

A Review of Concrete Strengthening Methods Using Synthetic and Natural Composites [†]

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Abstract

Currently, the need to repair and strengthen structures is very important. The reinforcement of structures aims to repair or bring existing structures into conformity, either for reasons of loss of initial properties or for reasons of refurbishment level linked to new standards or new uses. One of the methods which has met with great success in the field of upgrading reinforced concrete structures is exterior bonding using composite materials. This article summarizes some of the methods used for the strengthening of concrete elements, and compares them from a technical and environmental point of view.

Keywords: composite material; concrete; repair; FRP; natural fibers; synthetic fibers

1. Introduction

The field of structural reinforcement has undergone evolution, and this has been confirmed by a number of studies which have demonstrated the effectiveness of concrete reinforcement using polymers [1,2]. Wu, 2004 [3] confirmed that strengthening beams by using synthetic fibers increases the ultimate strength by decreasing the deflection. Correia et al., 2015 and Mosallam and Mosalam, 2003 [4,5] showed that reinforcement with carbon fibers increased the stiffness of the slabs and consequently reduced the deflection for a specific load level. Wong and Vecchio (2003) [6] have shown that carbon fiber reinforcement increases the ultimate load capacity.

Synthetic fibers have a number of disadvantages, including high energy consumption during the manufacturing process. They are not environmentally friendly [7]. Jute and flax are among the most widely used biodegradable fibers in the composites industry, as they are characterized by low density and low cost. For this reason, several research studies have focused on the use of alternative reinforcing fibers based on natural components [8]. For example, natural fibers are used as a structural reinforcement system for reinforced concrete elements such as columns, beams, and slabs [9,10].

This paper presents most of the methods used in the external strengthening of RC structures using FRP composites. The first part discusses a strengthening method using composites with synthetic fibers, and the second part presents some results on the use of natural fiber-based composites.



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2. External Strengthening of RC Members with FRP Composites

The technique used to externally reinforce concrete members involves bonding pre-cured strips or laminates using an epoxy resin (see Figure 1). This method is known as Externally Bonded Reinforcement (EBR). It offers several advantages, including

- Ease of adaptation to various geometries;
- Ease of implementation;
- High resistance to fatigue;
- Enhanced durability;
- Minimum of maintenance.



Figure 1. Examples of external strengthening of RC members.

Wong and Vecchio (2003) [6] have shown that strengthening RC members with carbon fiber composites increases ultimate load capacity. Wu (2004) [3] confirmed that bonding composites with a laminate of RC members increases both the ultimate strength of reinforced beams and their stiffness. As a result, it limits crack propagation (see Figure 2). Correia et al. (2015) [4] also indicated that strengthening increased the stiffness of slabs reinforced with carbon epoxy composites and consequently reduces deflection for a specific load level.

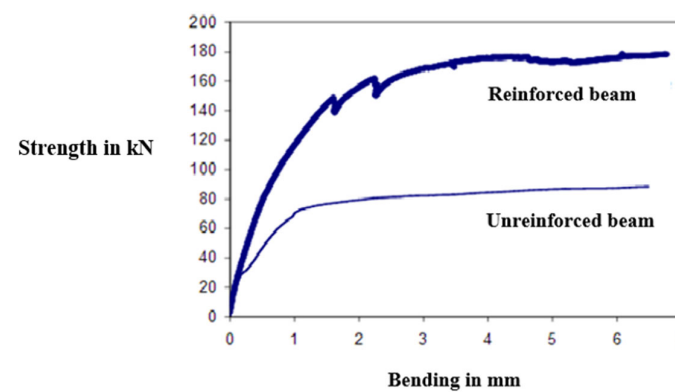


Figure 2. Comparison of behavior between reinforced and non-reinforced beams (Wu, 2004) [3].

David et al. (2001) [11] found a 51% and 73% gain in bending of specimens P2 and P5, respectively (see Figure 3), as compared with to the control beam P1; also, test results indicated an increase in stiffness and a decrease in steel elongation, as well as a reduction in mid-span deflection of 18 mm and 16 mm for P2 and P5 versus 50 mm for the control beam.

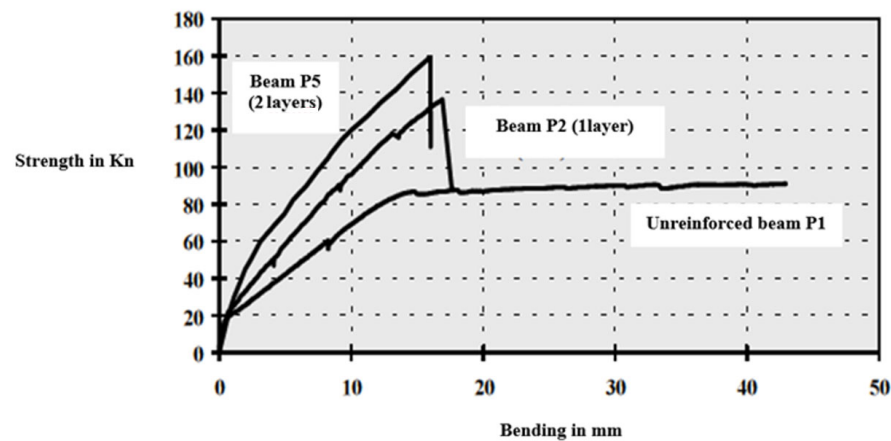


Figure 3. Comparison between a beam strengthened with a single layer of CFRP and a beam strengthened with two layers (David et al., 2001) [11].

Wu, 2004 [3] confirms that flexural failure of strengthened beams can occur when the strengthening RC member is strengthened with thick composite laminate FRP fabric. They noted that, for a beam with low shear reinforcement (reinforcement ratio $< 0.2\%$), increasing the amount of longitudinal fabric only slightly improves ultimate strength.

This proves that the effectiveness of reinforcement is indeed linked to the number of layers used.

3. Externally Bonded Reinforcement in Grooves (EBRIGI) Technique

EBRIGI is a method which consists of creating longitudinal grooves of predefined dimensions at the level of the surface of the concrete, then a step of cleaning with compressed air precedes the complete filling with epoxy glue [12]. The next stage of strengthening involves fixing the sheet of impregnated fibers in the groove (see Figure 4).



Figure 4. Reinforcement of the exterior using the EBRIGI technique (Mostofinejad and Shameli, 2013) [12].

Hosseini and Mostofinejad (2013) [13] found that groove depth and width could play an important role in shear strengthening using carbon fiber-reinforced polymer (FRP) sheets. Based on their results, cutting longitudinal grooves on the tension face of beams instead of conventional surface preparation can increase the loading capacity by up to 80%. In addition, longitudinally reinforced specimens can achieve higher ultimate loads and, in some cases, failure may be due to FRP failure instead of FRP debonding.

Mostofinejad et al. (2016) [14] compared percentage improvements in ultimate load between beams strengthened by different methods and control beams in each group; beams were strengthened by EBR-V, EBRIG-V, EBR-D, and EBRIG-D methods (EBR and EBRIG methods with vertical and diagonal CFRP sheets: the strengthening methods were

designated as EBR-V, EBR-D, EBRIG-V, and D EBRIG). They recorded ultimate loads of 127.6, 147.67, 169.28, and 172.78 kN, respectively; which indicate improvements of 62%, 87%, 115%, and 119%, respectively.

4. Externally Bonded Reinforcement on Grooves (EBGOR) Technique

This technique consists of inserting strips of carbon fibers in engravings previously made in the concrete covering the stretched surfaces, then filled with an epoxy resin to fix them (see Figure 5) [12].



Figure 5. Reinforcement with the EBRIG technique (Hosseini and Mostofinejad, 2013) [15].

According to Davood Mostofinejad et al. (2016) [14], the ultimate capacity of CFRP sheets bonded to the concrete surface using the EBRIG technique was increased by up to 27.8% compared to beams externally bonded with CFRP sheets using the EBR technique. They also observed that the failure of the EBR-strengthened beam was due to disbonding of the CFRP sheet from the concrete substrate, whereas the failure of all specimens strengthened by the GM technique was due to CFRP failure, irrespective of groove.

5. Near-Surface-Mounted (NSM) Technique

Several researchers have proven the effectiveness of this technique compared to the technique of gluing from the outside (see Figure 6) [16].

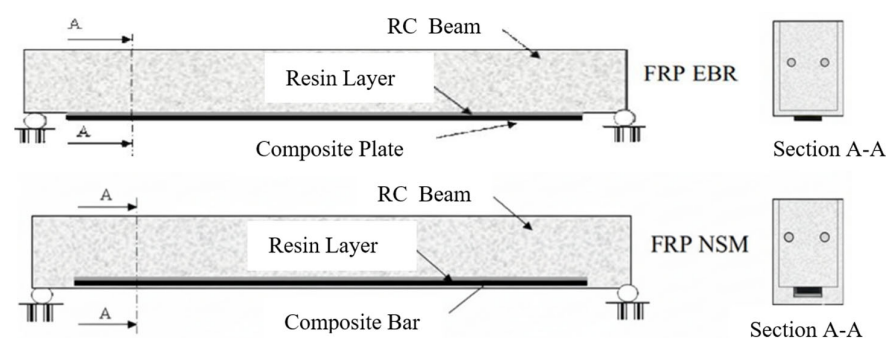


Figure 6. Reinforcement by the external EBR method and the NSM method (Merdas et al., 2011) [16].

They found an increase in maximum capacity after the formation of the shear cracks and an increase in stiffness (Capozucca, 2009; El-Hacha and Rizkalla, 2004; Szabò and Balazs, 2007, Mosallam et al., 2022 and 2024) [17–21].

Seo et al., 2011 and Bilotta et al., 2016 [22,23] confirmed that NSM significantly improves resistance capacity compared to reinforcement from the outside (EBR).

Capozucca, 2009 [17] also confirmed that the use of CFRP NSM rods results in a notable increase in resistance capacity and an increase in stiffness of RC members.

De Lorenzis and Nanni (2001) [24] obtained a significant increase in shear strength of 106% (in the absence of internal stirrups) compared to the reference beams.

According to De Lorenzis and Teng (2007) [25], over a decade of research and applications have proven that strengthening using the NSM technique offers the following advantages:

- Reduced surface preparation and, in some cases, even installation work can be minimized;
- FRP reinforcements can easily be anchored to the adjacent elements preventing delamination failures;
- The strengthening effective levels are higher, as FRP reinforcements are protected by the embedding concrete and are therefore less exposed to mechanical damage, fire, and vandalism;
- The visual appearance of the reinforced structure is virtually unchanged.

Sharaky et al. [26] results indicated that increasing groove size and bond length increases breaking loads.

6. Strengthening Techniques of Embedded Through Section (ETS)

The Embedded-Through-Section (ETS) technique consists of inserting fiber-reinforced polymer bars into vertical holes that are drilled upwards from the underside into the shear wires of the beams (see Figure 7) [27].



Figure 7. Reinforcement with carbon fiber rods according to the ETS technique (Khodja, 2012) [27].

Chaallal et al., 2011 [28] proved that reinforcement by ETS reaches beyond the NSM method. They noticed an increase in average strength of 60% for the beams reinforced by the ETS and 31% by the NSM. On the other hand, the two methods EBROG and EBRIG greatly improved the maximum load of the beams compared to the NSM method.

7. Reinforcement Using Natural Fibers

The results of the test by Yan et al., 2016 [29] revealed that confining RC members with flax fiber composites significantly increased the compressive strength and ductility of the concrete compared to unconfined concrete.

Cervantes et al., 2014 [30] observed that the stiffness and the ultimate load capacity of RC beams are increased by adding plates of polymer composites reinforced with natural fibers.

Sen et al., 2013 [31] conducted a study where concrete cylinders were confined with FRP jute composites. The results showed an increase in load capacity of up to 48% as compared to controlled unconfined cylinders.

The same observation was reported by Ed-Dariy et al., 2021 [32], who concluded that the strengthening of concrete members with jute fiber-reinforced polymer results in an increase in the ultimate load capacity of up to 57.3% as compared to unstrengthened

specimens. It was also noted that increasing the number of layers increased the maximum load capacity of concrete by 36.6% and 57.3% in the case of specimens confined with two plies (C3-JFRP-2L) and three plies (C3-JFRP-3L), respectively.

According to the study of Tan et al., 2017 [33], wrapping concrete columns with jute fiber-reinforced polymers (FRP) increased the compressive strength, and by increasing the FRP layers of jute to one, three, and five layers, the ultimate compressive strength increased by 18.4%, 35.7%, and 58.7% respectively.

For Huang et al., 2016 [34], strengthening the concrete members by using flax composites increased the maximum load capacity from 15.5% to 112.2%, as well as the ductility. In Tanvir et al., 2017 [35], the load bearing capacity of beams increased by about 25% by jute FRP layer. Yan et al., 2016 [29] reinforced concrete columns with flax fibers; their results showed that increasing the number of fabric layers from two layers to six layers led to a strength increase of 30, 78, and 134%, respectively, compared to unreinforced concrete (As shown in Figure 8).

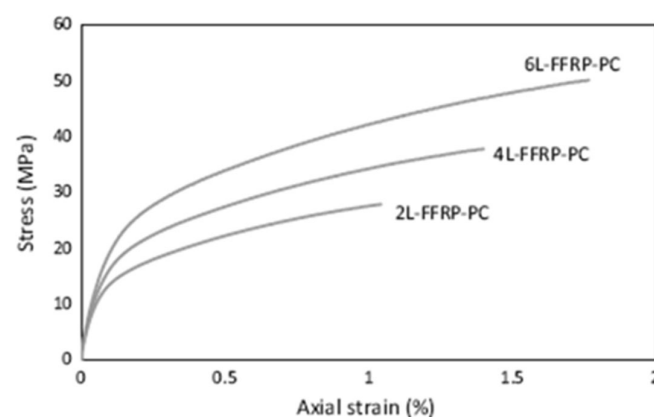


Figure 8. Loading curves vs. axial stress of specimens reinforced with different flax FRP layers (Yan et al., 2016) [29].

The results of Ngo, 2016 [36] showed that FRP reinforcement of flax exhibited a significant increase in shear strength compared to the reference beams (Figure 9). The result of Ed-Dariy et al., 2020 [37] have shown that the reinforcement of concrete elements with jute fiber fabrics increased the maximum load capacity by 19.6% compared to unreinforced specimens [38,39].

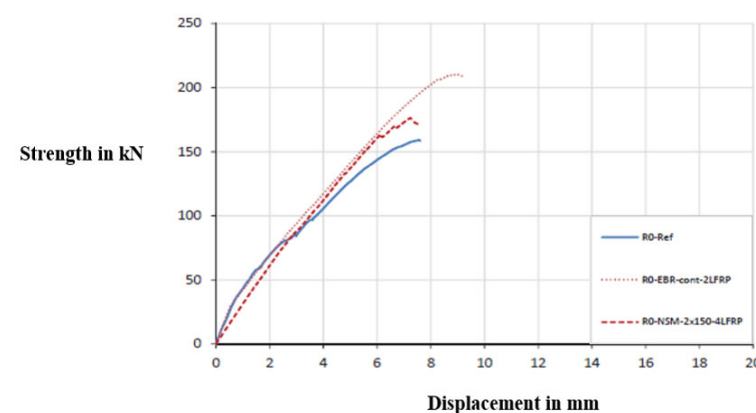


Figure 9. Strength-displacement curves (Ngo, 2016) [36].

8. Conclusions

The effectiveness of FRP composite strengthening depends, to a large extent, on load transfer in the concrete–carbon composite interface. This adhesion depends on the

conditions under which the composite repair is applied. Despite some of the advantages of the EBR technique, such as quick and easy installation, the main problem that has considerably hampered the use of this method is the premature debonding of composite FRP from the concrete substrate. For this reason, recent research has focused on the innovation of other methods, including NSM, EBROG, EBRIG, NSM, and ETS.

Published studies have demonstrated the effectiveness of the techniques described in this paper, including

- Increased load-bearing capacity;
- Reduced deflection;
- Increased ductility;
- Increased stiffness.

The two new methods, EBRIG and EBROG, have produced relatively better results compared with the NSM and EBR methods. The latter methods have been widely investigated; however, only a few studies have been published on the EBRIG, EBROG, and ETS methods.

Use of natural fiber composites is often limited to interior and non-structural applications due to their inferior mechanical properties and high moisture absorption. Results of studies conducted on natural fiber composites confirm the existence of significant challenges preventing their advancement as structural components. In addition, the literature review highlighted interest in developing the use of jute fiber composites as a sustainable alternative for structural reinforcement in civil engineering.

9. Patent

The research presented in this manuscript has led to the filing of the following patent: “Technique for Strengthening Concrete Elements Using Jute Fiber-Based Composite Materials”, by Ed-Dariy Yasmina, Lamdouar Nouzha, and Cherradi Toufik. The patent was published on 30 December 2022, by the Moroccan Patent Office (MA) under Patent Number MA 53525 A1, with Filing Number 53525.

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Abbreviations

The following abbreviations are used in this manuscript:

FRP	Fiber-Reinforced Polymer
EBRIG	Externally Bonded Reinforcement In Grooves
EBROG	Externally Bonded Reinforcement On Grooves
ETS	Embedded Through-Section
NSM	Near-Surface Mounted
CFRP	Carbon Fiber-Reinforced Polymer
EBR	Externally Bonded Reinforcement
RC	Reinforced Concrete

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