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Advanced polymeric composites and strengthening concrete structural members

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Summary

The use of fiber reinforced polymer (FRP) composites for structural strengthnening of reinforced concrete (RC) load-bearing elements has become a common practice in the last decades. However, the efficient of these new materials and systems must be preceeded by a carefull evaluation of their potential and constrains. The paper presents the main strengthening solutions of the RC elements made of concrete and their critical evaluation based on the existing experience in the area of structural rehabilitation.

KEYWORDS: seismic retrofit, wet lay-up, epoxy resins, glass and carbon fibres

1. INTRODUCTION

Over the last three decades structural strengthening of concrete structures has become an important issue due to ageing of infrastructure and the need for upgrading to fulfill more stringent design requirements. Also the seismic retrofit has become more important mainly in seismic active areas.

The use of fibre reinforced polymer (FRP) composites in strengthening solutions has become a viable alternative to some of the existing traditional methods due to some advantages such their features in terms of strength, lightness, corrosion resistance and ease of application.

Such techniques are also most attractive for their fast execution and low labour costs. FRP composite products for structural strengthening are available in the form of prefabricated strips, precured shapes or uncured sheets applied through wet lay-up procedure.

Prefabricated plates are typically 0.5-1.5 mm thick and 50-200 mm wide, and they are made of unidirectional fibres (glass, carbon, aramid) in a thermosetting matrix (epoxy, polyester, vinylester). Uncured sheets typically have a nominal thickness of less than 1 mm, are made of fibres (unidirectional or bidirectional) preimpregnated or in situ impregnated with resins. Bonding is achieved with epoxy adhesives when prefabricated composite elements are utilized and with impregnating resins in the latter case. Composites were first applied as confining reinforcement of reinforced concrete (RC) columns [1], and as flexural strengthening materials for RC bridge girders [2].

Since the first applications the developments have been tremendous and the range of applications has expanded to timber, masonry and metallic materials. The number of applications involving FRP composites as strengthening materials for RC elements and structures has expanded from a few, about 15 years ago to more than ten thousand nowadays.

2. STRENGTHENING SOLUTIONS OF RC MEMBERS

2.1 Traditional methods

Strengthening solutions of RC members can range from repair of damaged members so that their original load-carrying capacity is restored, to adding elements to increase their strength. All solutions are project-specific to a certain application but some general approaches are commonly utilized. The most traditional techniques for strengthening the RC structures are as follows [3]:

- Increase the reinforced concrete cross-section
- Add prestressing to relieve the dead load
- Use plate bonding to enhance tensile reinforcement of the RC elements
- Add confining elements to improve behaviour of the concrete in the compression members
- Shear strengthening by installing external straps

2.2 FRP composite based solutions

Strengthening of old and/or deteriorated reinforced concrete (RC) members is often required due to the following causes [4,5]:

-*The inadequacy of longitudinal reinforcement* in beams and columns, leading to flexural failure. In such cases the bending capacity of concrete elements can be increased through the use of externally bonded FRP plates, strips or fabrics. Alternatively near-surface mounted strips or rods with the fibre direction parallel to the member axis can be utilized.

-*The inadequacy of transverse reinforcement*, which may have as effect brittle shear failure in structural members like columns, beams, shear walls and beam-column joints. The shear capacity of concrete members can be enhanced by providing externally bonded FRP with the fibres oriented in the transverse direction to the member axis direction, in the case of columns and beams, or in the direction of both the column and the beam direction in the case of beam-column joints.

-Poor detailing in the regions of flexural plastic hinges where the flexural cracking may be followed by cover concrete spalling, failure of transverse steel reinforcement, and buckling of longitudinal steel reinforcement or compressive crushing of concrete. This mode of failure is usually accompanied by large inelastic flexural deformation. By adding confinement in the form of FRP jackets with fibres placed along the column perimeter, the spalling of cover concrete is prevented and the buckling of the longitudinal steel bars is restrained. In this way more ductile responses can be developed and larger inelastic deformations can be sustained.

-Poor detailing in lap splices. This mode occurs in columns in which the longitudinal steel reinforcement is lap spliced in the maximum bending moment regions near the column ends. Debonding may occur once vertical cracks develop in the cover concrete and progresses with cover spalling. By increasing the lap confinement with fibres along the column perimeter the flexural strength degradation can be prevented or limited.

The use of FRP reinforcement cannot modify the stiffness characteristics of existing RC elements; hence the FRP strengthening technique is not applicable if the structural intervention is aiming at increasing stiffness rather than strength or ductility [5].

2.2.1 Flexural strengthening of beams

The need for methods of repair and strengthening of RC beams and girders has been imposed by: degradation due to corrosion of steel reinforcement, cracking of concrete due to excessive carbonation, freeze-thaw action, spalling of concrete cover, effects of alkali-silica reactions and changing in loading patterns [6]. In case of bridges the need for increasing their load carrying capacities requires the adoption of a cost-effective technology that will not distress the traffic significantly.

In buildings the materials deterioration and changing needs for building occupancy imposes, in many cases, the strengthening of existing beams. One of the conventional methods for external strengthening implies the addition of adhesive-bonded steel plates on the tension side of the RC beams. The use of epoxy-bonded steel plates is very frequent in Europe and the United States but it suffers from a number of disadvantages:

Steel plates are heavy and difficult to transport, handle and install; the length of individual steel plates is restricted to 8-10m to enable handling and even at these lengths it may be difficult to erect them due to pre-existing service facilities; durability and corrosion effects remain uncertain; contaminants on structural members prior to bonding; surface preparation including the priming systems; steel plate thickness at least 5 mm to prevent distortion during blasting operation; complex profiles are difficult to be shaped with steel plates; expensive false work is required to maintain steel plates in position during bonding.

Composites fabricated either through wet processes on-site or prefabricated in plates, Figure1, and then adhesively bonded to the concrete surface provide an efficient means of strengthening, that can be carried out with no or little disruption in use. The efficacy of the method depends mainly on the appropriate selection of the composite material and on the efficiency and integrity of the bond between the composite and the concrete surface.

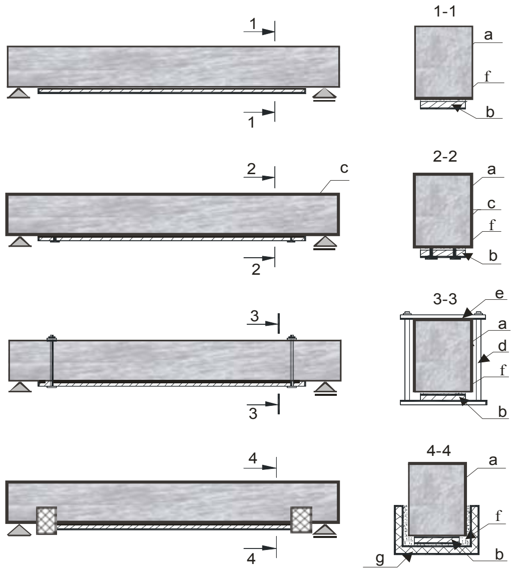

Figure 1. Strengthening of RC beams with FRP soffit plates. a- concrete; b-FRP plate; c-anchor bolts; d, e - elements of the metallic jig; f - adhesive layer

2.2.2 Shear strengthening of beams

When a RC beam is deficient in shear, or when its shear capacity is less than the flexural capacity after flexural strengthening, the shear strengthening of the respective beam has to be considered. It has been realized that the FRP bonded to the soffit of a RC beam does not modify significantly the shear behaviour from that of the unstrengthened beams [7,8].

Therefore, the influence of FRP strips bonded to the soffit for flexural strengthening may be ignored in predicting the shear strength of the beam. Various

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bonding schemes of FRP strips have been utilized to improve the shear capacity of reinforced concrete beams. The shear effect of FRP external reinforcement is maximized when the fibre direction coincides to that of maximum principal tensile stress.

For the most common case of structural members subjected to transverse loads the maximum principal stress trajectories in the shear-critical zones form an angle with the member axis which may be taken about 45^{o}. However, sometimes it is more practical to attach the external FRP reinforcement with the principal fibre direction, perpendicular to the axis direction, Figure 2, [9].

Because FRPs are strong in the direction of fibres only their orientation is recommended to control the shear cracks best. Shear forces in a beam may be reversed under reversed cyclic loading and fibres may be thus arranged at two different directions to satisfy the requirement of shear strengthening in both directions.

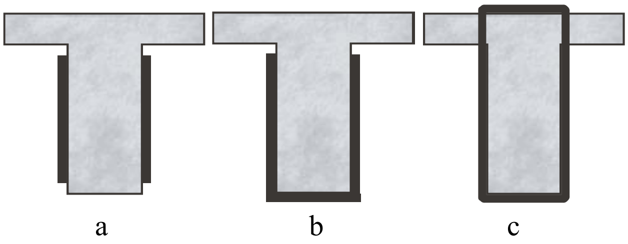

Figure 2. Shear strengthening schemes with FRP composites. a - FRP bonded to the web sides only; b-U jacketing; c-complete wrapping

2.2.3 *Strengthening of RC plates*

When the RC plates are simply supported the one-way plates are strengthened by bonding FRP strips to the soffit along the required direction, Figure 3. For two-way plates strengthening must be applied for both directions, by bonding FRP strips in both directions, Figure 4.

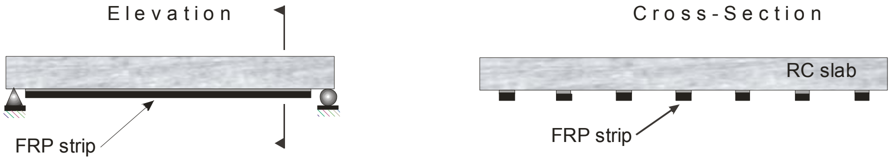

Figure 3. FRP strengthening of one-way simply supported plate:

a- elevation; b- cross section

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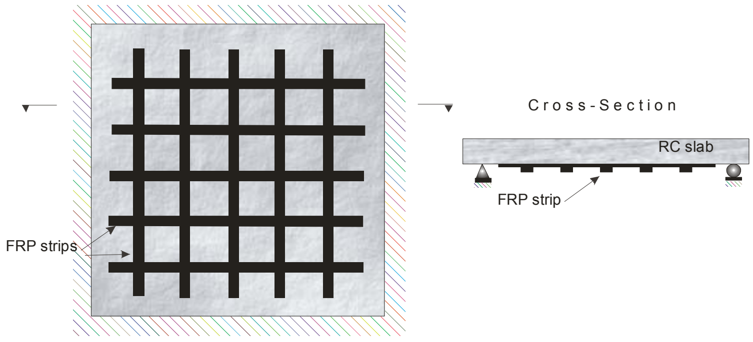

a.

b.

Figure 4. FRP strengthening of a two-way slab:

a- slab soffit; b- cross section

The possible collapse mechanism of a two-way slab suggests that the strengthening of such a plate can be concentrated in the central region, Figure 4, and the FRP strips can be terminated far away from the edges [4]. The load capacity of such strengthened plates can be predicted by a yield line analysis, as the part of the slab without bonded FRP strips has enough ductility for the formation of yield lines.

2.2.4 Strengthening of RC columns

Conventional strengthening measures for RC columns range from the external confinement of the core by heavily reinforced external concrete sections to the use of steel cables wound helically around the existing column at close spacing that are then covered by concrete and the use of steel jackets welded together in the field confining the existing columns [10].

Some of these methods are effective but they have some disadvantages: they are time consuming and labour intensive; can cause significant interruption of the structure functioning due to access and space requirements for heavy equipment; rely on field welding, the quality of which is often questionable; susceptible to degradation due to corrosion; introduce changes in column stiffness, influencing the seismic force levels.

The strengthening of existing RC columns using steel or FRP jacketing is based on a well established fact that lateral confinement of concrete can substantially enhance its axial compressive strength and ductility [11]. The most common form of FRP column strengthening involves the external wrapping of FRP straps. The use of FRP composites provides a means for confinement without the increase in stiffness (when only hoop reinforcing fibres are utilized), enables rapid fabrication of cost effective and durable jackets, with little or no traffic disruption in most cases.

In FRP-confined concrete subjected to axial compression, the FRP jackets are loaded mainly in hoop tension while the concrete is subjected to tri-axial compression, so that both materials are used to their best advantages. As a result of the confinement, both the strength and the ultimate strain of concrete can be enhanced, while the tensile strength of FRP can be effectively utilized. Instead of the brittle behaviour exhibited by both materials, FRP-confined concrete possesses an enhanced ductility.

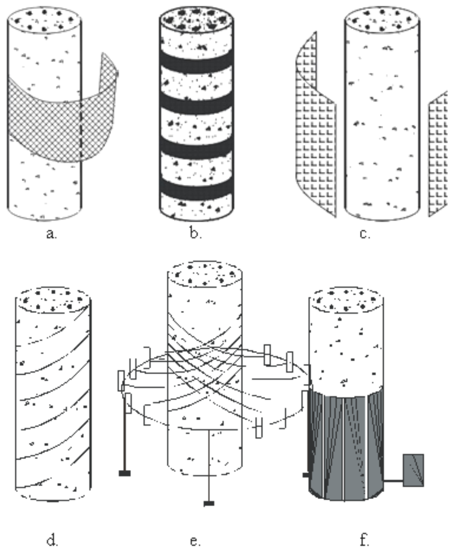

Figure 5. Methods of FRP strengthening for RC columns:

a. wrapping of fabric; b. partially wrapping with strips; c. prefabricated jackets
d. spiral rings; e. automated winding; f. resin infusion.

For FRP wrapped, axially loaded columns the design philosophy relies on the wrap to carry tensile forces around the perimeter of the column as a result of lateral expansion of the underlying column when loaded axially in compression. Constraining the lateral expansion of the column confines the concrete and, consequently increases its axial compressive capacity.

It should be underlined that passive confinement of this type requires significant lateral expansion of the concrete before the FRP wrap is loaded and confinement is initiated. In case of columns rectangular or square in cross section the confinement is effective at the column corners only with negligible resistance to lateral expansion being provided along the flat column sides.

A number of different methods (based on form of jacketing material or fabrication process) have been tested at large or full-scale many of which are now used commercially all over the world. A suitable classification of FRP composite jackets is given in, Figure 5 [12, 13].

3. ADVANTAGES OF FRP COMPOSITE STRENGTHENING

- FRP composite have higher ultimate strength and lower density than steel, although the strength to density ratio much higher than steel plate can not be generally fully utilized.
- The lower weight of FRP materials makes handling and installation significantly easier than in case of steel plates. Composite plates applied to the soffit of bridge girders do not require heave lifting equipment. When FRP plates are applied pressure is exerted to their outer surface to remove adhesive in excess and entrapped air. They can practically be left unsupported. In general there is no need to use bolts for FRP plate fixing and this avoids the risk of damaging the existing steel reinforcing bars.
- FRP composite sheets are available in long lengths (compared to steel plates generally limited to 6m) and their installation is much simpler: laps and joints are not required; the material can accommodate some irregularities; the thin FRP plates and sheets can follow a slightly curved shape without prebending; overlapping required when strengthening plates in two directions is not a problem because the composite products are thin.
- The energy required to produce FRP materials is less than for traditional materials fact that leads to sustainable solutions with minimum impact on the environment.
- The combination of all these advantages leads to simpler and quicker strengthening processes than when steel products are utilized. This is especially important for bridges because of the high costs of circulation lanes closures.

4. DISADVANTAGES OF FRP COMPOSITE STRENGTHENING

- The most important disadvantage of FRP externally strengthened structures seems to be the risk of accidental damage, vandalism or fire occurrence. However strengthening using FRP plates affected by the composite products damage can only reduce the overall factor of safety and it is unlikely to lead to collapse.

- New unfamiliar failure mechanisms are possible particularly in FRP plate bonding and specialist expertise should be provided [13].
- Workmanship skill and quality are critical to the success of applying an FRP composite strengthening solutions. Therefore certification schemes for workers and supervisors are needed to be developed prior to application of these procedures especially at important works.
- It is difficult to control the quality of the adhesive layer or the presence of the entrapped air than can affect the bond between FRP plate and the concrete surface.
- Experience on the long-term properties of FRP strengthening schemes is limited, and this can be a disadvantage for structural members requiring a very long design life.
- The relatively high initial cost of the FRP materials and products used in the strengthening schemes is a perceived disadvantage but the comparisons should be made on the complete strengthening procedure and life-cycle assessment.
- Many potential clients may claim the lack of experience of most operators in the construction market but this can be overcome by choosing qualified designers and contractors.

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