tr>
<td>Carbon</td>
<td>1.3</td>
<td>1.15</td>
</tr>
<tr>
<td>Aramid</td>
<td>1.3</td>
<td>1.15</td>
</tr>
<tr>
<td>Glass</td>
<td>2.13</td>
<td>1.89</td>
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4. STRENGTHENING CONCRETE STRUCTURES

General

4.1 The guidelines set out in this Chapter are applicable to the design of strengthening schemes for reinforced concrete beams and slabs.

Strengthening for Flexure

4.2 FRP materials can be bonded to the tension face of beams or slabs to act as additional reinforcement, increasing the moment of resistance of the section. The FRP reinforcement can be either externally bonded to the concrete structure or near-surface mounted (NSM), where the bars are installed into grooves that have been cut into the concrete. The bonding operation can frequently take place with no or minimal disruption to traffic and without a need for temporary propping.

4.3 Structures strengthened with FRP to increase their flexural capacity can exhibit the same ultimate failure modes as reinforced concrete structures, for example, compressive failure of the concrete. However, in addition, their capacity may also be governed by fracture of the FRP or by the loss of composite action between the FRP and the concrete, sometimes referred to as FRP separation, debonding or peeling. Failure modes in which the FRP separates from the concrete section have frequently been found to be critical in experimental studies.

4.6 Structures strengthened with FRP to increase their shear capacity can fail due to separation of the FRP from the concrete. The significance of such failure modes is reduced when a beam is fully encased in FRP. However, it is frequently difficult to achieve this, for example where beams are continuously connected to a deck slab.

4.7 Whenever practicable, shear strengthening should be undertaken by wrapping FRP completely around a beam. However, when as in most cases this is not possible, the FRP wrapping should be applied to the sides and either the top or underside of a beam. Whilst not encouraged, bonding to only the sides of beams is permissible in cases where it is not possible to continue the FRP around the top or the underside of a beam. When FRP is not wrapped completely around a beam consideration should be given to the use of additional FRP anchorage systems. Specialist advice should be sought in such cases.

4.8 Design rules for externally bonded FRP for shear strengthening are set out in Clauses 4.33 to 4.40. These rules have been calibrated against published experimental data for shear strengthening using carbon and aramid systems. The limit states given are also relevant to the design of shear strengthening using glass fibre systems. However, there is currently very limited experimental data on the use glass fibre in this application and the requirements of Clause 2.5 should be carefully considered before it is used. The design rules presented are not applicable to NSM FRP reinforcement.

4.9 In view of the potentially brittle nature of the shear failure of FRP-strengthened elements, the relative effectiveness of shear strengthening would be expected to diminish as the size of the element being strengthened increases. The extrapolation of experimental results from small specimens to real structures must therefore be undertaken with caution. Such a potential size effect has been taken into account in the design rules in this Standard.

Strengthening for Shear

4.5 Bonding FRP to the webs of beams has been shown experimentally to increase the shear strength of the section. The bonded material acts as external shear reinforcement. The use of FRP for shear strengthening is less well established than its use for flexural strengthening and has been the subject of fewer experimental studies.
Limit States

4.10 The design of strengthened structures shall be considered for the ultimate limit states in accordance with the relevant clauses of BS 5400: Part 4: 1990 (BSI 1990) as implemented by BD 24 (DMRB 1.3.1), except where amended by other clauses in this Standard. The appropriate loads and load factors shall be taken from BD 37 (DMRB 1.3.14).

4.11 The criteria for the serviceability limit states given in Clause 4.1.1 of BS 5400: Part 4, shall be followed, except where amended in this Standard.

Flexural Capacity

4.12 The analysis of a concrete section strengthened for flexure using FRP shall be based on the following:

(i) The strain at any level in the section shall be determined assuming that plane sections remain plane.

(ii) The FRP is a linear elastic material, as shown in Figure 4.1.

(iii) The stress-strain behaviour of the concrete is as given in BS 5400: Part 4. A rectangular stress block shall only be used when considering concrete crushing.

The stress-strain behaviour of the steel reinforcement is linear-elastic in tension, with an elastic modulus of 200 kN/mm², until the yield stress \( f_y \gamma_{ms} \) is reached, as shown in Figure 4.1.

4.13 For concrete members strengthened for flexure, the following modes of failure shall be considered, assuming that composite action is retained between the FRP and the concrete section:

(i) FRP rupture; and

(ii) crushing of the concrete.

4.14 FRP rupture should be considered to occur when the strain in the FRP reaches \( e_{frp} / \gamma_{mf} \). Concrete crushing should be considered to occur when the strain in the concrete at the compressive face reaches 0.0035. If the section analysis indicates that concrete crushing occurs before the steel reinforcement has reached its yield stress, then the required moment of resistance of the strengthened section should be increased by 15%.

---

Figure 4.1 Short-term Stress Strain Curve for Steel and FRP Reinforcement

\[ E_s = 200 \text{ kN/mm}^2 \]
4.15 For concrete members strengthened for flexure, failure can also occur when there is a loss of composite action between the FRP and the concrete section. Typically failures occur through the development of a longitudinal failure plane close to the interface between the FRP and the concrete or at the level of the main reinforcement. Such longitudinal failure planes can initiate from:

(i) Ends of FRP;

(ii) Shear cracks;

(iii) Flexural cracks;

(iv) Concave surface profiles.

4.16 The bond behaviour of externally bonded FRP differs markedly from embedded steel reinforcement. It is possible to anchor steel reinforcement by providing a sufficient anchorage length such that, beyond this anchorage length, the full strength of the reinforcement can be developed. However this is not typically the case for externally bonded FRP. Experiments have demonstrated that the longitudinal shear stress that can be transferred between the FRP and the concrete is not independent of the bonded length, as typically assumed in design for embedded steel reinforcement. In tests on the anchorage of FRP externally bonded to concrete, it has been found that beyond a limiting bonded length, of the order of 50-300mm, there is no further increase in the ultimate anchorage load-capacity with increased bonded length. Furthermore, this ultimate anchorage capacity can be very much less than the ultimate tensile capacity of the FRP.

4.17 Experimental findings have indicated that the maximum force that can be developed in FRP externally bonded to concrete that is uncracked under the applied load is limited to the anchorage force given in Clause 4.27. In cases where the FRP is externally bonded to a structural element that remains uncracked under the ultimate load case for which it is being strengthened, the maximum force in the FRP must be limited to the anchorage capacity given in Clause 4.27. Instances where this requirement may be applicable include structural members with significant changes in section properties, for example the transverse strengthening of thin outstands cantilevered from a bridge deck.

4.18 Failure modes where there is a loss of composite action between the FRP and concrete section shall be considered in the design of FRP strengthening. Such failure modes may be avoided by limiting:

(i) the strain in the FRP;

(ii) the longitudinal shear stress between the FRP and the concrete section;

(iii) irregularities in the profile of the surface to which the FRP is bonded;

(iv) the stress in the FRP near its end (i.e. in the anchorage region).

Guidance on suitable limits is provided in Clauses 4.21 to 4.29. These limits may be relaxed if a rigorous analysis is undertaken or based on experimental results using representative sized specimens. The likelihood of failure modes involving a loss in composite action may be decreased for externally bonded FRP by reducing the FRP thickness and by tapering the FRP when multiple layers are used.

4.19 Tests have shown that bolts can be used with multi-directional externally bonded FRP laminates to prevent loss of composite action. Where used, the anchorage strength shall be verified through appropriate testing.

4.20 Specialist advice shall be sought in cases where shear cracks could initiate a loss of composite action. Such a mode of failure may be disregarded if the maximum applied shear force can be carried by the concrete alone, neglecting any contribution to the shear capacity made by shear reinforcement.

4.21 The maximum strain in the FRP shall not be greater than 0.008. This limit will generally be more onerous than the factored ultimate FRP tensile strain capacity. The likelihood of failure modes occurring that involve a loss of composite action has been found experimentally to increase if this strain limit is exceeded. The data upon which this limit is based comes predominantly from tests using externally bonded carbon. In the absence of more comprehensive test data it is also required for NSM FRP strengthening. This limit may be relaxed.
based on experimental results using representative sized specimens. This would be subject to the agreement of the Overseeing Organisation.

4.22 The longitudinal shear at the interface between the adhesive and concrete shall not exceed the ultimate values given in Table 31 of BS 5400: Part 4, Clause 7.4.2.3. The longitudinal shear at the interface between the FRP and the adhesive shall not exceed 20% of the shear capacity of the adhesive.

The longitudinal shear shall be checked, at least, at terminations in the FRP and the position in the span where the steel reinforcement yields. The longitudinal shear stress may be determined from:

\[
\tau_1 = t_{fp} \left( \frac{\sigma_{fp2} - \sigma_{fp1}}{\Delta x} \right) \quad \text{for externally bonded FRP}
\]

\[
\tau_1 = \frac{\pi \phi_{fp}^2}{4p} \left( \frac{\sigma_{fp2} - \sigma_{fp1}}{\Delta x} \right) \quad \text{for NSM FRP}
\]

where \( \sigma_{fp1} \) is the stress in the FRP at the location of interest and \( \sigma_{fp2} \) is the stress in the FRP at a small distance \( \Delta x \) from the location of interest in the direction in which the applied moment is increasing, \( \phi_{fp} \) is the nominal diameter of the NSM FRP bar and \( p \) is the effective perimeter of the interface at which the longitudinal shear is being checked. \( \sigma_{fp1} \) and \( \sigma_{fp2} \) may be determined from a section analysis in accordance with Clause 4.12.

For NSM FRP, in special cases where the preparation or condition of the concrete does not allow the complete concrete interface to be fully effective in resisting longitudinal shear, specialist advice shall be sought and the value for \( p \) shall be reduced accordingly. It may be appropriate to reduce the effective perimeter \( p \) to \( w_g + h_g \) in cases where the method of preparing the grooves results in sides which cannot be assumed to achieve effective bond with confidence, where \( w_g \) and \( h_g \) are the width and height of the groove in cross section.

4.23 For sections where the design indicates that the steel reinforcement would yield or where the compressive strain in the concrete is such that its behaviour is significantly non-linear, standard elastic methods for determining the longitudinal shear stress in prismatic sections should not be used.

4.24 Provided that the stresses due to permanent loads prior to strengthening have a negligible effect on the stresses due to ultimate loads, which may be assumed to be the case if the structure is uncracked in the region being strengthened, the longitudinal shear stress at the location in the span where the reinforcement yields for prismatic elements with solid, rectangular sections strengthened with externally bonded FRP may be conservatively taken as:

\[
\tau_i = \frac{\lambda V t_{fp}}{A_{fp} h} \quad \text{provided} \quad \frac{d}{h} > 0.7
\]

where \( \lambda \) is determined from Figure 4.2 for mild steel reinforcement (up to \( f_y = 250 \text{N/mm}^2 \)) and Figure 4.3 for high yield steel reinforcement (up to \( f_y = 460 \text{ N/mm}^2 \)). In Figures 4.2 and 4.3:

\[
\omega_s = \frac{A_i \left( \frac{f_y}{\gamma_{mc}} \right)}{bh \left( \frac{f_{cu}}{\gamma_{mc}} \right)} \quad \text{and} \quad \omega_f = \frac{A_{frp} \left( \frac{E_{frp}}{\gamma_{mfE}} \right)}{bh \left( \frac{f_{cu}}{\gamma_{mc}} \right)}
\]
4.25 If FRP is bonded to a concrete surface with a concave profile, the likelihood of FRP separation failure is increased. Unless justified through a rigorous analysis or experimental results, the gap under a 1m long straight edge held to the surface of the FRP following installation shall nowhere exceed 3mm. If preformed laminates such as pultruded plates are used, the gap under a 1m long straight edge held to the surface of the concrete prior to the installation of the FRP may be up to 5mm provided the depth of adhesive is varied to achieve the required FRP straightness after installation. Where fabric systems are used particular care is required in the surface preparation since such systems will closely follow the surface profile of the concrete. For NSM FRP systems the grooves should be cut to allow the bars to be installed straight.
4.25 If FRP is bonded to a concrete surface with a concave profile, the likelihood of FRP separation failure is increased. Unless justified through a rigorous analysis or experimental results, the gap under a 1m long straight edge held to the surface of the FRP following installation shall nowhere exceed 3mm. If preformed laminates such as pultruded plates are used, the gap under a 1m long straight edge held to the surface of the concrete prior to the installation of the FRP may be up to 5mm provided the depth of adhesive is varied to achieve the required FRP straightness after installation. Where fabric systems are used particular care is required in the surface preparation since such systems will closely follow the surface profile of the concrete. For NSM FRP systems the grooves should be cut to allow the bars to be installed straight.

4.26 Sufficient anchorage shall be provided beyond the point at which the FRP is no longer required to ensure that any force in the FRP developed within this anchorage region can be sustained. The force in the FRP developed within the anchorage region may be determined by undertaking an analysis of the strengthened section at the point where the FRP is no longer required in accordance with Clauses 3.4 and 4.12. A minimum anchorage length of 500mm shall be provided when the FRP is terminated within a span.

4.27 For externally bonded FRP, the maximum anchorage force may be assumed to be given by:

\[ F_{c_k, \text{max}} = 0.5k_b b_{frp} \sqrt{ \frac{E_{frp} t_{frp} f_{com}}{\gamma_{mfr} \gamma_{mc}} } \]  

(N)

where

\[ k_b = 1.06 \frac{2 - b}{1 + \frac{b}{400}} \geq 1.0 \]

and \( b_{frp} \) and \( t_{frp} \) have units of mm and \( E_{frp} \) and \( f_{com} \) have units of N/mm².

The anchorage length required to develop this force may be assumed to be given by:

\[ L_{c, \text{max}} = \frac{E_{frp} t_{frp} f_{com}}{2f_{com}} \]  

(mm)

For shorter anchorage lengths, \( L_a < L_{c, \text{max}} \), the anchorage force is given by:

\[ F_{c_k} = F_{c_k, \text{max}} \frac{L_a}{L_{c, \text{max}}} \left[ 2 - \frac{L_a}{L_{c, \text{max}}} \right] \]  

(N)

4.28 For NSM FRP, the maximum anchorage force per bar may be assumed to be given by:

\[ F_{c_k, \text{max}} = 1.5 \left( \frac{E_{frp} \pi \phi_{frp}^2}{4} \frac{w_g + 2h_g}{f_{com}} \right) \]  

(N)

The anchorage length required to develop this force may be assumed to be given by:

\[ L_{c, \text{max}} = 4.5 \left( \frac{E_{frp} \pi \phi_{frp}^2}{4} \frac{w_g + 2h_g}{f_{com}} \right) \]  

(mm)

where \( \phi_{frp} \) is the nominal diameter of the FRP bar, measured in mm, \( w_g \) and \( h_g \) are the width and height of the groove in cross section, measured in mm, and \( E_{frp} \) and \( f_{com} \) have units of N/mm².

For shorter anchorage lengths, \( L_a < L_{c, \text{max}} \), the anchorage force is given by:

\[ F_{c_k} = F_{c_k, \text{max}} \frac{L_a}{L_{c, \text{max}}} \left[ 2 - \frac{L_a}{L_{c, \text{max}}} \right] \]
4.29 The adhesive used in NSM FRP strengthening schemes shall have sufficient strength to prevent a splitting failure in the adhesive under ultimate loading. This requirement may be taken to be satisfied if the following criteria are met, in addition to the requirements of 4.28:

- \( f_{\text{fatm}} \geq 5.0 f_{\text{cmin}} \)
- \( f_{\text{fatm}} \geq 12 \text{ MPa} \)
- \( 1.5 \phi_{\text{frp}} \leq w_{g} \leq 2.5 \phi_{\text{frp}} \)
- \( 2.0 \phi_{\text{frp}} \leq h_{g} \leq 5.0 \phi_{\text{frp}} \)

where \( f_{\text{fatm}} \) is the characteristic tensile strength of the adhesive.

4.30 If the force in the FRP developed within the anchorage region is in excess of the anchorage capacity then consideration should be given to reducing the thickness and increasing the width of externally bonded FRP. Alternatively a rigorous analysis of the development of the force in the FRP within the anchorage region may be used to demonstrate that extending the FRP further into the anchorage region will enable the required anchorage force to be developed. However, if such a rigorous analysis is undertaken, particular care should be taken if the FRP is extended into a region where the concrete is likely to be cracked at ULS.

4.31 If the FRP extends into areas in compression, buckling of the FRP might occur, resulting in a loss of composite action. Where it is necessary to extend the FRP into an area in compression, the possibility of buckling should be considered.

4.32 It is recommended that when several strips of FRP are required these should be applied next to each other rather than in layers. If it is necessary to install multiple layers of FRP then, unless proven by rigorous analysis or experimental testing, the maximum number of layers should be limited to three for pultruded strips or five for cured in-situ fabrics.

**Shear Capacity**

4.33 For concrete members strengthened for shear, the following modes of failure shall be considered at the ultimate limit state:

(i) FRP rupture;

(ii) FRP separation from concrete;

(iii) excessive shear-crack widths (resulting in a loss of effectiveness of the concrete in carrying shear through aggregate interlock and friction).

These failure modes may be avoided by limiting the strain in the FRP. Guidance on suitable limits is provided in Clause 4.37.

4.34 The shear capacity of the FRP strengthened concrete section, \( V_s \), shall be determined by adding the contributions from the concrete, steel and FRP, i.e.

\[
V_u = V_c + V_s + V_{\text{frp}}
\]

The contribution from the concrete and the steel may be determined in accordance with BD 44. The area of any longitudinal FRP reinforcement shall be ignored in the calculation of the shear capacity of the concrete section. The combined contributions from the steel and FRP shall not be less than 0.4bd (N).

4.35 The maximum shear stress shall not exceed the limits specified in BS 5400: Part 4.

4.36 The contribution to the shear capacity from FRP with principal fibres at an angle, \( \alpha \), to the vertical is given by (See Figure 1.1):

\[
V_{\text{frp}} = \frac{E_{\text{frp}}}{\gamma_{\text{frp}}} \varepsilon_{\text{frp}} A_{\text{frp}} \left( \frac{d}{s_{\text{frp}}} \frac{n L_{c,\text{max}}}{3} \right) \left( \cos \alpha + \sin \alpha \right)
\]

where \( L_{c,\text{max}} \) is determined in accordance with Clause 4.28 and \( n \) is taken as zero, except when considering FRP separation from the concrete as described in Clause 4.37, when it should be taken as zero for a fully wrapped beam, 1.0 when FRP is bonded continuously to the sides and bottom of a beam and 2.0 when it is bonded to the sides of a beam only.
4.37 To prevent FRP rupture, FRP separation from the concrete and excessive shear crack widths, the effective strain in the FRP, $\varepsilon_{frp}$, shall not be greater than the minimum of:

(i) $\frac{\varepsilon_{frp}}{2\gamma_{mlc}}$

(ii) $0.64 \sqrt{\frac{\gamma_{mlc}f_{cim}}{E_{frp}f_{frp}\gamma_{mc}}}$

(iii) 0.004

unless a rigorous analysis is undertaken or based on experimental results using representative sized specimens, with the agreement of the Overseeing Organisation.

4.38 Where individual strips are used the centre to centre spacing, measured along the span, shall be less than 0.75 times the effective depth of the section to prevent a shear crack forming between strips, i.e. $s_{frp} < 0.75d$. (See Clause 4.36)

4.39 When shear is applied to a concrete beam or slab associated tensile forces are developed in the longitudinal reinforcement. These are additional to forces due to bending. Adequate longitudinal reinforcement and FRP should be provided to sustain these additional tensile forces. This requirement may be satisfied by ensuring that the reinforcement and axial FRP extend a distance $d$ beyond the point at which they are required for bending alone.

4.40 Alternatively, one of two different approaches may be used depending upon whether strengthening is required for shear and flexure or for shear alone. At sections requiring strengthening for shear and flexure, the area of FRP required to resist the ultimate applied bending moment should be increased by the following factor:

$$F_{frp} = \left[1 + \frac{V}{2F_{frp}}\right]$$

Where, at the section being considered, $V$ is the shear force due to the ultimate loads and $F_{frp}$ is the force in the longitudinal FRP due to bending determined from a section analysis in accordance with Clause 4.12.

If strengthening is required for shear only (i.e., if no longitudinal FRP is required to strengthen the beam or slab to resist the ultimate bending moment) then:

(i) The area of longitudinal steel reinforcement which is effective in resisting flexure should be determined by reducing the area of steel in the tension face by an amount equal to:

$$\frac{V}{2(f_y / \gamma_{ml})}$$

(ii) The ultimate bending capacity of the beam or slab should be rechecked using this reduced area of reinforcement to ensure that it is still has adequate capacity to sustain the ultimate applied bending moment. If not, then longitudinal FRP should be added to increase the moment capacity of the beam or slab.

Fatigue

4.41 No fatigue check is required for FRP itself. If the existing structure complies with relevant fatigue requirements then no further fatigue check is required.

Serviceability

4.42 The strengthened structure shall conform to the general serviceability requirements given in Clause 4.1.1 of BS 5400: Part 4. However, provided the structure has been performing satisfactorily in service with no evidence of cracking and the future loading to be carried by the structure is not significantly increased then the serviceability requirements for cracking may be deemed to be satisfied. The limitation on stress in the reinforcement under service load given in Table 2 of BS 5400: Part 4 will ensure that the steel does not yield under service loads.
4.43 Deflection at serviceability loading can be calculated using elastic analysis and cracked or uncracked section properties as appropriate. Deflections shall be restricted to a level that will not impair the appearance or functionality of the structure. This can be ensured by limiting the maximum deflection to the effective span/250. If the structure has been performing satisfactorily in service and the future loading to be carried by the structure is not significantly increased then the serviceability requirements for deflection may be deemed to be satisfied.

Detailing

4.44 Mechanical systems and transverse overlapping FRP may resist failure modes involving a loss in composite action between the FRP and the concrete sections. Such approaches are currently the subject of research and are permitted with the approval of the Overseeing Organisation and provided their effectiveness has been substantiated through testing. Bolting is not appropriate for uni-directional FRP systems. However, tests have shown the bolting can provide effective anchorage where multi-directional FRP laminates are used.

4.45 If FRP is bonded to the top surface of slabs or beams and subsequently buried by the road surfacing, a protective system should be provided to prevent the FRP being damaged if the surfacing is removed. Such a system could include studs, with a thickness greater than that of the FRP, bolted to the structure adjacent to the FRP laminates.
5. STRENGTHENING METALLIC STRUCTURES

5.1 Externally bonded FRP may be used for strengthening metallic structures constructed from cast iron or steel. Wrought iron structures should only be strengthened in accordance with Clause 2.13. Bonding of FRP to metallic structures can be advantageous since the need for welding can be eliminated. Strengthening of metallic structures using FRP has received less research attention than concrete structures and there have been fewer practical applications.

5.2 Detailed guidance on the design of FRP strengthening for metallic structures, based upon current best practice and knowledge, is included in CIRIA Report C595[5]. It is recommended that C595 be used in conjunction with this Standard for the design of FRP strengthening schemes for metallic structures.

5.3 The behaviour of FRP-strengthened metallic 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 metallic structures the behaviour of the adhesive itself can govern the capacity of the strengthened member, and requires detailed consideration in the design.

5.4 The coefficient of thermal expansion of FRP can differ significantly from that of metallic elements. As a result differential thermal expansion can lead to significant stress concentrations at the ends of externally bonded FRP plates and at any other geometric discontinuities. Such effects must be taken into account in the design of FRP strengthening schemes for metallic structures by considering the timing of the operation and the range of effective bridge temperatures likely to be encountered. Temperature loads shall be taken from BD 37 (DMRB 1.3.14), with cast iron structures categorised as Group 2 structures in Figure 9 of BD 37, unless a rigorous temperature analysis is undertaken.

5.5 Although not covered by this Standard, externally bonded FRP could potentially also be used to enhance the fatigue life, shear capacity, bearing capacity or buckling resistance of metallic elements or to enhance the capacity of connections. When considering such strengthening schemes, guidance should be sought from specialist designers and materials suppliers, and the appropriate design approach agreed with the Overseeing Organisation. Because of the limited experimental work that has been undertaken into such strengthening applications, it may be necessary to undertaken testing on representative specimens to prove the effectiveness of the technique.

5.6 Cracked metallic structures shall not be strengthened using FRP without the agreement of the Overseeing Organisation. Guidance shall be sought from specialist designers in such cases.

Strengthening for Flexure

5.7 FRP materials bonded to the tension flanges of beams increase the effective area of the tension flange and therefore enhance the moment of resistance of the section and its stiffness. The bonding operation can frequently take place with no or minimal disruption to traffic and without a need for temporary propping.

5.8 Structures strengthened with FRP to increase their flexural capacity can exhibit the same ultimate failure modes as conventional metallic sections, for example, local buckling of the compression flange or lateral torsional buckling. However, in addition, their capacity may also be governed by fracture of the FRP or by the loss of composite action between the FRP and the metallic section, because of failure of the adhesive joint.

5.9 A particular complexity in the design of FRP strengthening for metallic elements is that the behaviour of the adhesive joint and of the anchorage region near the ends of the FRP strengthening cannot be analysed making the assumption that plane sections remain plane, see Clause 5.18. This assumption may, however, be used in undertaking sectional analyses away from end regions, see Clause 5.13.
Limit States

5.10 The design of strengthened steel structures should be considered for the ultimate limit states in accordance with the relevant clauses of BS 5400: Part 3: 2000 (BSI 2000) as implemented by BD 13 (DMRB 1.3.14), except where amended by other clauses in this Standard. The appropriate loads and load factors should be taken from BD 37 (DMRB 1.3.14).

5.11 The criteria for the serviceability limit states given in Clause 4.2.2 of BS 5400: Part 3, should be followed for steel elements, except where amended in this Standard.

5.12 Strengthened cast iron elements should be analysed on a permissible stress basis, as described in BD 21 (DMRB 3.4.3).

Section Capacity and Stiffness

5.13 The evaluation of the flexural capacity and stiffness of a metallic section strengthened using FRP should be based on the following:

(i) The strain at any level in the section may be determined assuming that plane sections remain plane.

(ii) Account should be taken of the stresses in the structure when the FRP is installed (see Clause 3.4).

(iii) Differential thermal expansion of the FRP and metallic elements should be taken into account.

(iv) The FRP is a linear elastic material, as shown in Figure 4.1.

Guidance on the analysis of FRP-strengthened metallic sections is included in C595[5].

5.14 The following modes of failure shall be considered:

(i) FRP rupture;

(ii) rupture of the metallic element;

(iii) global or local buckling of the element; and

(iv) rupture of the adhesive.

5.15 FRP rupture shall be considered to occur when the strain in the FRP reaches $\varepsilon_{fpu} / \gamma_{mf}$.

5.16 For cast iron elements, rupture shall be considered to occur when the stress in the metal reaches the limits specified in BD 21 (DMRB 3.4.3). Yielding of ductile materials such as steel is acceptable at ultimate limit state.

5.17 It has been found that FRP strengthening can result in global or local buckling becoming the critical failure mode for an element. Global and local buckling in steel elements should, therefore, be considered in accordance with BS 5400: Part 3: 2000 (BSI 2000) as implemented by BD 13 (DMRB 1.3.14) using the transformed properties of the FRP-strengthened section. Guidance on the evaluation of the buckling properties of FRP-strengthened metallic elements is included in the ICE design and practice guide[6] and CIRIA report C595[5]. Buckling of FRP-strengthened cast iron elements should be considered using Clause 5.2.8 of C595[5].

5.18 The adhesive joint shall be checked at the ends of the FRP strengthening and at any discontinuities in the structure or changes in the FRP thickness to ensure that it has sufficient capacity to sustain the stresses due to:

(i) live loading; and

(ii) differential thermal expansion.

The analysis of the adhesive joint shall be based upon the elastic analysis approach set out in C595[5], unless an alternative approach, such as one based upon fracture mechanics, is agreed with the Overseeing Organisation. The principal stress in the adhesive shall satisfy the following condition:

$$\sigma_{ai} < f_a / \gamma_{ma}$$

5.19 If the FRP extends into areas in compression, buckling of the laminate might occur, resulting in a loss of composite action. Where it is necessary to extend the FRP into an area in compression, the possibility of buckling should be considered.
5.20 The analysis of the adhesive joint shall take account of any lack of straightness in the FRP. Requirements for the straightness of the FRP as installed shall be specified by the designer. It is generally recommended that a limit be used based upon the gap under a 1m long straight edge held to the surface of the FRP following installation nowhere exceeding 3mm. For moderate sized plates the effect of this lack of straightness will be small, although this may not be the case for thick stiff FRP plates.

5.21 For FRP-strengthened steel elements in which yielding occurs at the ultimate limit state, account shall be taken of the effect of the yielding on the stresses developed in the adhesive joint. In particular, account shall be taken of the effect of the yielding on the longitudinal shear stresses in the adhesive.

**Anchorage**

5.22 Sufficient anchorage shall be provided beyond the point at which the FRP is no longer required, to enable stress development in the FRP and provide robustness of the design. In the absence of a rigorous analysis, the anchorage length may be based upon the approach given in C595\(^5\) with the stress development length determined using an elastic analysis of the adhesive joint.

The anchorage length that is required beyond the position at which strengthening is no longer needed may be taken as the section depth.

**Fatigue**

5.23 No fatigue check is required for FRP itself. If the existing structure complies with relevant fatigue requirements then no further fatigue check is required provided the installation of the FRP does not increase the stress ranges experienced by fatigue sensitive details and the stresses in the adhesive at the plate ends due to live loading are small in relation to those due to thermal effects.

**Serviceability**

5.24 The strengthened structure should conform to the general serviceability requirements given in Clause 4.2.2 of BS 5400: Part 3. Deflections should be restricted to a level that will not impair the appearance or functionality of the structure. This can be ensured by limiting the maximum deflection to the effective span/250. If the structure has been performing satisfactorily in service and the future loading to be carried by the structure is not significantly increased then these serviceability requirements may be deemed to be satisfied.

5.25 For steel structures, yielding shall not occur at FRP strengthened sections under serviceability limit state loading unless agreed with the Overseeing Organisation.

**Detailing**

5.26 Stresses in the adhesive may be reduced by increasing the width of the FRP and by tapering the FRP near the end of the strengthening. Alternatively, mechanical anchorage systems may be used. As the width of pre-manufactured FRP plates is increased, the difficulty of expelling the air under the plate during installation also increases. Special consideration should therefore be given to this issue for pre-manufactured plates with a width in excess of 300mm.

5.27 When a carbon fibre based system is used to strengthen a metallic structure, galvanic corrosion can occur. To eliminate the risk of galvanic corrosion on such schemes, a glass fibre insulating layer shall be interposed between the carbon fibre and metallic substrate to electrically isolate the FRP. The effectiveness of the system must comply with the requirements of Clause 2.5.
6. MATERIALS

6.1 The manufacturer or supplier of an FRP system shall provide test data and evidence of the properties and performance both of the materials and the application method to demonstrate its suitability to the satisfaction of the Overseeing Organisation.

FRP

6.2 FRP products are manufactured in many different forms including:

(i) FRP sheet with fibres orientated in one or more directions. These are saturated with resin and bonded to the member on site;

(ii) FRP sheet pre-impregnated with resin (prepreg) with fibres orientated in one or more directions and boded with additional resin;

(iii) uni-directional factory impregnated laminates formed using the pultrusion process and supplied in standard thicknesses (normally 1 to 2mm) and widths (typically 50 – 120mm);

(iv) multi-directional laminates with variable thickness (normally 1mm – 30mm) and width (normally 50mm – 500mm);

(iv) pre-formed shells manufactured to size and bonded to the member.

These products may be manufactured with different types of fibre. The fibre types suitable for strengthening concrete structures are aramid, carbon and glass. Further details of FRP products and manufacturing processes are given in TR55\(^1\).

Adhesive

6.3 Any adhesive may be used provided it satisfies the requirements for strength and durability, and is appropriate for the installation method. The adhesive shall be suitable for the environmental conditions to which it will be exposed during both installation and service. Special consideration is required if the adhesive will be subjected to high temperatures or if it will be submerged in service.

6.4 Epoxy based adhesives have been used most commonly in FRP-strengthening of concrete structures, both in experiments and practical applications, and their use is recommended. Their durability has been established over a period in excess of fifteen years for steel plate bonding. Further information on adhesives is provided in [1], [2] and [3].

Fixings

6.5 All materials used in fixings shall be of a non-corrosive nature, with durability consistent with that of the FRP system and the requirements of Clause 3.3. All fixings shall be compatible with the composite materials.

6.6 Coatings may be used to provide additional protection or surface finish. It should be noted, however, that these may interfere with future inspections. Any coating used should be fully compatible with the FRP material.
7. INSTALLATION INSPECTION AND MAINTENANCE

7.1 The effectiveness of FRP strengthening is highly dependent upon the quality of installation.

7.2 Where innovative materials or systems are proposed, a trial panel strengthened using the proposed materials and method of application should be constructed in order to demonstrate to the Engineer that all aspects of the installation scheme are practicable, including the preparation of the surfaces, application of resin, installation of the FRP and curing.

7.3 For all schemes, consideration should be given to the use of procedure trials to prove the method of application and quality of installation.

Preparation of Concrete Surfaces

7.4 The concrete surface shall be prepared so that the FRP is bonded to a sound surface with no protuberances, laitance or contaminants. Damaged areas, cracks wider than 0.2mm and porous areas shall be repaired and any holes filled. The prepared surface should be dust free and dry prior to installation of the FRP.

Preparation of FRP Surfaces

7.5 FRP surfaces shall be completely free of dirt, dust, grease, moisture or other contaminants. For prefabricated plates and laminates, suitable preparation methods may include light controlled mechanical abrasion or removal of a peel-ply provided during manufacture.

Application of FRP

7.6 The environmental conditions during installation shall not be detrimental to the long-term performance of the FRP system. The FRP shall not be installed unless the environmental conditions, including temperature and humidity, are in accordance with the manufacturer’s recommendations.

7.7 The installation procedure shall be devised and implemented to avoid the formation of voids that affect the overall integrity of the bond between the FRP and the concrete, or between layers of FRP.

7.8 For fabric systems, sufficient resin should be used to ensure that all fibres are fully wetted. For pre-formed FRP laminate strips, the adhesive thickness should not be less than 1mm nor greater than 5mm. Typically the adhesive thickness should be between 1.5mm and 2.5mm.

7.9 Installation should only be undertaken by operatives experienced in the use of the FRP system.

Quality Control

7.10 Records shall be kept throughout the installation of the FRP system detailing the date and time of installation, references to uniquely identify the FRP installed, environmental conditions, sampling undertaken, inspections and test findings.

7.11 An independent testing authority shall be appointed to carry out an examination of the workmanship and the testing of the materials.

7.12 Tests shall be undertaken to demonstrate that the properties of the installed FRP are consistent with those used in the design. Such testing should include tests on the adhesive, the FRP laminates and to confirm the adequacy of bond between the FRP and the concrete.

7.13 Consideration should be given to installing additional FRP to facilitate long-term monitoring and future testing.
7.14 Following installation a survey shall be undertaken to identify any voids. The findings of this survey shall be reported to the Overseeing Organisation together with proposals to address any voids identified. At present, it is recommended that a light tapping test is used for this survey. More sophisticated methods are currently being developed and they should be considered once their application has been proven, subject to the agreement of the Overseeing Organisation.

In-Service Inspection And Maintenance

7.15 A comprehensive manual of procedures for inspection and maintenance of the strengthened structure shall be prepared including requirements for long-term monitoring and testing. The manual shall include all relevant technical literature relating to the products used, installation records, drawings, test findings and photographs of critical details. Procedures for minor repairs should also be included.

7.16 Inspections shall take place every six months for at least two years after completion of the works. The frequency of further inspections shall be agreed with the Overseeing Organisation after a review of the inspection reports.

Abnormal Loads

7.17 If a significant abnormal load is routed over a structure that has been strengthened, consideration should be given to undertaking an inspection of the FRP strengthening before and after its passage.
8. REFERENCES

Bibliography


Standards


PR EN 1542: Products and systems for the protection and repair of concrete structures – Test methods, the pull-off test.

Design Manual for Roads and Bridges

DMRB 1.1: BD 2: Technical approval of highways structures on motorways and other trunk roads.


DMRB 3.4: BD 37: Loads for highway bridges.

DMRB 3.4: BD 21: The assessment of highway bridges and structures.
9. ENQUIRIES

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

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The Highways Agency  
123 Buckingham Palace Road  
London  
SW1W 9HA  
G CLARKE  
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Chief Highway Engineer  
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Department for Economy & Transport  
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The Department for Regional Development  
Roads Service  
Clarence Court  
10-18 Adelaide Street  
Belfast  
BT2 8GB  
R J M CAIRNS  
Director of Engineering
ANNEX A  FLOW CHART FOR FRP STRENGTHENING DESIGN

Identify need for strengthening

Check structure capacity
(Clause 2.1)

Check headroom
(Clause 2.14)

Check structure condition
(Clauses 2.8-2.11)

Identify suitable FRP strengthening techniques
(Clauses 2.4-2.6)

Economic appraisal
(Clause 2.3)

Undertake pull-off tests
(Clauses 2.12, 2.13)

Specification and Design
(Chapters 3-6)

Installation
(Chapter 7)

In-service Inspection and Maintenance
(Chapter 7)