ANNEX J

Strengthening with carbon fibre

EC DG ENTR -C-2
Innovation and SME Programme
IPS-2000-0063

REHABCON
Strategy for maintenance and rehabilitation in concrete structures
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1 DESCRIPTION

The strengthening or repair of concrete structures using externally bonded fibre reinforced polymer (FRP) provides an alternative solution to traditional methods of strengthening such as externally bonded steel plates. FRP materials are currently being used for upgrading existing structures because of their resistance to corrosion and their light weight. Different types of fibre can be used, i.e., glass, carbon, aramid, but only carbon fibres are considered in the document.

In the strengthening of reinforced concrete elements using bonded FRP systems, three elements are involved:

- **Substrate**: The material of the existing structure to which the FRP reinforcement is bonded.
- **FRP reinforcement**: The FRP material bonded to the substrate to act as external reinforcement
- **Bonding agent**: The adhesive provided with the bonded FRP system. This is normally provided as a two part cold cured epoxy resin. Depending on the type of system used, the resin may also be used to impregnate the fibres.

There are two different systems that can be used. The first consists of preformed laminates fabricated provided as strips, shells, jackets or angles which are bonded to the substrate. In the second, the FRP is provided in the form of sheets or fabrics and these are bonded and cured on site using a “wet lay-up” or “hand lay-up” systems. Other innovations have also been developed, for example, where the FRP plates are anchored and tensioned to combine the advantages of externally bonded FRP reinforcement with those of conventional post-tensioning.

The FRP is applied to different reinforced concrete elements such as beams, columns, and slabs, to provide substantial increase in strength and durability. Typical FRP application are:

![Figure 1.- Typical applications of bonded FRP strengthening systems](image-url)
- **Flexural strengthening** of slabs or beams: The FRP is bonded to the tension zones with the fibres parallel to the principal stress direction.
- **Shear strengthening** of beams and columns: The FRP is bonded to the sides of the concrete elements with the fibres parallel to the principal tensile stresses, to act as external shear reinforcement. The FRP is most effective when it fully wraps the element, but partial wrapping can also be used where full wrapping is not possible.
- **Column wrapping**: The capacity of columns can be increased by wrapping them with FRP materials through the confinement effect provided by the FRP.

This document describes the basic technique of applying FRP reinforcement to an existing reinforced concrete member. Other special techniques such as post-tensioned systems are beyond the scope of this document.
2 DESIGN CRITERIA

This section of the manual presents general considerations for engineers to carry out the design of fibre reinforced polymer strengthening systems for reinforced concrete structures. Although all the documents consulted to develop this report are included in section 5 “References”, the following list states the main documents, which are the base of the design requirements given in this section:

- **ACI 440.2R-02.** Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures
- **BD 85/02 (draft).** Strengthening of highway bridges using externally bonded fibre reinforced polymer.
- **BD 84/02.** Strengthening of concrete bridge supports using fibre reinforced polymers.
- **CHALMERS UNIVERSITY OF TECHNOLOGY.** A comparative study of models on confinement of concrete cylinders with FRP composites.

The success of this strengthening system will be based on the selection of the most suitable FRP reinforcement method. Moreover, it should be designed by an engineer with experience in structural repairs, and with the design and application of bonded FRP systems.

In the following, reference is made to reinforced concrete members strengthened with externally bonded FRP reinforcement. The same principles could be applicable to the case of strengthening prestressed concrete elements however, some additional considerations are necessary to take into account the long term phenomena (creep, shrinkage, relaxation) in the preliminary assessment of the existing structure and how they are accounted in the evaluation of the FRP strengthening. The evaluation of the strengthening should be carried out in accordance to appropriate standards.

The design of FRP strengthening techniques is based on the limit state principles:

- Verification of the ultimate limit state (ULS)
- Verification of the serviceability limit state (SLS)

In the design, it is necessary to take into account all the possible design situations and load combinations. These are outlined in the relevant design standard.

The effectiveness of externally bonded FRP is highly dependent on the performance of the bond between the FRP and the concrete surface and the integrity of the surface concrete itself. This interface must be capable of sustaining the stresses necessary for tension forces to be developed in the FRP. When considering the suitability of a structure for the application of externally bonded FRP, investigations should 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.
Next sections discuss the following topics:

- Safety factors
- Design requirements: Flexural strengthening
- Design requirements: Shear strengthening
- Design of column strengthening

In addition to recommendations given in each design section respectively, it is necessary to **verify the load bearing capacity of the structure before strengthening**. This means that the unstrengthened structure has to present sufficient strength to ensure that catastrophic collapse will not occur if the reinforcement fails. This consideration has special importance for this type of reinforcement because it can be damaged by fire, impact, vandalism, etc.

### 2.1 Safety factors

The purpose of introducing partial safety factors in the design is to compensate the existing uncertainties in the material and adding safety margins.

In this section the FRP safety factors are discussed according to different references and they should be taken into consideration in the design equations presented in the following sections.

According to the Technical Report No 55 (11), design safety margins are introduced by dividing the characteristic mechanical properties by: $\gamma_{\text{mf}} = \gamma_{\text{mf}} \times \gamma_{\text{mm}}$.

Where $\gamma_{\text{mf}}$ is a coefficient that takes into account the type of fibres, its value is 1.4 for carbon FRP (CFRP). $\gamma_{\text{mm}}$ depends on the application or manufacture method. The possible values of $\gamma_{\text{mm}}$ are given in the next table:

<table>
<thead>
<tr>
<th>Type of system and application or manufacture method</th>
<th>Additional partial safety factor ($\gamma_{\text{mm}}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plates</td>
<td></td>
</tr>
<tr>
<td>Pultruded</td>
<td>1.1</td>
</tr>
<tr>
<td>Prepreg</td>
<td>1.1</td>
</tr>
<tr>
<td>Preformed</td>
<td>1.2</td>
</tr>
<tr>
<td>Sheets or tapes</td>
<td></td>
</tr>
<tr>
<td>Machine-controlled application</td>
<td>1.1</td>
</tr>
<tr>
<td>Vacuum infusion</td>
<td>1.2</td>
</tr>
<tr>
<td>Wet lay-up</td>
<td>1.4</td>
</tr>
<tr>
<td>Prefabricated (factory –made) shell</td>
<td></td>
</tr>
<tr>
<td>Filament winding</td>
<td>1.1</td>
</tr>
<tr>
<td>Resin transfer moulding</td>
<td>1.2</td>
</tr>
<tr>
<td>Hand lay-up</td>
<td>1.4</td>
</tr>
<tr>
<td>Hand-held spray application</td>
<td>2.2</td>
</tr>
</tbody>
</table>

Table 1.: Recommended values of $\gamma_{\text{mm}}$ (partial safety factor) according to the Technical report No 55 of the Concrete Society (11)
An additional safety factor ($\gamma_{mE}$) is proposed by TR 55 (11). It is applied to the modulus of elasticity of the FRP in order to take into consideration the possible changes of these characteristics with time. The value proposed to this factor is 1.1 for CFRP.

The value of the design strength is given by dividing the characteristic strength by the above safety factors:

$$f_{d} = \frac{f_{k}}{\gamma_{mf} \cdot \gamma_{mm} \cdot \gamma_{mE}}$$

In the same line the draft of the BD 85/02 (5) proposes for the ultimate limit state the following safety factors:

<table>
<thead>
<tr>
<th>$\gamma_{mfE}$ (material partial safety factor for FRP stiffness)</th>
<th>$\gamma_{mfC}$ (material partial safety factor for FRP strain capacity)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.15</td>
<td>1.15</td>
</tr>
</tbody>
</table>

Table 2.- Values of partial factors for FRP materials according to the BD 85/02 (5).

This reduction factors shall be applied to the characteristic values of the material properties.

- Fib bulletin nº 14 (14) determines the design strength ($f_{d}$) according to the following expression:

$$f_{d} = \frac{f_{k}}{\gamma_{f} \cdot \frac{\varepsilon_{fu}}{\varepsilon_{fum}}}$$

Where $\gamma_{f}$ is the material safety factor. It is introduced to consider the differences in the long-term behaviour of CFRP influence by the application method.

<table>
<thead>
<tr>
<th>$\gamma_{f}$</th>
<th>Application of prefab FRP systems under normal quality control conditions.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.20</td>
<td>Application of wet lay-up systems under high degree of quality control.</td>
</tr>
<tr>
<td>1.35</td>
<td>Application of wet lay-up systems under normal quality control condition.</td>
</tr>
<tr>
<td></td>
<td>Application of any system under difficult on-site working conditions.</td>
</tr>
</tbody>
</table>

Table 3.- CFRP safety factor according to fib bulletin 14 (14).

The ratio $\varepsilon_{fu}/\varepsilon_{fum}$ shows the relation between the effective ultimate FRP strain expected in-situ and the mean strain obtained through uniaxial tensile testing. This ratio is
normally equals 1, its value may be lower in the case of application of multiple layers, wrapping of FRP around very sharp corners, multi-axial state of stress, etc...

According to fib bulletin 14 (14) the modulus of elasticity is not affected by a reduction factor, however it is taken as $E_{fu} = f_{uk}/\varepsilon_{fuk}$ with $E_{fu} \geq E_{f0.05}$. Where $E_{fu}$ is the modulus of elasticity at ultimate, $f_{uk}$ is the characteristic strength corresponding to 5% fractile of the strength and $\varepsilon_{fuk}$ corresponds to 5% fractile of the failure strain.

This reference introduces a safety factor ($\gamma_b$) in shear strengthening design (see subsection 2.3.1) when dominates the bond failure leading to peeling-off. The value of this coefficient is 1.3.

Fib (14) also gives some indications for the safety factors for serviceability limit state. In these verifications the material safety factor is taken equal to 1.0 and the modulus of elasticity considered is the characteristic secant modulus $E_{f0}$ (it usually corresponds to 5% fractile).

- ACI 440.2R-02 (3) introduces a reduction factor to the material properties in order to take into account the environmental exposure condition in which the FRP reinforcement is going to be working. In this line the design ultimate tensile strength of the FRP material and its design rupture strain are reduce using the factors recorded in following table for carbon fibre:

<table>
<thead>
<tr>
<th>EXPOSURE CONDITIONS</th>
<th>REDUCTION FACTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interior exposure</td>
<td>0.95</td>
</tr>
<tr>
<td>Exterior exposure</td>
<td>0.85</td>
</tr>
<tr>
<td>Aggressive environment</td>
<td>0.85</td>
</tr>
</tbody>
</table>

Table 4.- Exposure condition reduction factor according to ACI 440.2R-02 (3)

In order to obtain the design strength provided by a strengthened member ACI 440.2R-02 (3) recommends the use of the strength reduction factors $\phi$ which appear in ACI 318-99 (1) introducing an additional reduction factor to take into account the lower reliability of the FRP reinforcement. This additional reduction factor is evaluated as follows:

<table>
<thead>
<tr>
<th>TYPE OF REINFORCEMENT</th>
<th>ADDITIONAL REDUCTION FACTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexural contribution of FRP</td>
<td>0.85</td>
</tr>
<tr>
<td>Shear contribution of FRP when the member is completely wrapped</td>
<td>0.95</td>
</tr>
<tr>
<td>Shear contribution of FRP in the case of three-sided U-wraps or bonded face piles</td>
<td>0.85</td>
</tr>
<tr>
<td>FRP contribution to axial compression strength</td>
<td>0.95</td>
</tr>
</tbody>
</table>

Table 5.- Additional strength reduction factor according to ACI 440.2R-02 (3)
2.2 Design requirements: Flexural strengthening

Concrete elements may be strengthened in flexure by bonding FRP to the tension zones, with fibres parallel to the principal stress direction.

Different verifications are involved in the design of the FRP reinforcement. These are discussed in the following sections.

Before going through the design verifications it will be said that the failure mode of the unstrengthened structure is an indicator of the suitability of the FRP reinforcement. This kind of reinforcement will be profitable in sections where failure mode is FRP rupture or concrete crushing after steel yielding. However, over-reinforced sections where the failure mode is concrete crushing without the steel yielding the reinforcement will be of little intention (large amount of FRP material will be needed in order to obtain short increase in the bending capacity).

2.2.1 Verification of Ultimate Limit State (ULS)

There are two different failure modes in a reinforced concrete member subjected to flexure with externally bonded FRP:

- Assuming that composite action is retained between the FRP and the concrete section the following failure modes should be considered:
  - FRP rupture
  - Crushing of the concrete

  Furthermore in flexural strengthening shear stresses have to be verified and shear strengthening with FRP has to be carried out where it is needed. The area of longitudinal FRP strengthening should be ignored in the calculation of shear capacity.

- Failure can also occur when there is a loss of composite action between the FRP and the concrete section. Bond failure may occur at different interfaces:
  - in the concrete near the surface or along a weakened layer
  - in the adhesive (cohesion failure)
  - at the interfaces between concrete and adhesive or adhesive and FRP (adhesion failure).
  - inside the FRP (interlaminar shear failure)
  - combinations

  Typically failures occur through the development of a longitudinal failure-plane close surface layer of concrete or at the level of the main reinforcement.
Design of the FRP reinforcement assuming full composite action

The design of FRP strengthening is carried out assuming full composite action on the strengthened member.

The composite cross section is determined in order to achieve the design moment capacity after strengthening.

The form in which the flexural capacity is evaluated in FRP strengthened members is based on internal equilibrium of forces and strain compatibility, as in conventional reinforced concrete design (see Figure 2).

Some assumptions should be made along the calculation process:

- Plane sections remain plain after bending
- There is no slip between the FRP and the concrete
- The tensile strength of concrete is ignored
- The stress-strain response for concrete and steel reinforcement follows the curves presented in codes
- FRP has a linear strain–stress relationship to failure.

The different failure modes that can be presented in a strengthened element in flexure are the following:

- Steel yielding followed by concrete crushing, while FRP is intact.
- Steel yielding followed by FRP tensile fracture.
- Concrete crushing before the steel yields.

In the calculation, it is important to consider the initial strain of the element to be reinforced ($\varepsilon_o$), in the extreme tensile fibre (concrete/FRP interface). Normally, when retrofitting takes place the concrete member will be carrying some load. The initial strain may be neglected if the load acting on the element produces a bending moment.
lower than the cracking moment. The initial strain can be evaluated using elasticity theory.

The different failure modes listed above can be controlled by evaluating the strain levels in the concrete, steel and FRP. Composite materials failure can occur if the FRP reaches its ultimate flexural design strain. However, in order to avoid debonding failure mode related to cracks in the concrete, a limit is placed on the strain level in the FRP.

In this point, the different documents introduce a limit to the FRP strain:

<table>
<thead>
<tr>
<th>Reference</th>
<th>Limitation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fib bulletin 14</td>
<td>$\varepsilon_f$</td>
<td>0.0050 For concrete type C35/45 or lower.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.0075 For concrete type higher than C35/45.</td>
</tr>
<tr>
<td>TR 55 (11)</td>
<td>$\varepsilon_f$</td>
<td>0.0060 Elements subjected to high shear and bending moment.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.0080 If loading is distributed uniformly.</td>
</tr>
</tbody>
</table>

Table 6.-FRP strain limitation according to Concrete Society TR 55 (11) and fib bulletin 14 (14).

ACI 440.2R-02 (3) also limits the strain level of the FRP by applying a factor $k_m$ to the rupture strain. This reduction factor is no greater than 0.9.

In the strengthened element it is necessary to check the ductility of the section. The ductility of a strengthened flexural element usually decreases with respect to the unstrengthened member. In some cases the ductility reduction is negligible.

In order to ensure a ductile section, the internal steel should be sufficiently yield at failure. In this line, fib bulletin 14 (14) and TR 55 (11), limit the depth of the neutral axis to a value that assures the steel yielding.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Limitation</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fib bulletin 14</td>
<td>$x \leq 0.45 d$</td>
<td>$d =$ effective depth of the section</td>
</tr>
<tr>
<td></td>
<td>$x \leq 0.35 d$</td>
<td>$x =$ depth of the neutral axis</td>
</tr>
<tr>
<td></td>
<td>for concrete types C35/45 or lower</td>
<td></td>
</tr>
<tr>
<td></td>
<td>for concrete types higher than C35/45</td>
<td></td>
</tr>
<tr>
<td>TR 55 (11)</td>
<td>$x \leq 0.45 d$</td>
<td></td>
</tr>
</tbody>
</table>

Table 7.- Limitation of the depth of the neutral axis according to Concrete Society TR 55 (11) and fib bulletin 14 (14).

If the strengthened member does not fulfil this condition, both documents propose to design the element with a higher reserve of strength. In this case the section should be analysed for greater acting load (20 % according to fib (14) or 15 % according to TR 55 (11)).

This subject is treated in ACI 440.2R-02 (3) by applying a strength reduction factor. This reduction factor in the case of ductile section equals 0.9, which is the safety factor used by ACI 318-99 (1) (see subsection 2.1 “Safety factors”), in the case of brittle sections the reduction factor equals 0.7. Between this two values a linear variation is considered.
Verifications of failure modes where there is a loss of composite action

After dimensioning the FRP reinforcement assuming full composite behaviour between concrete and FRP is necessary to verify that the failures modes in which the bond is affected are avoided.

As previously discussed, assuming concrete is the weakest zone of the bond, failure planes are in concrete (line close to the surface or at the level of the main longitudinal steel reinforcement). The failure mode may be initiated at the ends of the FRP due to the discontinuity as a result of the termination of the laminate and it is related with normal and shear stresses in the adhesive due to FRP deformation, this type of peeling failure usually results in ripping off the concrete cover along the level of internal steel reinforcement towards the centre of the member. At Flexural and shear cracks high stresses in the FRP may be generated, these stresses could only be dissipated by debonding.

In general these failure modes may be avoided by limiting the strain in the FRP (condition included in the full composite action verification), the longitudinal shear stress between the FRP and the concrete section, the stress in the FRP near its end (i.e. 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 premature debonding also may occur if the surface preparation of the concrete is not adequate and the surface present unevenness. This mechanism may be avoided with a good quality control during execution (see subsection 3.2.1 Requirements of concrete substrate).

In general the likelihood of failure modes involving a loss in composite actions is decreased by reducing the FRP thickness and by tapering the FRP when multiple layers are used. If the force in the anchorage region exceeds the anchorage capacity then considerations should be given to reduce the thickness and increase the width of the FRP.

Regarding to the recommendations of TR 55 (11) the analysis of failure modes where there is a loss of full composite action comprises the following verifications (see table 8):

- End plate separation failure will be avoided by anchoring the FRP by extending it beyond the point at which it is theoretically no longer required and limiting the longitudinal shear stress between the FRP and the substrate to 0.8 N/mm². The last verification should be checked at the location in the span where the steel reinforcement first yields an at plate ends.

- In order to avoid the risk of debonding by the formation of flexural and shear cracks the strain in the FRP is limited.
According to Fib bulletin 14 (14) the analysis of failure modes where there is a loss of full composite action comprises the following verifications (see table 9):

- Peeling at shear cracks is avoided by limiting the acting shear force to the shear resistance of the reinforced concrete (see modifications to equations given in the different standards in table 9). In this verification the shear reinforcement is not taken into account.

  If the shear capacity is lower than the required a shear strengthening is needed.

- In order to avoid peeling at the end anchorage and at flexural cracks three different approaches are proposed:
  - Verification of end anchorage and strain limitation in the FRP
  - Verification according to the envelope curve of tensile stresses in FRP
  - Verification of the end anchorage and of force transfer at the FRP-concrete interface

In table 9 only the recommendations and equations related to the first approach are given.

- The phenomenon of end shear failure (rip off) is studied based in the concept of fictitious shear span.

In relation with the loss of full composite action ACI. 440.2R-02 (3) gives some indications (no equations) to check the bond stresses and introduces some recommendations for the location of cut-off points for the FRP laminate instead of limiting the stress at the termination point of the FRP laminate.
The maximum ultimate bond force ($T_{k,\text{max}}$) and the corresponding maximum anchorage length ($l_{t,\text{max}}$) needed to activate this bond force can be estimated by:

$$T_{k,\text{max}} = 0.5 \cdot K_b \cdot b_f \cdot \left( E_f \cdot t_f \cdot f_{ctm} \right)^{1/2}$$

$$l_{t,\text{max}} = 0.7 \cdot \left[ \frac{E_f \cdot t_f}{f_{ctm}} \right]^{1/2} \geq 500 \text{mm}$$

where:

- $E_f$: design value of the elastic modulus of the plate
- $t_f$: plate thickness (mm)
- $b_f$: plate width (mm)
- $b$: beam width or plate spacing for solid slab (mm)
- $f_{ctm}$: tensile strength of concrete (MPa)
- $f_{ctm} = 0.18 \cdot (f_{cu})^{2/3}$
- $f_{cu}$: characteristic compressive cube strength of concrete
- $K_b$: geometry factor $K_b = 1.06 \cdot \left( 2 - (b_f/b) / (1 + (bf / 400)) \right)^{1/2}$

$T_{k,\text{max}}$ can be used to estimate the theoretical cut-off point of the FRP reinforcement.

FRP should be extended to the greater of $l_{t,\text{max}}$ and 500 mm from this point.

Where it is no possible to provide $l_{t,\text{max}}$, the bond force will be less than the ultimate value:

$$T_k = T_{k,\text{max}} \cdot \frac{l_t}{l_{t,\text{max}}} \cdot \left( 2 - \frac{l_t}{l_{t,\text{max}}} \right)$$

Limiting the longitudinal shear stress ($\tau$) between FRP and the substrate to 0.8 N/mm²:

$$\tau = V \cdot A_f \cdot \alpha_f \cdot \frac{(h-x)}{I_{cs} \cdot b_a}$$

where:

- $V$: ultimate shear force.
- $\alpha_f$: short term modular ratio of FRP to concrete ($E_f/E_c$)
- $A_f$: area of FRP
- $x$: depth of neutral axis of strengthened section
- $h$: overall depth of section
- $I_{cs}$: second moment of area of strengthened concrete equivalent cracked section
- $b_a$: width of adhesive layer

The longitudinal shear stress should be checked at the plate ends (the shear force is the greatest) and at the locations where the steel reinforcement first yields. At this location the steel reinforcement does not contribute to $x$ an $I_{cs}$ values, as its elasticity is theoretically zero.

The strain in the concrete at the FRP interface should be:

- $\varepsilon_r \leq 0.008$ when loading is uniformly distributed.
- $\varepsilon_r \leq 0.006$ if combined high shear forces and bending moments are present

where:

- $\varepsilon_r$: FRP strain
- $\varepsilon_i$: the initial strain in the extreme concrete tensile fibre (concrete/FRP)

Table 8: Equations proposed by TR 55 (11) to verify the separation failure.
**Fib bulletin 14 (14)**

Peeling-off at shear cracks may be prevented by limiting the acting shear force to the shear resistance of reinforced concrete member without shear reinforcement (EC2 (13) approach) with the following modification:

\[
\tau_{Rk} = 0.15 \cdot f_{ck}^{1/3}
\]

\[\frac{A_s + A_f \cdot \frac{E_f}{E_s}}{b \cdot d} \cdot \rho_{eq}
\]

Where:

- \(\rho_{eq}\): equivalent reinforcement ratio
- \(\tau_{Rk}\): characteristic shear strength of concrete
- \(A_s\): total area of longitudinal steel reinforcement
- \(A_f\): area of FRP reinforcement.
- \(f_{ck}\): characteristic value of the concrete compressive strength.
- \(E_f\): modulus of elasticity of FRP
- \(E_s\): modulus of elasticity of steel.

In case the design shear capacity falls below the required, an appropriate means of shear strengthening should be provided.

---

**PEELING OFF CAUSED AT SHEAR CRACKS (Approach 1)**

The maximum anchorage length \((l_{b,\text{max}})\) can be estimated by:

\[
l_{b,\text{max}} = \frac{E_f \cdot t_f}{\sqrt{c_2 \cdot f_{c,\text{m}}}}
\]

As in the Technical Report No 55 of the Concrete Society (11) \(l_{b,\text{max}}\) is the anchorage length needed to activate the ultimate bond force \(N_{f_{a,\text{max}}}.\)

\[
N_{f_{a,\text{max}}} = \alpha \cdot c_1 \cdot K_c \cdot b_f \cdot \sqrt{E_f \cdot t_f \cdot f_{\text{c,\text{m}}}}
\]

where:

- \(c_2\): may be obtained through calibration with test results (for CFRP strips \(c_2=2\))
- \(f_{c,\text{m}}\): mean value of the concrete tensile strength (MPa).
- \(\alpha\): reduction factor \((\approx 0.9)\) to account the influence of inclined cracks on the bond strength \((\alpha=1 \text{ in beams with sufficient internal and external shear reinforcement and in slabs})\).
- \(K_c\): factor accounting for the state of compaction of concrete, \(K_c = 1 \text{ in general, } K_c = 0.67 \text{ for FRP bonded to concrete faces with low compaction.}\)
- \(K_k\): geometry factor: \(K_k = 1.06 \cdot (2-(b_f/b)) / (1 + (b_f / 400))^{1/2} \geq 1 \text{ with } b_f/b \geq 0.33\)
- \(c_1\): may be obtained through calibration with test results (for CFRP strips \(c_1=0.64\))
- \(b_f\): plate width (mm)
- \(t_f\): plate thickness (mm)
- \(E_f\): elastic modulus of the plate (MPa).
- \(b\): beam width.

\(N_{f_{a,\text{max}}}\) is used to estimate the theoretical cut-off point of the FRP reinforcement.

When bond lengths \(l_b < l_{b,\text{max}}\), the ultimate bond force is given by:

\[
N_{f_{a}} = N_{f_{a,\text{max}}} \cdot \frac{l_{b}}{l_{b,\text{max}}} \left(2 - \frac{l_{b}}{l_{b,\text{max}}}\right)
\]

To prevent peeling-off far from the anchorage a strain limitation should be applied:

\(\varepsilon_f \text{ ranging from } 0.0065 - 0.0085\)

(consideration introduced when full composite action is assumed)
Based on fictitious shear span concept:

\[ V_{sd} \leq V_{Rd} = \tau_{Rd} \cdot b \cdot d \]

\[ \tau_{Rd} = 0.15 \cdot \frac{\frac{d}{a_L}}{3} \cdot \left(1 + \frac{200}{d}\right) \cdot \frac{\sqrt{100 \cdot \rho_s \cdot f_{ck}}}{\rho_s} \]

\[ a_L = 4 \sqrt{\frac{1 - \left(\frac{\rho_s}{a_L}\right)^2}{\rho_s}} \cdot d \cdot L^3 \]

\[ a > L + d \]

\[ a_L < a \]

where:

- \( V_{sd} \): design shear force
- \( V_{Rd} \): design shear resistance
- \( \tau_{Rd} \): design value of resisting shear strength of concrete
- \( L \): distance from the end of FRP to supports (mm).
- \( a \): shear span (mm).
- \( \rho_s \): longitudinal steel reinforcement ratio
- \( \rho_s = A_s / (b \cdot d) \)
- \( d \): effective depth of the member
- \( b \): width of beam
- \( f_{ck} \): characteristic value of the concrete compressive strength

Table 9: Equations proposed by fib bullet 14 (14) to verify the separation failure.

In the design, the expressions commented and the parameters defined above should be affected by adequate safety factors (global reduction factors and FRP material safety factors) according to the selected reference. For a design purposes, the complete evaluation procedure should be followed from the selected reference.
2.2.2 Verification of Serviceability Limit State (SLS)

In order to verify the serviceability limit state there are many empirical equations, which depend on parameters such as the thickness and the section of FRP, the type and the thickness of the resin, etc. Although a more conservative and easier criterion to verify the SLS is to use the methods usually accepted for the reinforced concrete (17).

The strengthened structure shall conform to the general serviceability requirements given in the relevant design code. 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 the code (eg, BS 5400: Part 4) will ensure that the steel does not yield under service loads.

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.

Additional information related to the verification of the serviceability limit state (SLS) is given in the TR 55 (11), fib bulletin 14 (14) and ACI.440.2R-02 (3).

2.2.3 Design recommendations

Additionally to the design bases given in above subsections, in this section some recommendations are given:

- According to fib bulletin 14 (14) the maximum spacing between strips should be less than 0.2·l (l = span length), 5·h (h = total depth) and 0.4·l_c (l_c = length of cantilever).

- Fib (14) recommends that the distance from FRP reinforcement to the edge of the beam should be equal or greater than the concrete cover of the internal steel reinforcement.

- Joints should be avoided. If they are necessary lap joints of strips should only be provided in sections where the maximum tensile force in the FRP reinforcement is equal or less than 60% of tensile force at ultimate (14).

- According to fib (14) the maximum number of layers that is recommended to be applied is:
  - 3 layers of pultruded strips
  - 5 layers of cured in-situ fabrics
The distance between the end of the strip and the face of the support should be less than 50 mm in the strengthening of simple supported beams according fib (14).

In situations where it is not possible to provide the adequate anchorage length (e.g. anchorage in negative bending zones), or where the correct work of the bonding between the fibre and the substrate could not be sure, mechanical anchorage devices and additional transverse laminates can be used to avoid failure modes where there is a loss in composite action. About these special anchorage device there is not enough knowledge available, so any innovate system should be verified by testing.

2.3 Design requirements: Shear strengthening

Shear strengthening of concrete reinforced elements using FRP may usually be provided by bonding the external reinforcement with the principal fibre orientation either 45° or 90°. The strengthening will be more efficient when its fibres are parallel to the maximum principal tensile stress.

The shear contribution of FRP to the strengthened element is influenced by many factors such as size and geometry of the member, properties of concrete, internal shear and flexural reinforcements, loading conditions, method of strengthening, properties of the bond, anchorage length, type of anchorage, thickness of the FRP, rigidity of the FRP, the fibre orientation, etc. To determine it many studies have been undertaken but there is no generally accepted or definitive design method.

Figure 3.- Configurations of FRP shear reinforcement.
The most accepted procedure is to idealise the FRP material in analogy with internal stirrups. The FRP stress at failure will be less than the ultimate stress; this effective stress will depend on the failure mode.

The main failure modes are FRP debonding and FRP tensile rupture. FRP rupture occurs at a strain level, which is less than the fracture strain. This level of strain is called effective strain, and is defined as a part of the ultimate FRP strain. There are different experimental approaches to determine it.

2.3.1 Design of FRP reinforcement based on the Ultimate Limit State (ULS)

In the same way as in unstrengthened reinforced concrete members, at ultimate limit state, the shear failure may be caused by two basic phenomenon:

- Diagonal tension at the web reinforcement.
- Diagonal compression at the concrete web

In case of diagonal tension failure for FRP strengthened members, the shear capacity is obtained adding the composite material contribution to the conventional components (concrete and steel).

The required FRP cross-section is determined in order to achieve the design shear capacity after strengthening.

In the shear strengthening it is also necessary to check the flexural capacity of the member because additional axial FRP may be required due to beam and column elements subject to shear force will experience additional axial tensile forces to those from bending.

Assuming that the shear cracks are inclined 45° to the longitudinal axis of the member and the angle between the principal direction of the fibres of the FRP reinforcement and the longitudinal axis of the member is 90°. The shear resistance is:

\[ V_{f,d} = A_{fs} \cdot \left( E_{f} \cdot e_{fs} \right) \cdot \frac{d_{f}}{s_{f}} \]

The parameters that appear in the above equations are defined according to ACI 440.2R-02 (3) as follows:

- \( A_{fs} \): area of FRP shear reinforcement
- \( A_{fs} = 2 \cdot t_{f} \cdot w_{f} \) assuming that the FRP is placed on both sides of the member, \( t_{f} \) is the thickness of the FRP reinforcement and \( w_{f} \) is the width of the FRP reinforcement.
\( \varepsilon_{fe} \): effective strain level in FRP reinforcement

\( E_f \): modulus of elasticity of FRP

Definitions given by TR 55 (11) for the same parameters are the following:

- \( A_{fs} \): area of FRP shear reinforcement
  \[ A_{fs} = 2 \cdot t_f \cdot w_{fe} \]
  assuming that the FRP is placed on both sides of the member, \( t_f \) is the thickness of the FRP and \( w_{fe} \) is the effective width of the FRP, where FRP is in the form of U-jacket: \( w_{fe} = d_f - L_e \), where FRP is bonded to side faces: \( w_{fe} = d_f - 2 \cdot L_e \) (see figure 5).

- \( L_e \): effective bond length
  \[ L_e = \frac{461.3}{(t_f \cdot E_f)^{0.58}} \]

- \( \varepsilon_{fe} \): effective strain in the FRP

- \( d_f \): effective depth of FRP shear reinforcement, usually equal to \( d \) for rectangular sections and \( (d - \text{slab thickness}) \) for T sections.

- \( s_f \): spacing between the centre line of FRP plates (\( s_f = w_{fe} \) for continuous sheet)

- \( E_f \): elastic modulus of the FRP at ultimate limit state
In the design, the expressions commented and the parameters defined above should be affected by adequate safety factors (global reduction factors and FRP material partial safety factors) according to the selected reference. For design purposes, the complete evaluation procedure should be followed from the selected reference.

Comparing both documents the following conclusion are carried out; on one hand in the case of continuous FRP shear reinforcement, both references give the same result (apart from the variations introduced by the safety factors), on the other hand in the case of FRP strips reinforcement the differences in the “FRP area” parameter makes that formulation according ACI (3) is more conservative unless some errors may exist in the TR 55 (11) consulted document (published by the Concrete Society 2000).

The design strain in the FRP will depend in both documents of the type of failure mode:

- Loss of aggregate interlock
- FRP rupture
- Delamination of the FRP from the concrete surface

In the case of fully wrapped jackets, the bonded length is usually enough, whereas in unwrapped (side or U-jackets) the bond length is normally limited by the behaviour of the bond between FRP and concrete. In this situation, it is necessary to consider FRP debonding failure mode.

Similar experimental formulation are given in both documents to compute the effective FRP strain level. This formulation depends on the failure mode and the effective strain ($\varepsilon_{fe}$) in the FRP should be taken as the lesser value.

<table>
<thead>
<tr>
<th>COMPLETELY WRAPPED ELEMENTS</th>
<th>TR 55 (Concrete Society)</th>
<th>ACI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loss of aggregate interlock</td>
<td>$\varepsilon_\mu = 0,004$</td>
<td>$\varepsilon_\mu = 0,004$</td>
</tr>
<tr>
<td>FRP rupture</td>
<td>$\varepsilon_f = \varepsilon_f \cdot \left[0,5622 \cdot (\rho_f \cdot E_f) \cdot 1,2188 \cdot (\rho_f \cdot E_f) + 0,778\right]$</td>
<td>$\varepsilon_{fe} = 0,75 \cdot \varepsilon_{fu}$</td>
</tr>
</tbody>
</table>

$\varepsilon_{fu}$: ultimate failure strain in FRP
$\rho_f$: FRP shear reinforcement ratio
$\rho_f = 2\cdot t_f/b_w$ for continuously bounded FRP of thickness $t_f$
$\rho_f = 2\cdot t_f/(w_f/s_f)$ for strips or sheets of width $w_f$ at a spacing $s_f$

Table 10: Equations proposed by ACI440.2R-02 (3) TR 55 (11) to evaluate the effective FRP strain.
BONDED U WRAPS OR BONDED FACE PLIES

<table>
<thead>
<tr>
<th>TR 55 (Concrete Society)</th>
<th>ACI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loss of aggregate interlock</td>
<td>$\varepsilon_{\mu} \leq 0.004$</td>
</tr>
</tbody>
</table>

**FRP rupture**

$\varepsilon_{fu} = \varepsilon_{\mu} \left[ 0.5622 \cdot \left( \frac{\rho_f \cdot E_f}{\varepsilon_{fu}} \right)^2 - 1.2188 \cdot \left( \frac{\rho_f \cdot E_f}{\varepsilon_{fu}} \right) + 0.778 \right]$  

$\rho_f \cdot E_f \leq 0.0011 kN/mm^2$

$\varepsilon_{fu}$: ultimate failure strain in FRP  
$\rho_f$: FRP shear reinforcement ratio

$\rho_f = 2 \cdot t_f / b_w$ for continuously bounded FRP of thickness $t_f$  
$\rho_f = 2 \cdot t_f / b_w \cdot (w_f / s_f)$ for strips or sheets of width $w_f$ at a spacing $s_f$

$b_w$: beam width of cross section or plate spacing  
$E_f$: elastic modulus of the FRP at ultimate limit state

$\varepsilon_{fu} = 0.75 \cdot \varepsilon_{\mu}$  
$\varepsilon_{\mu}$: ultimate failure strain in FRP

**Delamination of the FRP for the concrete surface (Based on Maeda et al. and Khalifa et al.)**

$\varepsilon_{\mu} = \frac{0.0042 \cdot (0.835 \cdot f_c)^{0.5} \cdot (d_f - L_e)}{(t_f \cdot E_f)^{0.5} \cdot d_f}$  

(FRP in the form or U jackets)

$\varepsilon_{\mu} = \frac{0.0042 \cdot (0.835 \cdot f_c)^{0.5} \cdot (d_f - 2 \cdot L_e)}{(t_f \cdot E_f)^{0.5} \cdot d_f}$

(FRP bond to side faces)

$f_c$: compressive stress in concrete (N/mm²)  
$L_e$: effective bond length; $L_e = 461.3 \left( \frac{t_f \cdot E_f}{f_c} \right)^{0.5}$  
$t_f$: thickness of the FRP reinforcement (mm)  
$d_f$: effective depth of FRP shear reinforcement (mm)  
$E_f$: elastic modulus of the FRP (N/mm²)

$\varepsilon_{\mu} = 0.2176 \cdot (f_c)^{0.5} \cdot \left( \frac{d_f - L_e}{t_f \cdot E_f} \right)^{0.5} \cdot d_f$  

(FRP in the form or U jackets)

$\varepsilon_{\mu} = 0.2176 \cdot (f_c)^{0.5} \cdot \left( \frac{d_f - 2 \cdot L_e}{t_f \cdot E_f} \right)^{0.5} \cdot d_f$  

(FRP bond to side faces)

$\varepsilon_{\mu}$: ultimate failure strain in FRP

**Table 11: Equations proposed by ACI440.2R-02 (3) TR 55 (11) to evaluate the effective FRP strain.**

In the design, the expressions given and the parameters defined in table 10 and table 11 should be affected by adequate safety factors (global reduction factors and FRP material partial safety factors) according to the selected reference. For design purposes, the complete evaluation procedure should be followed from the selected reference.
Because there have been a number of developments since the first edition of TR 55 in 2000, Concrete Society at present is revising TR 55 (11). In the latest draft they propose:

Assuming that the shear cracks are inclined 45º to the longitudinal axis of the member and the angle between the principal direction of the fibres of the FRP reinforcement and the longitudinal axis of the member is 90º. The shear resistance is given by:

\[
V_f = E_f \varepsilon_{fe} A_{fs} \left( \frac{d_f - \frac{n l_{\text{max}}}{3}}{s_f} \right)
\]

This is the same procedure recommend by BD 85/02 (draft) (5).

Where:

- \(n\) is 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 only the sides of a beam.
- \(\varepsilon_{fe}\): effective strain in the FRP
- \(A_{fs}\): area of FRP for shear strengthening measured perpendicular to the direction of the fibres.
- \(d_f\): effective depth of the FRP strengthening, measured from the top of the FRP to the tension reinforcement (mm)
- \(E_f\): tensile modulus of the FRP laminate (N/mm²)
- \(l_{\text{max}}\): anchorage length required to develop full anchorage capacity (mm)

\[
l_{\text{max}} = 0.7 \left( \frac{E_f}{f_{\text{ctm}}} \right)^{\frac{1}{2}}
\]

- \(f_{\text{ctm}}\): tensile strength of the concrete (N/mm²)
- \(t_f\): thickness of the FRP reinforcement (mm)
- \(s_f\): longitudinal spacing of the FRP laminates used for shear strengthening.

In this approach the verification of separation failure mode is applied as in the previous one to the case FRP bonded either to the sides of beams or the sides and the tension face of beams but also to fully wrapped beams.
The effective strain in the FRP should not be greater than the minimum of the values given in table 12:

<table>
<thead>
<tr>
<th>Loss of aggregate interlock</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_{p} \leq 0.004$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FRP rupture</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_{p} \leq \frac{\varepsilon_{fu}}{2}$</td>
</tr>
<tr>
<td>$\varepsilon_{fu}$: ultimate failure strain in FRP</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Debonding of the FRP</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_{p} \leq 0.64 \cdot \frac{f_{cm}}{E_{f} t_{f}}$</td>
</tr>
<tr>
<td>$f_{cm}$: tensile strength of the concrete (N/mm²)</td>
</tr>
<tr>
<td>$t_{f}$: thickness of the FRP reinforcement (mm)</td>
</tr>
<tr>
<td>$E_{f}$: elastic modulus of the FRP at ultimate limit state (N/mm²)</td>
</tr>
</tbody>
</table>

Table 12: Equations proposed in the latest draft of the Concrete Society and in the BD 85/02 (draft) (5).

In the design, the expressions given and the parameters defined in table 10 and table 11 should be affected by adequate safety factors (global reduction factors and FRP material partial safety factors) according to the selected reference. For design purposes, the complete evaluation procedure should be followed from the selected reference.
According to fib bulletin 14 (14) the following analytical approach has been used to compute the FRP shear contribution:

\[ V_f = 0.9 \cdot \rho_f \cdot b_w \cdot E_f \cdot \varepsilon_f \cdot d \]

where:
- \( \varepsilon_f \): effective FRP strain
- \( b_w \): minimum width of cross section over the effective depth
- \( d \): effective depth of cross section
- \( \rho_f \): FRP shear reinforcement ratio
  - \( \rho_f = 2 \cdot t_f / b_w \) for continuously bounded FRP of thickness \( t_f \)
  - \( \rho_f = 2 \cdot t_f / b_w (w_f / s_f) \) for strips or sheets of width \( w_f \) at a spacing \( s_f \)
- \( E_f \): elastic modulus of FRP in the principal fibre orientation at ultimate limit state

According to fib bulletin 14 (14) when full wrapping is not possible the FRP strips should be anchored to the compressive zone of the reinforced concrete member. It is recommended to use the whole height of the compression zone for anchoring. When anchorage in the compression zone is insufficient fib bulletin (14) recommends that the inner lever arm should be reduced.

The value of the effective FRP strain \( (\varepsilon_f) \) will depend on the failure mode as in the previous approach of the shear resistance. The FRP strain should be taken as the lesser of the following values (the values given in the table should be affected by the adequate safety factors given in section 2.1 “Safety factors”.

### Side or U-shaped CFRP jackets

<table>
<thead>
<tr>
<th>FRP peeling-off</th>
<th>( \varepsilon_f = K \cdot 0.65 \cdot \left( \frac{f_{cm}^{2/3}}{E_f \cdot \rho_f} \right)^{0.56} \cdot 10^{-3} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>where:</td>
<td>( f_{cm} ): mean compressive strength of concrete (N/mm²)</td>
</tr>
<tr>
<td></td>
<td>( E_f ): modulus of elasticity of FRP at ultimate (KN/mm²)</td>
</tr>
<tr>
<td></td>
<td>( K ): constant relating the characteristic to the mean value of the effective FRP strain (K=0.8)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FRP fracture</th>
<th>( \varepsilon_f = K \cdot 0.17 \cdot \left( \frac{f_{cm}^{2/3}}{E_f \cdot \rho_f} \right)^{0.30} \cdot \varepsilon_f )</th>
</tr>
</thead>
<tbody>
<tr>
<td>where:</td>
<td>( f_{cm} ): mean compressive strength of concrete (N/mm²)</td>
</tr>
<tr>
<td></td>
<td>( E_f ): modulus of elasticity of FRP at ultimate (KN/mm²)</td>
</tr>
<tr>
<td></td>
<td>( \varepsilon_f ): ultimate FRP strain</td>
</tr>
<tr>
<td></td>
<td>( K ): constant relating the characteristic to the mean value of the effective FRP strain (K=0.8)</td>
</tr>
</tbody>
</table>

Table 14: Equations proposed by fib bulletin 14 (14) to evaluate the effective FRP strain.
Fully wrapped (or properly anchored) CFRP

<table>
<thead>
<tr>
<th>FRP fracture controls</th>
<th>$\varepsilon_{ue} = K \cdot 0.17 \left( \frac{f_{cm}}{E_f \cdot \rho_f} \right)^{1/3} \cdot \varepsilon_{fu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>where:</td>
</tr>
<tr>
<td></td>
<td>$f_{cm}$: mean compressive strength of concrete (N/mm²)</td>
</tr>
<tr>
<td></td>
<td>$E_f$: modulus of elasticity of FRP at ultimate (KN/mm²)</td>
</tr>
<tr>
<td></td>
<td>$\varepsilon_{fu}$: ultimate FRP strain</td>
</tr>
<tr>
<td></td>
<td>$K$: constant relating the characteristic to the mean value of the effective FRP</td>
</tr>
<tr>
<td></td>
<td>strain ($K=0.8$)</td>
</tr>
</tbody>
</table>

Table 15: Equations proposed by fib bulletin 14 (14) to evaluate the effective FRP strain.

Fib bulletin 14 (14) also introduces a limitation of the effective strain in order to avoid the loss aggregate interlock. The effective strain should be limited for fully wrapped members, two sides or U shape jackets to a maximum value of 0.006. Comparing this limitation with the one given by ACI (3) and TR 55 (11) a large limit is accepted in this approach.

Fib (14) also highlights that one drawback of the previous approach is that the FRP bonded length is not taken explicitly into account. However, one could estimate the maximum force that may be carried by the FRP prior to debonding according to concepts presented in section 2.2.

In the design, the expressions given above and the parameters defined in table 14 and table 15 should be affected by adequate safety factors (global reduction factors and FRP material partial safety factors) according to the selected reference. For design purposes, the complete evaluation procedure should be followed from the selected reference.

2.3.2 Verification of Serviceability Limit State (SLS)

Regarding serviceability limit state only some considerations are given in fib bulletin 14 (14), they are related with limiting the strain in the FRP in the serviceability limit state.

2.3.3 Design recommendations

Additionally to the design bases given in above subsections, in this section some recommendations are given:

- To avoid that a diagonal crack may be formed without intercepting a strip, the spacing of strips should not exceed (see table 16):
ANNEX J Strengthening with carbon fibre

| TR 55 (11) | \( s_f \leq \min\left\{0.8 \cdot d; \frac{w_f + d}{4}\right\} \)
Where:
- \(w_f\) is the width of the FRP strip
- \(d\): effective depth of the beam |

| fib bulletin 14 (14) | If the strips are used vertically:
- \( s_f \leq 0.9 \cdot d - \frac{w_f}{2} \) for rectangular cross section
- \( s_f \leq d - h_f - \frac{w_f}{2} \) for T-beams
Where:
- \(w_f\) is the width of the FRP strip
- \(h_f\): slab thickness
- \(d\): effective depth of the member |

Table 16: Maximum spacing of strips according fib bulletin 14 (14) and TR 55 (11).

The latest draft of the Concrete Society introduce that the maximum spacing between strips should be less than \(0.8d_f d_f - (n/3)l_{t,\text{max}}\) or \(w_f + d_f /4\).

Where \(n\) is 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 only the sides of a beam.

\(l_{t,\text{max}}\): anchorage length required to develop full anchorage capacity (mm)
\(l_{t,\text{max}} = 0.7 \left( \frac{(E_f \cdot t_f)}{f_{\text{cm}}} \right)^{\frac{1}{2}} \)
\(d_f\): effective depth of the FRP strengthening, measured from the top of the FRP to the tension reinforcement (mm)
\(E_f\): design tensile modulus of the FRP laminate (N/mm2)
\(t_f\): thickness of the FRP (mm)
\(w_f\): width of the FRP (mm)
2.4 Design of column strengthening

It is experimentally proved that when uniaxially loaded concrete is confined (retrained from dilating laterally), it exhibits an increase in strength and axial deformation capacity.

The effect of confinement can be achieved by FRP jacketing with fibres orientated transverse to the longitudinal axis of the member.

Providing confinement to a concrete compression element with a FRP jacket enhances:

- Concrete strength (increasing the axial load capacity of the concrete compression element)
- Ductility (increasing the maximum compressive strain in the concrete before compressive failure)
- Prevents buckling of the longitudinal reinforcement and concrete spalling

Depending on the purpose of the strengthening the shear strength and axial strength can be increased by wrapping. In the case of flexural strengthening, axial FRP is needed. However, if FRP wrapping is applied over the axial one, in the compression zone it increases its strain capacity and enhances its compressive strength. Furthermore, for circular columns, the compressive strength of the axial FRP may be used in the design (according to BD 84/02 (4)) if confinement is provided.

In order to improve the behavior under seismic loads not only strength but also ductility needs to be increased.

The most common methods for FRP jacketing are the following:

- Fibre wrapping with fabrics (wet lay-up process)
- Filament winding (automated method)
- Prefabricated shells

A passive and active confinement are possible but the most common is the passive one. The active confinement is achieve by introducing stress to fibres in the wrapping process or by injecting a mortar or a resin between the FRP jacket and the column.

The effectiveness in the confinement effect of the FRP jacket is influence by different parameters as the concrete strength, the type of fibres and resin, the percentage in volume of fibres and the alignment of the fibres in the jacket, the thickness of the reinforcement, the adherence between the concrete and the FRP reinforcement, the shape section and the slenderness of the column.

In following subsections, general remarks for design of column strengthening are given. For design purposes, the complete evaluation procedure should be followed from the selected reference because this document is a partial reproduction. Furthermore the formulations given are pending to introduce the safety factors according to each technical document.
2.4.1 **Evaluation of the confining pressure**

Assuming uniform tension in the FRP, for uniaxially loaded cylindrical concrete member confined with FRP reinforcement with fibres circumferentially aligned and covering the total concrete surface, the maximum lateral confining pressure that the FRP jacket can exert is the following:

\[
\sigma_l = \frac{2 \cdot E_f \cdot \varepsilon_{fu} \cdot t_f}{D} = \frac{1}{2} \cdot \rho_f \cdot E_f \cdot \varepsilon_{fu} = K_{conf} \cdot \varepsilon_{fu}
\]

\[
\rho_f \approx \frac{4 \cdot t_f}{D}
\]

\[
K_{conf} = \frac{1}{2} \cdot \rho_f \cdot E_f
\]

Where:

- \(E_f\): modulus of the FRP jacket
- \(\varepsilon_{fu}\): effective failure strain in the FRP jacket
- \(t_f\): thickness of the FRP jacket
- \(D\): diameter of the column
- \(\rho_f\): volumetric ratio of the FRP jacket
- \(K_{conf}\): stiffness of the FRP confinement

**Effective failure strain in the FRP jacket**

It is experimentally proved that failure of the FRP jacket occurs at a strain lower than the ultimate strain of the FRP material. There are several reasons for this reduction:

- A multiaxial stress state exists in the jacket. The FRP jacket provides transverse confinement action, at the same time, due to the composite action, it is subjected to axial loading.

- Local stress concentrations in the FRP jacket at high load levels. They are due to the non-homogeneous deformations in the cracked concrete.
The curved shape of the FRP jacket, especially at corners with small radius.

The quality of the execution. In presence of local misalignment of fibres, part of the circumferential deformation is used to stretch the fibres. Also fibres may be damaged or suffer local stress concentration due to an inadequate surface preparation (for example presence of voids or local protrusions).

Size effect when multiple layers are applied

In the references there are different equations to predict the reduction factor for the ultimate strain of the FRP material but more research are needed in order to develop a more accurate factor (10).

According to fib (14) the value for the effective failure strain in the FRP jacket should be justified by experimental evidence.

**Effective lateral confining pressure**

The confinement effect exerted by the FRP jacket, as it is stated in section 2.4, is influenced by different parameters. In some of the references, considerations for non fully wrapped members, fibre orientation not perpendicular to the longitudinal axis, square or rectangular member shape are taken into account in the design by introducing an effectiveness coefficient \(K_e\) to determine the lateral confining pressure.

The effective lateral confining pressure is determined as follow:

\[
\sigma_f = \frac{1}{2} \cdot K_e \cdot \rho_f \cdot E_f \cdot \varepsilon_{fu} = K_{conf} \cdot \varepsilon_{fu}
\]

\[K_{conf} = \frac{1}{2} \cdot \rho_f \cdot E_f \cdot K_e\]
The value of $K_e$, according to references (14) and (9), is given in the following table:

<table>
<thead>
<tr>
<th>CONSIDERATION</th>
<th>$K_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Partial wrapping</strong></td>
<td>$K_e = \frac{A_e}{A_c}$ (14)</td>
</tr>
<tr>
<td></td>
<td>$A_e=$ effectively confined concrete area</td>
</tr>
<tr>
<td></td>
<td>$A_c=$ concrete area (the longitudinal steel area is discounted)</td>
</tr>
<tr>
<td><strong>Fibre orientation</strong></td>
<td>When fibres are helically applied: (14)</td>
</tr>
<tr>
<td></td>
<td>$K_e = \left[1 + \left(\frac{P}{\pi \cdot D}\right)^2\right]^{-1}$</td>
</tr>
<tr>
<td></td>
<td>$P=$ helix pitch</td>
</tr>
<tr>
<td></td>
<td>$D=$ diameter of the member</td>
</tr>
<tr>
<td><strong>Square or rectangular</strong></td>
<td>$K_e = \frac{A_e}{A_c}$ (14)</td>
</tr>
<tr>
<td>section*</td>
<td>$A_e=$ effectively confined concrete area</td>
</tr>
<tr>
<td></td>
<td>$A_c=$ concrete area (the longitudinal steel area is discounted)</td>
</tr>
<tr>
<td></td>
<td>$d/h=$ aspect ratio</td>
</tr>
</tbody>
</table>

Table 17
* Square or rectangular section.- In square or rectangular columns the confinement pressure is transmitted from the FRP jacket to the concrete through the four corners, it results in a reduction of the confined concrete volume.

The lateral confining pressure induced by the FRP are given in reference (14) as:

\[
\begin{align*}
\sigma_{lx} &= K_{conf} \cdot \varepsilon_{fu} \\
\sigma_{ly} &= K_{confy} \cdot \varepsilon_{fu}
\end{align*}
\]

With:

\[
\begin{align*}
K_{conf} &= \rho_{fx} \cdot K_e \cdot E_f \\
K_{confy} &= \rho_{fy} \cdot K_e \cdot E_f \\
\rho_{fx} &= \frac{2 \cdot b_f \cdot t_f}{s \cdot d} \\
\rho_{fy} &= \frac{2 \cdot b_f \cdot t_f}{s \cdot h}
\end{align*}
\]

Where:
\(\rho_{fx}\): volumetric ratio of the FRP jacket in x direction
\(\rho_{fy}\): volumetric ratio of the FRP jacket in y direction

Another option to obtain the lateral confining pressure in a rectangular column is to use as diameter of the column the hypotenuse of the rectangular section according to reference (9) or a reinforcement ratio of:

\[
\rho_f = \frac{2 \cdot t_f \cdot (d + h)}{d \cdot h}
\]

according to reference (3).

Because in the case of square or rectangular columns the FRP reinforcement is less effective, few researches have been carried out although this type of columns are usually presented in the structures. In general, experimental tests have shown that the increase of ultimate strength is highly influence and increases with the radius of the corners of square or rectangular sections. On the other hand, the increase of axial deformation capacity is up to 8 times that of unconfined concrete, even for the sharp edged sections (20).

Due to the many unknowns in this type of application in technical documents as for example ACI 440.2R-02 (3) or Concrete Society TR 55 (11) no recommendation is provided to evaluate the increases in the axial compression strength of the element.

However, ACI (3) accepts the improvement in the ductility of these sections if they verify the following geometric limitations (unless testing demonstrates their effectiveness):

<table>
<thead>
<tr>
<th>GEOMETRIC LIMITATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>d/h ≤ 1.5</td>
</tr>
<tr>
<td>d ≤ 900 mm</td>
</tr>
<tr>
<td>h ≤ 900 mm</td>
</tr>
</tbody>
</table>

Table 18
In this case ACI (3) also introduces an effectiveness coefficient to take into account the shape of the column. This reduction factor is similar to the ones given in table 17.

According to fib bulletin 14 (14) in rectangular columns with large aspect ratio to achieve confinement the FRP jacket need to be bolted to the structure in order to create shorter distances which are confined between bolts.

2.4.2 Evaluation of the increment in the concrete strength (FRP-confined concrete model)

An FRP-confined concrete model is necessary to calculate the increase in the concrete strength and strain due to the confinement.

Table 19 presents the prediction of the ultimate axial stress and strain of the confined concrete according to some of the existing models on confinement of concrete columns with FRP materials.

The confinement effect exerted by FRP jacket is a continuously increasing action hence an increase in the strain in FRP results in an increase in the confining pressure. Oppositely steel exerts a constant confining pressure when it reaches the yielding stress.

Several models are original for steel and they are based in a constant value of the confining pressure (triaxial confined concrete test) throughout the loading history. They are extended to the FRP confinement by introducing instead of the constant pressure the maximum confinement pressure that the FRP can exert (SM).

The rest of the models are specifics for FRP-confined concrete, attending to the different behaviour between steel-confined concrete and FRP-confined concrete (FM).

According to reference (10), both types of models are applicable to predict the strength. It is due to the strength independency from the way in which the confining stress is applied. However in the case of strain, its dependency is observed and hence large discrepancies are obtained in the predicted strain values.

The models proposed by the existing technical documents are included in the column “Ref” of the table 19. The model proposed by TR 55 (11) is based on the work of Cuninghame et al. where trying to avoid the inaccuracy strain prediction suggest that providing a circumferential FRP over the full length of the element, with the fibres oriented in the direction at 90° to the longitudinal axis and the effective hoop stiffness greater than 320 N/mm², an enhanced effective strength for confined concrete may be taken and assumed to vary linearly with strain from $f_{cu}$ at a strain of 0.0035 to 1.5-$f_{cu}$ at a strain of 0.01 (4) (11).

In conclusion some of the proposed models predict the strength of the confined column accurately. However, the errors in the prediction of the strain peak are larger and in most cases on the unconservative side. In general the accuracy of the FRP-confined concrete models still needs to be improved.
<table>
<thead>
<tr>
<th>REF</th>
<th>MODEL</th>
<th>THEORETICAL ( f_{\text{st}} )</th>
<th>THEORETICAL ( \varepsilon_{\text{st}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fardis and Khalili SM</td>
<td>( f_{\text{st}} = 1 + 4.1 \cdot \frac{\sigma_i}{f_{\text{co}}} )</td>
<td>Option 1 ( \varepsilon_{\text{st}} = \varepsilon_{\text{co}} + 0.0005 \cdot \frac{E_i}{f_{\text{st}}} ) (10)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( f_{\text{st}} = 1 + 3.7 \cdot \left( \frac{\sigma_i}{f_{\text{co}}} \right)^{0.296} )</td>
<td>Option 2 ( \varepsilon_{\text{st}} = \varepsilon_{\text{co}} + 0.001 \cdot \frac{E_i}{f_{\text{st}}} ) (10)</td>
<td></td>
</tr>
<tr>
<td>Saadatmanesh et al. SM</td>
<td>( f_{\text{st}} = 2.254 \cdot \left( 1 + 7.94 \cdot \frac{\sigma_i}{f_{\text{co}}} - 2 \cdot \frac{\sigma_i}{f_{\text{co}}} - 1.254 \right) \frac{\varepsilon_{\text{st}}}{\varepsilon_{\text{co}}} = 1 + 5 \cdot \left( \frac{f_{\text{st}}}{f_{\text{co}}} - 1 \right) )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Miyauchi et al. FM</td>
<td>Option 1 ( \varepsilon_{\text{st}} = 1 + 3.485 \cdot \frac{\sigma_i}{f_{\text{co}}} ) (10)</td>
<td>(10)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Option 2 ( \varepsilon_{\text{st}} = 1 + 2.98 \cdot \frac{\sigma_i}{f_{\text{co}}} ) (16)</td>
<td>(*) There are discrepancies in the evaluation of ( \varepsilon_{\text{st}} ) between references (10) and (16)</td>
<td></td>
</tr>
<tr>
<td>Kono et al. FM</td>
<td>( f_{\text{st}} = 1 + 0.0572 \cdot \sigma_i )</td>
<td>( \varepsilon_{\text{st}} = 1 + 0.280 \cdot \sigma_i )</td>
<td></td>
</tr>
<tr>
<td>Saaman et al. FM</td>
<td>( f_{\text{st}} = 1 + 6.0 \cdot \frac{\sigma_i^{0.7}}{f_{\text{co}}} )</td>
<td>( \varepsilon_{\text{st}} = \frac{f_{\text{st}} - f_{\text{co}}}{E_i} )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( f_{\text{st}} = 0.872 \cdot f_{\text{co}} + 0.371 \cdot \sigma_i + 6.258 ) option 1 ( E_i = 245.61 \cdot f_{\text{st}}^{0.2} + 0.6728 \cdot E_i ) option 2 ( E_i = 245.61 \cdot f_{\text{st}}^{0.2} + 1.3456 \cdot E_i ) (*) There are discrepancies in the evaluation of ( E_i ) in reference (10)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Toutanji FM</td>
<td>( f_{\text{st}} = 1 + 3.5 \cdot \left( \frac{\sigma_i}{f_{\text{co}}} \right)^{0.85} )</td>
<td>( \varepsilon_{\text{st}} = 1 + (310.57 \cdot \varepsilon_{\text{co}} + 1.90) \cdot \left( \frac{f_{\text{st}}}{f_{\text{co}}} - 1 \right) )</td>
<td></td>
</tr>
<tr>
<td>Saafi et al. FM</td>
<td>( f_{\text{st}} = 1 + 2.2 \cdot \left( \frac{\sigma_i}{f_{\text{co}}} \right)^{0.844} )</td>
<td>( \varepsilon_{\text{st}} = 1 + (537 \cdot \varepsilon_{\text{co}} + 2.6) \cdot \left( \frac{f_{\text{st}}}{f_{\text{co}}} - 1 \right) )</td>
<td></td>
</tr>
<tr>
<td>Spoelestra and Monti (approximate) FM</td>
<td>( f_{\text{st}} = 0.2 + 3.0 \cdot \left( \frac{\sigma_i}{f_{\text{co}}} \right)^{0.5} )</td>
<td>( \varepsilon_{\text{st}} = 2 + 1.25 \cdot \frac{E_i}{f_{\text{co}}} \cdot \varepsilon_{\text{co}} \cdot \left( \frac{\sigma_i}{f_{\text{co}}} \right) )</td>
<td></td>
</tr>
<tr>
<td>Seible et al.</td>
<td>( f_{\text{st}} = 2.254 \cdot \left( 1 + 7.94 \cdot \frac{\sigma_i}{f_{\text{co}}} - 2 \cdot \frac{\sigma_i}{f_{\text{co}}} - 1.254 \right) ) ( \varepsilon_{\text{st}} = 0.004 + \frac{2.5 \cdot f_{\text{st}} \cdot \sigma_i}{f_{\text{co}}} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Xiao and Wu FM</td>
<td>( f_{\text{st}} = 1.1 + \left( 4.1 - 0.75 \cdot \frac{f_{\text{co}}^{3}}{E_i} \right) \cdot \frac{\sigma_i}{f_{\text{co}}} )</td>
<td>( \varepsilon_{\text{st}} = \varepsilon_{\text{co}} - 0.0005 \cdot 7 ) ( \left( \frac{f_{\text{st}}}{f_{\text{co}}} \right)^{0.5} )</td>
<td></td>
</tr>
<tr>
<td>Cuninghame et al. FM</td>
<td>( f_{\text{st}} = 1.5 \cdot f_{\text{st}} )</td>
<td>( \varepsilon_{\text{st}} = 0.01 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( K_{\text{conf}} \geq 320 \text{N/mm}^2 ) ( K_{\text{conf}} \geq 320 \text{N/mm}^2 ) ( \text{ONLY CYLINDRICAL SECTION} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(4) (11)</td>
<td>( f_{\text{st}} = 2.254 \cdot \left( 1 + 7.94 \cdot \frac{\sigma_i}{f_{\text{co}}} - 2 \cdot \frac{\sigma_i}{f_{\text{co}}} - 1.254 \right) ) ( \varepsilon_{\text{st}} = \frac{1.71 \cdot (5 \cdot f_{\text{st}} - 4 \cdot f_{\text{co}})}{E_i} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(3)</td>
<td>( f_{\text{st}} = 1 + 2 \cdot \frac{\sigma_i}{f_{\text{co}}} ) ( \varepsilon_{\text{st}} = 2 + 15 \cdot \frac{\sigma_i}{f_{\text{co}}} (\text{CFRP}) )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 19
Where:

- $\sigma_l$: maximum lateral confining pressure
- $f'_{cc}$: compressive strength of the confined concrete
- $f'_{co}$: compressive strength of the unconfined concrete
- $f_{cu}$: concrete strength at ultimate
- $f_{cu}^*$: compressive cube strength of concrete
- $f_{cu}^{**}$: effective cube strength for confined concrete
- $\varepsilon_{cc}$: axial strain at peak stress of the confined concrete
- $\varepsilon_{co}$: axial strain at peak stress of the unconfined concrete
- $\varepsilon_{cu}$: ultimate concrete strength
- $\varepsilon_{fu}$: FRP jacket effective ultimate circumferential strain
- $E_c$: modulus of elasticity of concrete
- $E_{co}$: initial tangent modulus of elasticity of concrete
- $E_2$: second slope of the axial stress-strain curve of the confined cylinder in Saaman’s model
- $E_l$: confinement modulus ($E_l=(E_r t_f)/D$ for circular columns)
- $K_{conf}$: stiffness of the FRP confinement ($K_{conf}=(2E_r t_f)/D$ for circular columns)
- $E_r$: modulus of elasticity of the FRP jacket
- $D$: diameter of the column
- $t_f$: thickness of the jacket
- $\rho_f$: volumetric ratio of the FRP jacket
- $f_r$: ultimate strength of the FRP jacket
- $f_o$: parameter in Seaman’s model

As reminder each model presented in table 19 has been developed in base to a limit number of tests, so its applicability is not clear for a general situation.

2.4.3 Design recommendations

Additional to the design bases given in the above subsections, the following recommendations are given in the different references consulted:

- The minimum number of layers that shall be provided is two layers of FRP hoop fibres (4).
- The maximum number of layers that shall be provided is of 20-25 or according to the material supplier’s recommendations (14).
- The overlap needed at all joints shall be consulted to the manufacturer but the minimum overlap that shall be provided is of 200 mm. If the lap length is inadequate the failure of the FRP can occur due to debonding (11)(4).
- When two or more plies of FRP are applied to a column, lap joints should be placed on opposites sides (11).
2.5 Performance requirements

In this chapter, the repair technique is analysed in order to determine how it suits the different requirements and indicators that have been established in the process to evaluate and optimise the alternative options for any given repair (section 7.2 “Repair index method (RIM)” of the Manual).

2.5.1 Service life and durability

Although the durability of the FRP and the concrete is well documented, the long term behaviour of the combined system is not. Because the FRP-concrete interface is the critical component, the normal service life of an externally bonded FRP reinforcement could be considered reasonable over 30 years, the current experience of the adhesives uses in steel plate bonding. A good execution process and a good preparation of the surface are essential for the durability. It may however, be affected due to the deterioration of the protection layer. (11)

The main disadvantage of externally strengthening structures with fibre composite materials is that they can be damage by fire, vandalism, ultraviolet radiation or accidental damage, unless the strengthening is protected.

Although carbon is resistant to most forms of chemical attacks and environmental agents, for example alkali and acid environment, the durability of the FRP reinforcement may be influenced by other exposure classes. (11) (14)

As with all structural elements there will be a need to check the fibre composite strengthening system (feasibility of post repair). This check can be a visual inspection, where surface damages will be located as signs of cracking, delamination, impacts, etc. Instruments also can be used as part of the inspection if they are used in conjunction with a load test or long term monitoring where measured parameters as strain or deflection can indicate changes in the structural response. For detailed inspection other methods are needed such as tapping, ultrasonic techniques or thermography (see subsection 4 “Quality control”).

The after repair disturbances affecting the functionality of the structure are also minimal (not affecting the loading gauge for example). And incompatibilities with other repair systems have not been reported. Galvanic corrosion of steel reinforcement can arise if carbon FRP comes in direct contact with steel (14).

2.5.2 Structural stability and safety

Externally bonded FRP reinforcement as a method of strengthening has only recently been adopted for civil engineering structures, and only limited experience is available when compared to steel plate bonding for example.
Another structural aspect to consider is the possible of brittle failure mode of the FRP reinforcement, if the strengthened structural element is not well designed.

2.5.3 Execution

The application of FRP material is easy but to ensure a long service life requires specialized workers with experience in repair and strengthening techniques and knowledge in products, application methods and quality control tests. Good execution control is obtained by the verification of the following aspects:

- Supplied materials
- The suitability of the concrete surface for bonding
- Application process

Special disturbances during repair works are not specified, beyond those expected in normal civil engineering work.

To ensure the safety of workers on site, the use of rubber gloves and glasses is recommended during the application of epoxy resins. Special cautiousness is needed to avoid CFRP material go in contact with electrical wires because CFRP material is electrically conductive and short-circuit, derivations and electrical fusillade can occur.

Other risks of accidents are related to the use of tools that are needed to carry out the work, including elevated work platforms, ladders, etc.

Special risks for the safety of users apart from those deriving from the repair works are described elsewhere.

2.5.4 Environmental, health and sustainability

Regarding environmental impact and sustainability, the resins used are highly toxic and need special treatment. The energy used in the manufacture process of FRP materials is less than for conventional materials so there is a lower consumption of resources. The environmental impact arising from transport is minimum because of their light weight (11) (21) (23).

2.5.5 Economy

The cost of FRP strengthening (including material and labour work cost) will vary depending on the country where the retrofitting is taken place.

This costs will be modified according to the particular conditions of the strengthening structure and the auxiliary means involved in it. In this case the lower weight of FRP materials makes them handling and installation significantly easier than steel. Work can usually be carried out from man access platforms rather than full scaffolding (Access tools). However, when long laminates are used in the strengthening it is necessary to provide access to the entire surface where the laminates will be applied.
The low weight also allows FRP to be applied material to the member without the need for temporary supports.

To ensure that the FRP is applied correctly, good preparation of the concrete surface is vital. The substrate should fulfill strict conditions about its geometry, unevenness or strength (preparation of substrate) because it is necessary to assure the bonding performance (the weakest part of the strengthening is the bonding interface).

The maintenance cost over the remaining life of the structure should be added to the above costs. The maintenance activities of an FRP strengthening system will be reduced to renew the protection layer or finishing treatment, because in general, fibres and resins are durable and require little maintenance.

The strengthening period is usually short for this type of reinforcement due to the easy of application for example with regard to the steel laminates. The weather conditions could be a critical point: the curing temperature of the adhesive must be between 5-25°C. At low temperatures, electrical heaters, heating blankets or infrared heating can be used.

In general, thanks to the save in access tools and to the short period of repair this kind of strengthening is economically profitable.

### 2.5.6 Aesthetics

The effect of bonded FRP systems on aesthetics is minimal because of their thin thickness. The presence of FRP can be made more discrete by applying a suitable coating finish.

The aesthetic condition of a repair can be modified by the loss of colour of the composite material due to the ultraviolet radiation (14).
3 EXECUTION

3.1 Materials selection

In this chapter the main materials (FRP materials and bonding agent) used in the FRP reinforcement are presented briefly.

3.1.1 FRP materials

FRP materials consist of fibres embedded in a matrix of resin. Fibres give the stiffness and the strength to the material while the main purpose of the matrix is to transfer the stresses between the fibres and give the shape to the composite material. The matrix also protect the fibres from environmental or mechanical damage.

Different types of fibres can be used, the main types are carbon fibre, glass fibre and aramid fibre. In this document only carbon FRP is included. The matrix can also be of different types. For strengthening applications the use of epoxy resins is more convenient because they have better mechanical properties and an outstanding durability.

The general characteristics of the composite material are its high strength and its linear behaviour to failure. Modern systems have excellent resistance against corrosion and ambient agents attacks. The variability of the composite materials is high depending on the type of fibre and matrix used.

Different carbon FRP systems are available and they are described in the following sections.

Prefabricated or pre-cured systems

These are pre-formed composites products, which are given their final shape, strength and stiffness in the factory. Depending on the prefabrication system used, the maximum fibre content that can be reached is about 70%.

Prefabricated systems are installed through the use of adhesives. A thin layer of adhesive is applied on both the concrete and the FRP. Then the FRP is placed on the concrete surface applying pressure with a rubber roller and removing the extra adhesive. Only one layer is usually applied but multiple layers can be applied (See subsection 3.3.1).

Different configurations are available depending on the manufacturer. They are typically provided in the form of strips or laminates, with thickness of about 1.0 mm to 1.5 mm (the most common are 1.2 mm and 1.4 mm). The width varies from 50 mm to 150 mm. Different fibre orientations are also available, eg, unidirectional laminates, multidirectional (laminates with carbon fibre filaments oriented both in longitudinal direction and +/- 45°), and sandwich type (composite beams in balsa wood reinforced with carbon fibre).
Table 20 presents typical mechanical properties of commercial prefabricated CFRP products. At current prices, products with an elastic modulus of 150,000 – 165,000N/mm² appear to give best value for money.

<table>
<thead>
<tr>
<th>Elastic modulus (N/mm²)</th>
<th>Tensile strength (N/mm²)</th>
<th>Ultimate tensile strength (N/mm²)</th>
<th>Tensile failure strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150,000</td>
<td>90% ultimate tensile strength</td>
<td>2,400 to 3,200</td>
<td>1.7</td>
</tr>
<tr>
<td>230,000</td>
<td>90% ultimate tensile strength</td>
<td>2,400 to 3,200</td>
<td>1.3 –1.4</td>
</tr>
<tr>
<td>300,000</td>
<td>90% ultimate tensile strength</td>
<td>2,400 to 3,200</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Table 20- Mechanical properties of commercial pre-cured carbon systems

Physical characteristics such as the thermal strength and the coefficient of thermal expansion must be considered. The thermal strength is the temperature above which fibres and matrix start to disaggregate and stop working as a whole. Depending on the kind of FRP ranges from 100ºC-130ºC or it is even >500ºC. It is not a conditioning property because the glass transition temperature of the bonding agent is usually lower. Therefore the bonding agent should be the weakest element from a thermal point of view. The coefficient of thermal expansion shall be determined according to EN 1770 (CEN1998c) (7) (8) (14).

For design purposes, actual properties must be obtained from the manufacturer.

“Wet lay-up (hand lay-up)” or “in-situ cured” systems

FRP wet lay up systems are installed by hand on site. The dry FRP fabric is impregnated with resin immediately prior to application and cured on site. These systems are also called “dry fibre”, because the amount of resin inside is small and need the resin applied during application process for polymerisation (14).

Sheets are recommended for shear strengthening and confinement, and multiple layers can be applied if required.

The installation on the concrete surface requires apply on it a saturating resin after the primer has been applied. Then, flexible sheets or fabrics are applied on the concrete surface by pressing them. Impregnation and further pressing of the sheet or fabric is performed by applying adhesive on the top of the fabric or sheet with a roller brush. The application of the adhesive is required to both, bond the sheet to the concrete and impregnate the sheet (See chapter 3.3.3). (18)

They are available as unidirectional fabrics, which means that all the fibres are oriented in the longitudinal direction or multidirectional fabrics, with the fibres oriented both in longitudinal direction and in other directions (90°, +45°, -45°). A typical weight in g/m²
is between 200-300, the thickness of them vary according to this value and the width is usually 300 mm. (7) (8) (21) (24)

The typical CFRP commercial products in the form of fabrics have the mechanical properties given in Table 21. The values of these properties are higher than the laminate’s ones.

<table>
<thead>
<tr>
<th>Elastic Modulus (N/mm²)</th>
<th>Tensile strength (N/mm²)</th>
<th>Ultimate tensile strength (N/mm²)</th>
<th>Tensile failure strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>230.000-240.000</td>
<td>90% ultimate tensile strength</td>
<td>2.600 to 3.800</td>
<td>1.5-1.55</td>
</tr>
<tr>
<td>600.000</td>
<td></td>
<td></td>
<td>0.4</td>
</tr>
</tbody>
</table>

Table 21.- Mechanical properties of commercial “cured in-situ” systems

About the physical characteristics, the coefficient of thermal expansion shall be determined according to EN 1770 (CEN1998c) as in prefab系统. The thermal strength is determined by the resin used as bonding agent, because the fibres are not into a matrix. (14)

For design purposes, actual properties must be obtained from the manufacturer.
3.1.2 Bonding agent

The adhesive and the FRP material must be compatible, for that reason only adhesives recommended by FRP supplier should be used. Generally, the bonding agent is comprised by a resin and a hardener and the adhesive based is normally of epoxy. (12)

The main requirements of an adhesive are:

- Good adherence to the substrate.
- Low permeability to water.
- Appropriate physical and mechanical properties.

General adhesive requirements for structural bonding are specified in prEN 1504-4 (19).

The selection of the bonding agent depends on the FRP system being used “wet lay-up” or “prefab”. For “wet lay-up” the viscosity should be low in order to assure the impregnation of the fibres.

The following conditions have to be considered in order to get a good performance of the strengthening:

- Curing conditions.
- Open time.
- Workable life.
- Glass transition temperature.
- Moisture absorption.
- Thermal coefficients.
- Mechanical properties.
- Durability, fatigue and creep.
- Suitability of application.

In the design it is necessary to guarantee that the adhesive will be capable of curing under the most extreme site conditions of temperature and humidity, with a negligible shrinkage. The time of curing depend on the ambient temperature (6 hours at 30°C, 12 hours at 20°C and 24 hours at 10°C) so especial importance is given to the curing conditions. There are some products with curing times only half as long. (12)

**Open time** is the time after application of the adhesive within which the joint can be made.

Special attention must be paid to the **workable life (pot life)** of the mixed adhesive, to the open time and to the shelf life of it. If any of this limits has been exceeded the adhesives should not be used.

The selection of the adhesive should be made taking into account the difference between the **glass transition temperature** and the **service temperature**. If the adhesive reaches the glass transition temperature its mechanical properties should be reduced. The adhesive governs the maximum temperature at which the strengthening can work,
and it is taken as 15°C below the transition temperature for transient loading and 20°C below for sustained loading (a typical transition temperature for ambient temperature curing epoxy adhesives is 60 °C). (14) (12)

Recommended values and the standard test methods to determine some of these properties are given in the Table 22.

The moisture absorption lowers the glass transition temperature, it is a reversible process unless the transition temperature is reduced below the operating temperature. So the moisture transport through the adhesive should be minimized. The maximum water absorption after immersion in water shall not exceed 3% by weight.

Other physical properties that can be found in the manufacturer’s sheets are the fluent and the coefficient of thermal expansion.

Depending on the adhesive composition a wide variety of mechanical properties can be obtained. The main mechanical properties are the flexural modulus, the shear strength, the adhesion strength and the compressive strength. The recommended values according to fib (14) and prEN 1504-4 (19). The standard test to determine them are in Table 23.

In the manufacturer’s sheets other properties can be found as tensile strength and cizallam strength.

It is also necessary to test durability, fatigue and creep.

The durability of the adhesive should be proved by laboratory tests or by experience (at least 15 years). (14)

Also the suitability of the adhesive for application to vertical surfaces, soffits and horizontal surfaces should be verified.
<table>
<thead>
<tr>
<th>Physical properties</th>
<th>Pot life (min) [1]</th>
<th>Open time (min) [2]</th>
<th>Shelf life (month)</th>
<th>Shrinkage (%)</th>
<th>Curing conditions (°C) (% rel. humidity) [3]</th>
<th>Glass transition temp Tg (°C) [4]</th>
<th>Coefficient of thermal expansion</th>
<th>Viscosity</th>
<th>Moisture absorption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adhesive</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Determining</td>
<td>pr EN 14022</td>
<td>pr EN 12189</td>
<td>-</td>
<td>pr EN 12617-1 or pr EN 12617–3</td>
<td>-</td>
<td>pr EN 12614</td>
<td>pr EN 1770</td>
<td>ISO 3219 (ISO 1993 a and EN ISO 3219, CEN 1995)</td>
<td>pr EN 13580 CEN 2.001e.</td>
</tr>
<tr>
<td>Recommended</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>values</td>
<td>&gt;40 (20°C) (14)</td>
<td>&gt;20 (20°C) (14)</td>
<td>&gt;6 (5-25°C) (14)</td>
<td>&lt;0.1% (14) (19)</td>
<td>&gt;5°C ≤80% (14)</td>
<td>≥ 45°C or the maximum shade air temperature in service +20°C, whichever is the higher (14) (19)</td>
<td>≤ 50x10⁻⁶ per °C (19)</td>
<td>Maximum water absorption after immersion shall not exceed 3 % by weight (14)</td>
<td></td>
</tr>
</tbody>
</table>

[1] Pot life: pot or workable life before application to prepared surfaces (workable life is dependent of the batch quantity and ambient conditions in use. Workable life will usually be less than the pot life)
[2] Open time: time after application of the adhesive within which the joint can be made
[3] Curing conditions must be specified by the manufacturer. $T_{\text{max}}$ specified in relation with pot life and viscosity
[4] $T_g$ is applicable to resins and it is the molecular structure disaggregate and loose its mechanical properties

Termoendurecibles resins (epoxy, polyurethane) irreversible lost. Usually for epoxy resin $T_g=60^\circ$C approximately
Termoplasticas resins (PVC, polyethylene) reversible lost.

Table 22.- Recommended values of physical properties of bonding agents according to fib bulletin No14 (14) and pr EN 1504-4 (19)
<table>
<thead>
<tr>
<th>Adhesive</th>
<th>Mechanical properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Modulus of elasticity in flexure (N/mm²)</td>
</tr>
<tr>
<td>Determining according to the Standard</td>
<td>ISO 178</td>
</tr>
<tr>
<td>Recommended values</td>
<td>2.000-15.000 (14) (19)</td>
</tr>
</tbody>
</table>

Table 23.- Recommended values of mechanical properties of bonding agents according to fib bulletin No14 (14) and pr EN 1504-4 (19)
<table>
<thead>
<tr>
<th>Adhesive</th>
<th>Durability (thermal and moisture)</th>
<th>Fatigue under dynamic loading during cure and in service</th>
<th>Creep under sustained loading in service</th>
<th>Suitability of application (vertical surfaces)</th>
<th>Suitability of application (horizontal surfaces)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Determining according to the Standard</td>
<td>pr EN 13733</td>
<td>pr EN 104-852-1</td>
<td>pr EN 13584-1</td>
<td>pr EN 1799</td>
<td>pr EN 1799</td>
</tr>
<tr>
<td>Recommended values</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>The material shall not sag flow by more than 1 mm when spread in thickness less than 3 mm. (19)</td>
<td>The surface area of the bonding agent at the end of the squeezability test shall not be less than 3000 mm² (60 mm diameter). (19)</td>
</tr>
</tbody>
</table>

Table 24.- Performance requirements according to pr EN 1504-4 (19)
3.2 Preparing works

Before carry out the strengthening some works should be done regarding to the concrete substrate and the preparation of the FRP materials.

3.2.1 Requirements of concrete substrate

The FRP reinforcement improves the structural capacity of a member but it doesn’t stop other problems as steel corrosion. For that reason the concrete should be sound and other possible damages must be eliminated before the application of the reinforcement.

The surface conditions of the substrate have a high influence on the durability and correct work of the FRP reinforcement. The following aspects should be considered to determine the surface quality of the substrate:

- Concrete tensile strength by means of pull-off testing (according to EN 1542 (CEN 1999c)). Table 25 states the minimum acceptable values for the concrete tensile strength.

<table>
<thead>
<tr>
<th>TENSILE CONCRETE STRENGTH</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 1.5 MPa (15 kg/cm²) for “prefab”</td>
<td>(21) (7) (14)</td>
</tr>
<tr>
<td>&lt; 1.0 MPa (10 kg/cm²) for “cured in situ”</td>
<td>(23) (7)</td>
</tr>
</tbody>
</table>

Table 25.- Minimum values for the concrete tensile strength

- Unevenness of the concrete surface that can be allowed depends on the type of FRP externally bonded reinforcement. Table 26 presents the allowable values for the unevenness of concrete surface.

<table>
<thead>
<tr>
<th>TYPE OF FRP SYSTEM</th>
<th>Permissible unevenness on a 2.0 m base (mm)</th>
<th>Permissible unevenness on a 0.3 m base (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>“prefab” thickness &gt; 1 mm</td>
<td>10 (14)</td>
<td>4 (14)</td>
</tr>
<tr>
<td>“prefab” thickness &lt; 1 mm</td>
<td>6 (14)</td>
<td>2 (14)</td>
</tr>
<tr>
<td>“cured in situ”</td>
<td>4 (14)</td>
<td>2 (14)</td>
</tr>
</tbody>
</table>

Table 26.- Allowable values of unevenness of the concrete surface

- Any porous area shall be repaired and any hole filled. The superficial porosity should fulfil that the affected extension should be less than the 10% of the total surface with a porous surface under 3 cm² and a porous depth less than 5 mm. (21)

- The corners of the unstrengthened members should be round before the application of the FRP reinforcement to avoid local damage in composite
materials. It is recommended to round corners with a minimum radius of 10 - 15 mm. Anyhow the specification given by the supplier according to this topic should be followed. (23) (14)

- Degrees of roughness recommended for the substrate are from a concrete surface profile (CSP) 4 to CSP 6* according to the International Concrete Repair Institute (ICRI) (7).

- In general concrete surface must be in good conditions, free of oil, dust, and vegetation. Some aspects should be controlled such as carbonation depth, chloride content ($\leq 0.3\%$ by weight) and surface moisture ($< 4\%$). Moreover any cracks or joints wider than 0.2 mm should be injected. (14) (21)

### 3.2.2 Preparation of concrete substrate

It is important that the preparation of the concrete substrate is carried out well to provide an adequate bond with the adhesives. All the above restrictions should be fulfilled.

The preparation of the concrete substrate consists on concrete removal and cleaning. This chapter only exposes some notes related to these systems and FRP reinforcement.

**Concrete removal:** (7) (21) (23)

The concrete should be sound to eliminate serious imperfections and potential damage mechanisms, also the substrate should be free of contamination. After the concrete removal the substrate should obtain the suitable conditions of cohesion and roughness to guarantee the adequate adherence of the bonding agent.

Manual or mechanical techniques as pneumatic chipping hammer, high-pressure blasting (sand, water) can be applied.

**Cleaning:** (21) (23)

The objective is to get a perfectly clean surface before the application of the FRP materials.

There are different systems as in concrete removal that can be used, for example high pressure blasting (sand, grit, water jet blasting), vacuum cleaning or grinding can be also applied.

Regarding to the selection of the most suitable system it is decisive the type of FRP that is going to be applied. Most of the wet lay-up systems require a smoother surface (see Table 26) so in this case grinding may be the most appropriate method. Another

---

* CSP/Concrete Surface Profile (www.generalpolymers.com) . ICRI has identified nine distinct profile configurations that replicate degrees of roughness considered to be suitable for the application of sealers, coatings, or polymer toppings. The recommended method for achieving each profile is as follows: CSP 1 (Acid Etching), CSP 2 (Grinding), CSP 3 (Light Shotblast), CSP 4 (Light Scarification), CSP 5 (Medium Shotblast), CSP 6 (Medium Scarification), CSP 7 (Heavy Abrasive Blast), CSP 8 (Scabbling), CSP 9 (Heavy Scarification, Milling)
alternative could be the application of a putty to decrease the level of unevenness in the surface after roughening by means of blasting for example. (14)

When the chosen cleaning and concrete removal systems involve the use of water, for example, water jet blasting or others wet techniques, it is necessary to take into account that the concrete should be dry enough for the later application of the FRP. (11) (14)

During the concrete removal or cleaning activities internal steel reinforcement could became visible, in these zones a patch repair will be necessary. The steel will be cleaned by means of sand blasting or similar system and to eliminate the sand and dust products of the cleaning air jet blasting will be used. After, the reinforcements should be coated with a primer against corrosion and finally the section will be restored.

3.2.3 Preparation of Fibre Reinforced Polymer

Although it is possible that the FRP materials will be supplied to site at the specified width and cut to the necessary length as specified on the design drawings, due to flexibility of the laminates it is recommended to transport them in a roller piece of 250 m maximum in length and cut it in field. The cut should be carried out by means of a manual saw. (14) (21).

The laminates and sheets should be free from any contamination like oil, dust, etc. If laminates or sheets are provided with an in-built peel ply, to ensure a clean surface, the ply should be removed immediately before application and the surface must not be touched by hand. In other cases laminates usually require cleaning before use to obtain a satisfactory surface to bond. This should be performed as specified by the manufacturer. (14)
The FRP materials have to be verified for absence of possible damage resulting from transportation, handling or incorrect cutting. The laminates and sheets shall be free from unintended curves, bows, wraps, ondulations, twists or fibre misalignments. (14)

Along the preparation process the FRP materials should be handled with clean gloves and under dry conditions. (11)

3.3 Execution

In this section the instalation procedure for “prefab” and “wet lay up” systems is presented in an squematically way.

3.3.1 “Prefab” or “pre-cured” strips or laminates

I. Primer (optional)

Application of a primer is normally not necessary. However, if it is specified by the manufacturer of the adhesive a primer shall be used according to its specifications. (14)

The primer is usually a transparent and low viscosity epoxy, which is applied with a short-hair roller. It penetrates into concrete helping the bonding of the FRP and also limiting the absorption of the adhesive epoxy by the concrete. (7)

II. Adhesive application to the concrete

The adhesive is applied as a thin layer with a trowel or a brush to the concrete (see Photograph 2) immediately after mixing according to the manufacturer’s specifications (mixing life, thickness, etc).
III. Adhesive application to the laminates

The adhesive is applied as a thin layer to the roughest face of the laminates, as in the step II, it takes place immediately after mixing according to the supplier’s specifications (mixing life, thickness, etc).

![Adhesive application to the laminate](image1)

It is recommended to have slightly more thickness along the centre line of the plate. This will reduce the risk of forming voids when the strip is applied. (14)

A specific device (see Photograph 3) can help to apply the adhesive to the laminate surface.

IV. Positioning of the laminate

![Previous positioning of the laminated](image2)
The positioning starts with a preliminary positioning of the laminate without applying pressure until checking its correct place (see Photograph 4). After correct place is obtained pressure is applied by means of a rubber roller to ensure intimate contact with the concrete. The pressure is applied going from the centre not allowing the formation of voids. (7) (14)

The extra adhesive should be squeezed out along the sides.

V. Verification of the bond line

The final bond line should be of equal thickness along the strip and should correspond to a minimum adhesive thickness of 1.5 to 2.0 mm and maximum following specifications of the manufacturer. (14)

Alternatively, instead of applying the adhesive to both the concrete and the strip, adequate results have been reported when applying the adhesive only to one surface. (14)

For multiple layers repeat points from I to V. Besides more than 3 layers of pultruded strips are not recommended to apply unless proved by experimental. In any case, recommendations of the supplier must be followed. (14)

3.3.2 Multifibre laminates (applying anchors)

Multifibre laminates can be anchored with bolts through the laminate. This system presents the following advantages:

- The brittle failure, which can occur in a traditional system which is only glued, will not occur.
- Bolts will prevent delamination in the weak zone beneath the tension bars.
- In case of fire the bolts, which only have to be protected in the anchorage zone, will also prevent the structure from collapsing after disappearance of the epoxy glue and matrix.

The installation of this type of multifibre laminates is realised according to the above procedure, but after removing the redundant adhesive (point IV) holes are drilled through the laminate (with an electric drill) according to the design and bolts (for anchoring) are inserted. (24)

3.3.3 “Wet lay-up” type (sheets or fabrics)

I. Primer (optional)

See point I of subsection 3.3.1.

II. Putty application (optional)
Putty application with epoxy material (compatible with the resin adhesive) can be applied in order to obtain a regular and smooth concrete surface that guarantee a good bonding according to the manufacturer’s specifications (Almost no unevenness of the concrete surface is allowed for applying sheets). (14) (7)

III. Adhesive application to the concrete (or putty).

This step is called undercoating and it is similar to the step II of subsection 3.3.1. (14).

IV. Sheet application

Sheets should be applied in the correct direction and straight pulling of over the layer of adhesive before removing the protection paper sheet. The sheets soak up in the adhesive. (23)

Once the sheets are applied, adhesive has to be distributed with a roller until a homogeneous surface is obtained without voids.

V. Adhesive application (overcoating) (14)

Overcoating consists on the application of a second layer of adhesive with a roller. (7) (23)

For multiple layers repeat points from III to V. Besides more than 5 layers of cured in-situ fabrics are not recommended to apply unless proved by experimental (exception: confinement applications). Unless other wise specified, this may be done before the previous layer has cured. In any case, recommendations of the supplier must be followed. (14) (7)

Alternative to the above procedure and to increase the level of quality assurance, the sheet can be impregnated with the resin in a saturator machine. This enables saturating the sheet at a better-controlled resin rate and with a more uniform thickness. (14)

### 3.4 Finishing

In some cases the election of the adequate finishing layers can be crucial to the long-term integrity of the strengthened structure.

The compatibility between the externally bonded reinforcement and the finishing layer should be proved. If finishing layers or toppings involve heating, this must not damage the bond integrity. (14)

**Aesthetic purposes**

When the finishing only has an aesthetic purpose, paints can be used.
Mechanical or chemical protection

To protect the structure from mechanical or chemical hazards, the most adequate finishing are binder layer, mortar or plaster and painting. (7)

Protection against fire

One of the main risks of the FRP reinforcement is the fire. If no special protection is taken it must be considered in the design (accidental situation). When fire protection is provided, the fire resistance should be evaluated using a more refined calculation method (temperature distribution in the element, mechanical analysis with temperature-dependent material properties). The design of the protection will be based on a limitation for the temperature rise in the adhesive layer (weakest element of the cross-section) during a certain time period.

Different types of finishing layers can be provided such as:

- Special fireproofing mortars. (7)
- Fireproofing sheets (21) (23)
- Flameproof painting, previously checking adherence and compatibility with FRP (21) (23)
- Fireproofing sprayed fibres. (Ex: Fireproofing covering spray applied based on cement mortar with mineral wool. Aluminium-silicate fibres)

Protection against ultra violet radiation

In order to avoid the possible surface changes in composites due to sunlight, painting is needed.

UV protection can be afforded by the use of either an acrylic based paint or a polyurethane based paint. Paint should be applied within 72 hours and while the resin is still “tacky” to the touch. If the resin is too cured the light blasting or abrading of the surface before painting should be carried out. A light coloured paint (white or concrete grey) will reflect much of the heat from sunlight. (14)
4 QUALITY CONTROL

4.1 Quality control on the supplied materials

The materials involved in the FRP strengthening (adhesive and FRP) must have past the production quality control, and its properties should have been determined according to standard tests. If there is no certification of the products from an independent centre (different from the manufacture one) tests must be carry out. The number of test will depend on the importance of the work.

The main properties of these materials and some of the standard tests methods that can be followed to determine them have been described in this document (see subsection 3.1.1 for FRP material and 3.1.2 for the bonding agent).

Products shall be provided with general information: data concerning the material properties according to standard test methods; information concerning handling, transportation and storage; and safety data. The identification of each material is specially important when more than one type is being used. Before application, it is necessary to check that FRP materials does not present significant faults and have not suffered any damage during transportation and storage. During handling process damages should be also avoided.

In the case of FRP laminates which are manufactured in a pultrusion process and usually supplied in rolls it is also recommended to realize a dimensional control. Although pultrusion is a controlled manufacture process curved plates and misalignment of the fibres can occur. Furthermore rolled plates may not form a flat section when they are unrolled if they were rolled before the material had fully cured. The application of plates without paying attention to these phenomena can involve premature failure and delamination before full curing of the adhesive.

The tolerances recommended by Concrete Society Technical Report 57 (12) for FRP laminates are presented in table 27.

<table>
<thead>
<tr>
<th>PLATE LENGTH (m)</th>
<th>Straightness of edge (mm) [1]</th>
<th>Width (mm)</th>
<th>Flatness (mm)[2]</th>
<th>Squareness (mm)[3]</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 2</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>0.1</td>
</tr>
<tr>
<td>2-4</td>
<td>4</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>0.1</td>
</tr>
<tr>
<td>4-6</td>
<td>6</td>
<td>1</td>
<td>3</td>
<td>6</td>
<td>0.1</td>
</tr>
<tr>
<td>&gt;6</td>
<td>7</td>
<td>1</td>
<td>3</td>
<td>7</td>
<td>0.1</td>
</tr>
</tbody>
</table>

[1] Deviation from the intended line along the edge of the plate. There should be no sudden steps and any deviation should be uniformly spread along the length.
[2] Deviation under a metre straight-edge laid flat along the length of the plate.
[3] Measurement along the longer side of the plate. Measure the deviation from 90° with the shorter side taken as the base.

Table 27.- Dimensional tolerances in pultruded FRP plates according to Concrete Society Technical Report 57 (12).
Before application fib bulletin 14 (14) recommend to perform an applicability test to verified the application of the adhesive under controlled conditions. This test consist on strengthening a witness slab under specified conditions, after execution the FRP strengthening will be inspected to check for evidence of voids and unevenness, also the thickness of the bond line should be verified and other types of bond testing could be carry out.

In cases where more than one layer is going to be applied or joints are going to be required because FRP is not presented in a continuous length a joint test according to EN 1465 (CEN 1995) is recommended before execution (12).

4.2 Quality control during execution

During application it is necessary to check the suitability of surfaces to be bonded. The concrete surface should be prepared in accordance with the specifications given in the subsection 3.2.1 “Requirements of concrete substrate” otherwise according to the manufacturer’s guidelines. Moreover during the strengthening execution the concrete surface must not present free moisture.

Furthermore it is necessary to register and control the environmental conditions, recommended values for these parameters are presented in table 28.

<table>
<thead>
<tr>
<th>ENVIRONMENTAL CONDITIONS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature on the concrete surface</td>
<td>&gt;10ºC</td>
</tr>
<tr>
<td>Temperature above the actual dew point</td>
<td>&gt;5ºC</td>
</tr>
<tr>
<td>Atmospheric humidity</td>
<td>&lt;80%</td>
</tr>
</tbody>
</table>

Table 28.- Recommended values for the environmental conditions.

FRP material must be prepared according to the manufacturer’s data sheet in order to ensure a proper bond. Cutting of the FRP material to the appropriate length is usually done at construction site and it must also be performed according to the specifications of the supplier.

Regarding to the adhesive it has also to be ensure the proper adhesive mixture. It is essential to control that the different components are in the adequate ratio, mixing have been done until a homogeneous colour is obtained with a mixing speed that avoid the development of air bubbles and the application has been completed before the end of the open time. (12) (14)

If the strengthening require plate crosses a special following of the crosses execution should be carried out. The pressure applied to the outer laminate should be controlled, if excessive pressure is applied voids may be formed because of the tendency of the outer laminate to separate.
After application it should be controlled the thickness of the bond line (see section 3.3 “Execution”) and verified that FRP reinforcement is in the given direction and with proper amounts of fibres. FRP should be essentially straight according to Concrete Society Technical Report 55 (12) misalignments of more than 10 mm from the true location and other imperfections should be reported. Moreover, a concave surface may result in FRP peeling so the permissible unevenness of the surface according to fib bulletin 14 (14) are given in table 29.

<table>
<thead>
<tr>
<th>TYPE OF FRP SYSTEM</th>
<th>Permissible unevenness on a 0.3 m base (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prefab systems</td>
<td>4</td>
</tr>
<tr>
<td>Cured in situ systems</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 29.- Permissible unevenness according to fib bulletin 14 (14).

During execution test on representative samples to control the bonding procedure are applicable. This samples can be performed in the structure without damage the FRP strengthening or in independently coupons. Anyway the samples should be representative of the used materials and the application procedure of the strengthening so the result of the tests may be applicable to the strengthening system. This type of control could be also used before strengthening to select an adhesive or a work procedure.

During strengthening phase is recommended to check the strength of the adhesive to compare with the bond agent strength taken into account in the design. It is specially important in bridges strengthening when the retrofitting is carried out with no disruption to traffic because, it has been experimentally proof that vibration during adhesive curing may reduce its strength (12).

4.3 Quality control after execution

The bond interface is the weakest part of the strengthening so its control is one of the most important verifications.

The FRP should be inspected after installation to check for evidence of debonding or imperfection specially in critical areas as anchorage zones or plates crosses. Small voids, around 2mm diameter, occur naturally in the mixed resin and do not require repair (12). Table 30 present a suggestion of the permissible voids.

This check could be omitted only when the stress transmitted between the FRP and the concrete can be depreciated.
To verify that there are no large voids in the adhesive one of the following techniques can be used:

- **Tapping** (simple method which is based on the difference in sound between well bonded and unbonded areas).
- **Ultrasonic pulsed echo techniques**
- **Ultrasonic transparency techniques**
- **Thermography**

Tapping is the most extended technique although the obtained results depend on the operator’s skill.

<table>
<thead>
<tr>
<th>Voids/debonding areas</th>
<th>Size</th>
<th>Aspect ratio</th>
<th>Number of debond of 1000mm² in 1m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plates</td>
<td>≤ 5% of the width (12)</td>
<td>≤ 2 (length/width) (12)</td>
<td>-</td>
</tr>
<tr>
<td>Wet lay-up systems</td>
<td>≤ 1000mm² (12) or 1300 mm² (3) (except at edges)</td>
<td>≤ 5% of the total laminate area (3)</td>
<td>-</td>
</tr>
</tbody>
</table>

*Table 30.- Suggestion for acceptable voids in the adhesive according to Concrete Society Technical Report 57 (12) and ACI 440.2R-02 (3).*

At not critical areas of the reinforcement other type of test can be used:

- Surface adherence pull off test (EN 1542 (CEN 1999c)).
- Surface adherence shear test
- Surface adherence torque test

These tests involve a damage in the strengthening so they should not be applied in critical areas. An alternative is to bond to the structure additional FRP without a strengthening purpose this areas will be tested in order to evaluate the durability and the bond work. It is important testing areas will be executed in the same conditions as the rest of the retrofitting.

Regarding to the load level in the structure during installation, some references has been found in the bibliography. It is recommended to wait 7 days for loading the structural member to its maximum charge. This is the necessary time for the adhesive to hardening although during this period inferior charges can be supported if the limit strength of the adhesive is not exceed (7).
4.4 Future maintenance.

There will be a need to check the FRP strengthening system as part of the maintenance of structure. A inspection guidance should be prepared with the most important areas of inspection.

<table>
<thead>
<tr>
<th>Areas for inspection</th>
<th>Anchorage zones</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cracked areas</td>
<td></td>
</tr>
<tr>
<td>Where the adhesive thickness change</td>
<td>More than one layer of FRP has been applied</td>
</tr>
<tr>
<td></td>
<td>Crosses</td>
</tr>
</tbody>
</table>

Table 31. Important areas of inspection.

In a visual inspection only superficial damage such as cracking, delamination or impacts can be detected. For a detailed inspection all the techniques used in quality control after execution can be applied such as tapping, ultrasonic techniques or thermography.

In the same way as in quality control during and after execution destructive tests can be performed in the strengthening with this purpose. These test involve a damage in the strengthening than only may be avoided if additional FRP material has been bonded to the structure apart from the region to be strengthened. When importance of the work is large additional samples may be considered in the strengthening phase for testing during maintenance time according to the maintenance guidance.

<table>
<thead>
<tr>
<th>TEST</th>
<th>PORPOUSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pull-of tests</td>
<td>In order to guarantee that the failure mode is in the concrete</td>
</tr>
<tr>
<td>FRP tensile test</td>
<td>To check that FRP properties has not change</td>
</tr>
</tbody>
</table>

Table 32. Test recommended according to Concrete Society Technical Report 57 (12).

Instrumentation can also be installed as part of the process if it used in conjunction with a load test, vibration test or long term monitoring. The different types of instrumentation that can be used are strain or optical gauges and transducers.

Figure 11.- Strain gauge
The measured parameters (strain, deflection) can be used to indicate changes in the structural response. This variations can involve changes in the performance of the strengthening if a general instrumentation of the structure have been performed or to indicate changes in the behaviour of the FRP strengthening directly if the instrumentation is placed in the FRP reinforcement.

Instrumentation is usually recommended for structures with inaccessible zones or when the strengthening system used is new.
5 REFERENCES

(1) ACI 318-99. Building code requirements for structural concrete and commentary.


(5) BD 85/02 draft. Strengthening of highway bridges using externally bonded fibre reinforced polymer.

(6) BETEC. Integrated system for structural strengthening. Product data sheet

(7) BETTOR MBT Master Builders Technologies. Design guidance Mbrace. Structural Strengthening system


(9) Björn Täljsten. FRP Strengthening of Existing Concrete Structures Design Guidelines, Lulea University of Technology, 2002


(13) Eurocode 2


(19) **pr EN 1504-4:2000**


(22) **SIKA.** Structural strengthening with Prestressed Sika CarboDur CFRP Plate Systems. Product data sheet


(24) **TRADECC n.v.** PC Carbomomp systems for repair and strengthening of structures in concrete, steel and wood. Product data sheet.