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Industry CPD

Design approach for structural strengthening of reinforced concrete structures using fibre-reinforced polymers (FRP)

This CPD module, sponsored by MAPEI, introduces the use of FRP for the structural strengthening of reinforced concrete structures. It provides an overview of the composite materials and the design approach for flexural, shear and axial strengthening.

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Introduction

The use of FRP has numerous applications for the rehabilitation of reinforced concrete (RC), masonry, timber and metallic structures, including, but not limited to, increasing the shear and flexural capacity of masonry walls, reinforcing masonry vaults or arches, confining masonry columns, and upgrading in bending timber, steel and cast-iron beams.

With regard to RC structures, FRP can be used for flexural strengthening of beams and columns, to sustain the redistribution of bending moments over a slab after the formation of new openings, shear strengthening of beams and columns, and finally to provide confinement to columns and column–beam joints. It is for these reasons that the use of FRP for structural strengthening has proved an invaluable alternative to traditional strengthening solutions.

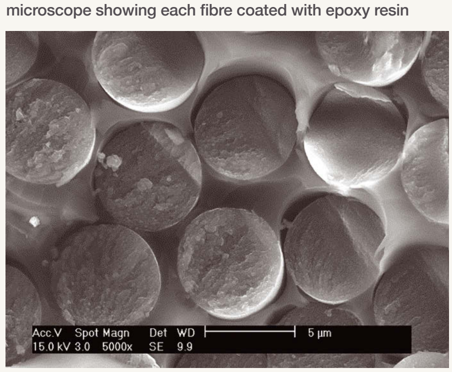
What are FRP?

Fibre-reinforced polymers, commonly known as FRP, are composite materials made up by the combination of fibres with an organic polymer matrix (**Figure 1**). The fibres, perfectly aligned in specific directions, constitute the reinforcement due to their high strength, stiffness and lightweight features. The matrix is the binder that holds the fibres together and distributes stress over the composite section.

While the matrix is usually an epoxy resin, the most common fibres used in civil and structural applications are carbon, glass, basalt and aramid.

The most effective fibre in terms of stiffness is carbon, which has a wide range of E-modulus, from 230GPa to values greater than 600GPa. At a lower grade, with E-modulus around 70 to 100GPa, there are other types of fibres like glass, basalt and finally aramid, which, due to its high cut resistance, can be particularly useful when attempting to reinforce a structural member against blast or high-speed impact damage.

FIGURE 1: Section of pultruded carbon fibre plate at microscope showing each fibre coated with epoxy resin



The constitutive model of a composite material depends on the mechanical properties of its components and their volumetric fractions[1].

From an engineering perspective, FRP deform elastically up to failure, and are effective only in tension, though their contribution to compression is negligible due to micro-buckling of the fibres. Another important mechanical aspect is their strong anisotropy, which implies that they respond better when stretched along the direction of the fibres.

Benefits

FRP represent an evolution of traditional strengthening techniques, thanks to the numerous benefits that are accompanied with their use. These can be summarised as:

- rehabilitation of structures without adding unwanted mass or stiffness
- limited loss of head height or floor space – meaning low visual impact and conservation of the appearance and geometry of structure
- speed of installation due to weight of materials – no need for equipment for lifting and supporting the application
- reversibility of the strengthening work (easy to remove or repair)
- cost-effectiveness – due to a quick and easy installation process.

Limitations

Limitations to the use of FRP in structural strengthening applications are mainly centralised around the risk of a loss of reinforcement in case of fire and under service conditions.

If during a fire the FRP reinforcement has to work compositely with the structural member to resist the accidental action, then the structural member must be protected with an adequate fireproof system. In certain situations, the existing structure is able to resist the fire actions and the scenario of loss of

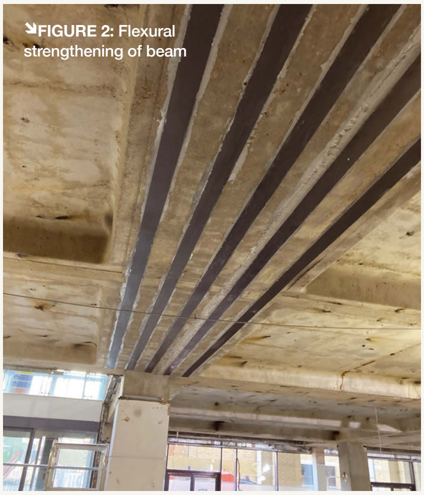


FIGURE 2: Flexural strengthening of beam

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FRP reinforcement is acceptable and the use of FRP is considered feasible. It should be noted that the structures could still need to be fireproofed in order to protect the steel reinforcement and not to avoid the loss of FRP.

Adopting a similar approach, the serviceability limit state (SLS) actions are compared with the capacity of the un-strengthened member, in order to prevent a potential loss of FRP from turning a service condition into an ultimate limit state (ULS) for the structural member.

FRP can also be compromised when there's an incorrect steel reinforcement layout, insufficient overlap length or anchorage between rebars and poor concrete substrate.

Flexural strengthening

A typical deflection curve for an RC beam that has been strengthened using FRP **(Figure 2)** in bending is shown in **Figure 3**.

At the time of strengthening – Point 0 – the existing beam is already deflected under the service loads, and for the correct evaluation of the state of stress of the FRP, it is essential to assess the magnitude of the strain of the concrete substrate in tension.

Once FRP is installed, the beam bends elastically with a slightly increased flexural stiffness and only after the yielding point – Point YS – the tension stiffening effect of the FRP produces an appreciable hardening post-elastic behaviour.

The failure of a strengthened beam can be initiated prematurely due to the loss of adhesion between FRP and concrete – Point DB – or in certain situations, when debonding does not occur, the beam reaches its ULS – Point UF – crushing the concrete in compression or breaking the FRP in tension.

A debonding check is an integral step of the design process, and is carried out with the purpose of mitigating all the causes that can initiate a separation failure, such as irregularities of the substrate, formation of significant cracks, high shear stresses at the level of the adhesive layer and a lack of length of anchorage at the end of the plate.

A flexural strengthening system is considered adequate when the resistance in bending is greater than the design moment at the ULS and also fulfils

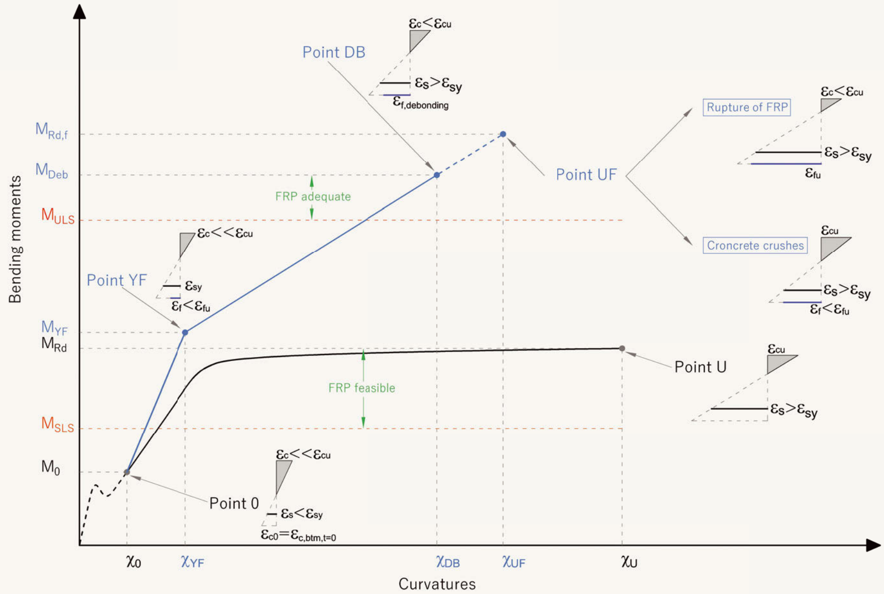

FIGURE 3: Deflection curve for FRP reinforced RC beam

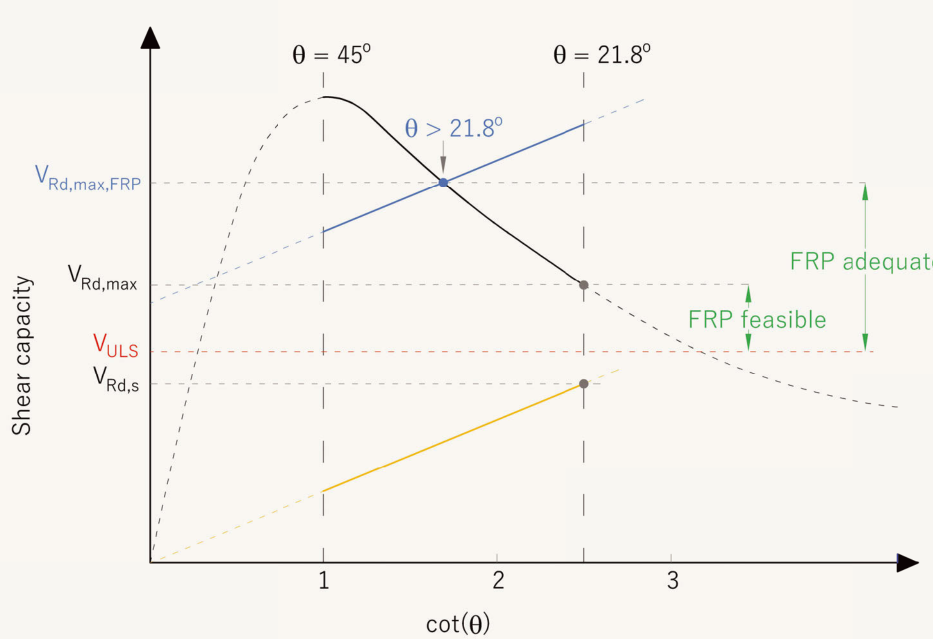

FIGURE 4: Steepening of inclination angle of concrete struts is beneficial effect of using FRP as shear reinforcement[3]

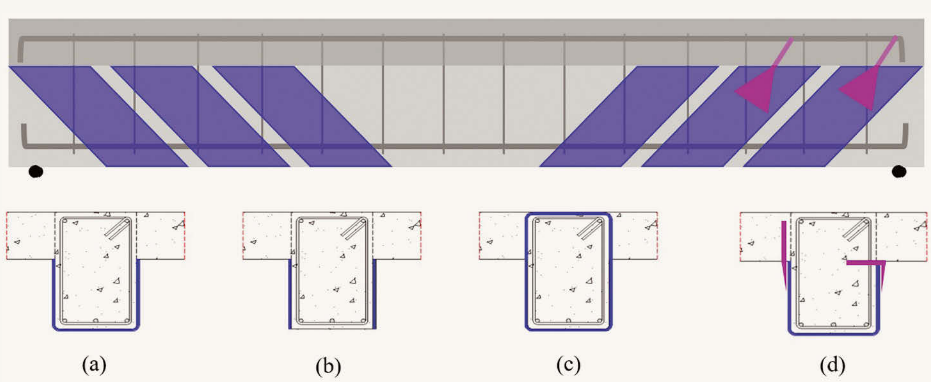

FIGURE 5: Different FRP configurations for shear strengthening: a) U-wrap; b) side only; c) fully wrapped; d) U-wrap anchored


FIGURE 6: Shear strengthening with anchored CFRP U-wrap strips

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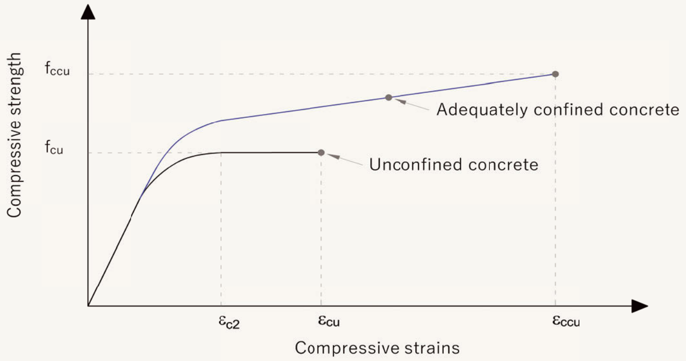

FIGURE 7: Effect of confinement


FIGURE 8: Axial strengthening of column

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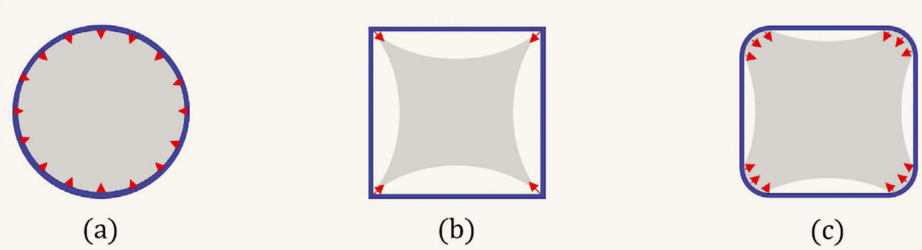

FIGURE 9: Effective confined concrete for different shapes of column: a) circular column; b) square column with sharp corners; c) square column with rounded corners

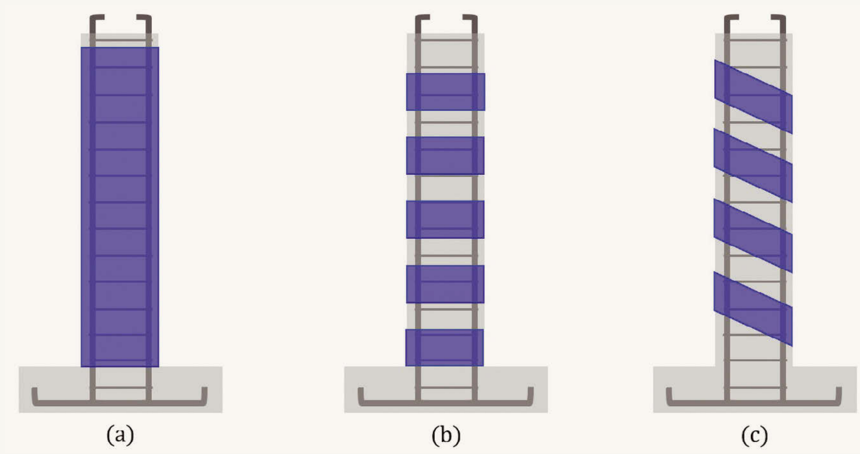

FIGURE 10: Different configurations of FRP for confinement: a) continuous; b) discontinuous; c) twisted

the ductility requirements.

It's worth noting that – in general – the ductility of a flexural member decreases when reinforced using FRP, and large strains of the tensile rebars cannot always be endured. In this instance, the design could still be considered adequate if a minimum safety factor is achieved[2].

Shear strengthening

The traditional shear design method for reinforced concrete, referred to as the 'Mörsh's truss model', can be used to design shear strengthening solutions using composites, and superimposing the FRP contribution to the resistance of the steel ties[3] **(Figure 4)**.

The main aspects that can influence the performance of shear strengthening systems are the angle of inclination of the fibres and the FRP configuration.

FRP layouts with the fibres placed parallel to the direction of the principle tensile stress – responsible for the formation of the shear crack – are expected to perform better than layouts with the fibres placed

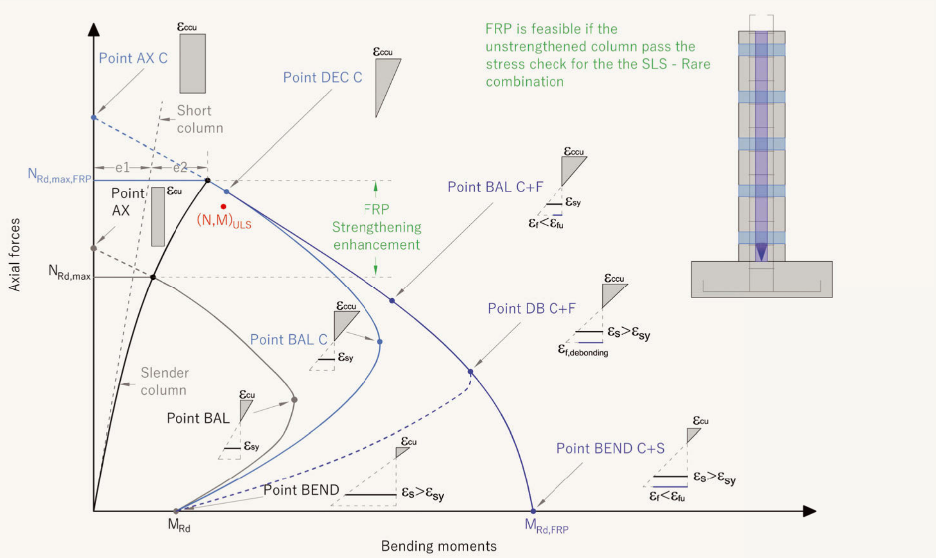

FIGURE 11: M-N interaction diagram for column reinforced using FRP[3]

perpendicular to the longitudinal axis of the beam.

In terms of configurations **(Figure 5)**, the best results are achieved when the FRP system can be considered fully anchored **(Figure 6)**, while less effective performance can be expected in cases where FRP is susceptible to debonding.

Axial strengthening

The axial capacity and the ductility of RC columns can be increased only by an adequate confinement, which will provoke the existing concrete to develop a hardening plastic behaviour, which will in turn sustain higher stresses and greater strains in compression **(Figure 7)**.

Confinement is obtained by wrapping the column with a composite material **(Figure 8)**, and the confining action is a consequence of the restrained lateral expansion induced by the axial loads.

The performance of an axial strengthening system using FRP is dependent on the stiffness of the composite, the longitudinal layout, the orientation of the fibre and the shape of the cross-section **(Figure 9)**. All these parameters can be summarised by an efficiency factor, defined as the ratio between the volume of the concrete effectively confined and the volume of the concrete element[1].

The best results in terms of confinement are achieved in circular columns where the confining pressure – uniformly distributed along the entire circumference – effectively confines the entire area of the cross-section.

For square columns, the concentration of confining pressures at the location of the sharp corners reduces the area of cross-section effectively confined, and can subsequently cause a premature rupture of the FRP. To increase the efficiency factor for these shapes, it is essential to round off the sharp corners, although the performance is unlikely to exhibit results achieved with circular columns. Additionally, it can prove even more difficult to confine rectangular columns, due to their elongated shape.

Longitudinally speaking, the best FRP configuration to maximise the volume of confined concrete is the continuous wrap **(Figure 10)**. Lower resistances are expected for the discontinuous wrap configurations, and for the twisted wrap, which also lacks efficiency due to the anisotropy of the composite.

The M-N interaction diagram for the FRP strengthened column is determined following the same approach used for a normal RC column **(Figure 11)**.

Confinement produces an enlargement of the upper part of the M-N interaction diagram, while the effects are negligible in the case of pure bending – Point 4 – as the compressive zone shrinks laterally, relaxing the FRP up to a point of extinguishing any beneficial effect of confinement.

Columns, in addition to the axial strengthening, can also be reinforced in bending by applying a longitudinal FRP reinforcement prior to wrapping the column for confinement. Considering the negligible contribution of the FRP in compression, the new M-N interaction diagram deviates from the one with only confinement after the configuration of strains corresponding to the decompression of the concrete section – Point DEC.

In certain situations, the longitudinal FRP can fail prematurely due to debonding at a certain point along the M-N interaction curve – Point DB – with a consequent return to the resistance of the unconfined column.

It must be stressed that the flexural capacity can be easily increased along the span of the column, and not at the connection with beams or foundations, where the FRP would need to be adequately anchored.

Conclusion

The use of FRP to strengthen reinforced concrete is by no means a new concept. In fact, FRP have been used in the UK for over 35 years. However, this article sets out the basic design principles necessary in order to consider an approach to projects using FRP, as well as providing insight into the various techniques that should be considered when planning and carrying out projects of differing natures. Through identifying advantages of the different methods and systems – from both a design point of view and the added benefits they offer to the client – engineers can consider FRP as an alternative and effective approach for any future projects where strengthening reinforced concrete is required.

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3) The Concrete Society (2012) *Design guidance for strengthening concrete structures using fibre composite material* (Technical Report 55; 3rd ed.), Camberley: The Concrete Society

Questions

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1) Which of the following statements about FRP is true?
- ☐ It is generally stiffer than steel
- ☐ Its strength is greatest orthogonally in the direction of the fibres
- ☐ It is susceptible to fire only at extremely high temperatures
- ☐ It has a high strength-to-weight ratio

2) Which of the following statements about FRP strengthening for concrete structures is true?
- ☐ It replaces primary steel reinforcement
- ☐ It always increases the ductility of the strengthened member
- ☐ It avoids corrosion of the steel
- ☐ Its low weight makes the installation work much easier

3) What is the benefit of using FRP for flexural strengthening of a concrete beam?
- ☐ It reduces deflection that has already occurred
- ☐ It works as additional steel reinforcement
- ☐ It has a tension stiffening effect when the steel is yielded
- ☐ It has high plastic deformations

4) Which of the following statements about FRP for shear strengthening is true?
- ☐ It improves the inclination angle of the concrete struts
- ☐ It can replace the existing shear links
- ☐ It increases the shear capacity of the steel links
- ☐ The steel links must not yield

5) What is the benefit of confinement?
- ☐ It reduces the slenderness of the column
- ☐ It increases the concrete grade
- ☐ It avoids crushing of the concrete
- ☐ It changes the constitutive model of the concrete

6) Which of the following statements about FRP for axial strengthening is true?
- ☐ Axial strengthening is due to the longitudinal FRP in compression, wrapped to avoid debonding
- ☐ Higher strains and stresses are beneficial for pure bending
- ☐ It enlarges the brittle portion of the M-N interaction diagram
- ☐ To increase lateral expansion, it is better to add loads before confining the column

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