Industrial Technology Journal
Faculty of Technology & Education
Suez University

(Review)

A Comprehensive Review of the Flexural Behavior of RC Beams Strengthened by Externally Bonded and Near-Surface Mounted Techniques Using FRP and Metal Materials

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Citation: A.Ali, I.A. Sharaky, A.H.H. Khalil, M. Attia. “A Comprehensive Review of the Flexural Behavior of RC Beams strengthened by Externally Bonded and Near-Surface Mounted Techniques using FRP and Metal Materials”.

Industrial Technology Journal **2025**, *15*, x.

https://doi.org/10.21608/itj.2025.394706.1032

Academic Editor: A. Ali

Received: 16-07-2025
Accepted: 07-08-2025

Abstract: Near surface mounted (NSM) uses of fiber reinforced polymer (FRP) in civil construction have become more common globally and can provide reliable strengthening and repair systems for concrete structures that are already in place. It has been extensively studied how concrete structural members that have been strengthened using FRP and the externally-bonded (EB) technique respond to fatigue and monotonic loads. However, little is known about how NSM FRP-rehabilitated concrete structures respond to monotony and fatigue. This research aims to review the literature on the behavior of R.C beams strengthened with both NSM and EB procedures because there aren't many prior review studies both EB and NSM methods or focus on NSM components. It compares the advantages and disadvantages of each strategy, makes recommendations for the future. The review also highlights the critical of different strengthening materials (both FRP, metallic materials), the techniques employed, the properties of the strengthening elements (like area, shape), other elements affecting the behavior of the RC beams for each technique. The results show that the load-carrying capability of the RC beams strengthened by both techniques had highly influenced by the strengthening elements' mode of failure. Furthermore, the NSM technique may significantly enhance the bonding behavior between FRP composites and the concrete. Additionally, at the FRP-adhesive interface over the grooves, 28.0% and 14.0% of all NSM bonds, respectively, suffered FRP rupture mode and a combination of FRP rupture and debonding.

Keywords: Externally bonded (EB), Flexural Strength, Fiber reinforced polymer (FRP), Near surface mounted (NSM), R.C Beams.

1. Introduction

According to building requirements, concrete structures must be constructed to last for at least 50 years [1]. However, to ensure that they comply to precise design, these buildings must be reinforced due to their deterioration from age, neglect, unintentionally carrying too much weight, poor design or construction [2–4].

Additionally, in order to achieve the required strength requirements, Extend its operating life, it had often necessary to enhance RC structural elements [5–7]. It is now necessary to strengthen or retrofit these RC structures in order to maintain or enhance their performance using a range of techniques [8]. These include NSM, which involves inserting strengthened bars or strips into slits made in the concrete cover [9–11], EB techniques [9–11], which include attaching FRP or steel plates to the tension side of the reinforced beams.

Because of its many benefits, including reduced installation time, enhanced bond capacity, post-strengthening protection, NSM had shown to be more critical than conventional strengthening procedures [12,13]. But so far, little was known about how well NSM-FRP bars bonded to concrete. [14–16].

The flexural performance of RC beams reinforced with both NSM, EBR procedures had examined by Bilotta et al. [17]. Their study found that beams reinforced with the NSM technique outperformed those reinforced with EB strips in terms of load-carrying capacity, even when utilizing fewer carbon fiber reinforced polymer (CFRP) strips through practical and numerical research on RC beams with NSM and EB-reinforced high-strength concrete (RHSC). M.H. Seleem [18] confirmed this finding as according to the findings, using steel RHSC layer and glass fiber reinforced polymer (GFRP) bars respectively, enhanced the load capacity by 172.0% and 147.9% when reinforced with NSM. However, because of the rapid debonding failure, these ratios had critically larger than those with EB-RHSC layers. This had in line with [19], who demonstrated that beams reinforced with NSM strips had a higher capacity load than those reinforced with EB, even when the same area of FRP had used. Also, Mohammed et al. [20] studied beams strengthened using multiple retrofitting methods, where three different reinforcement methods were used: EB-GFRP laminates, NSM-GFRP and steel plates, and U-jacket. In comparison to all other methods, the use of GFRP for strengthening led to a delay in the propagation of cracks before failure occurred in the reinforced concrete beams. In addition, the beam strengthened using NSM-steel plates recorded the highest ultimate load value, which was 33% higher than that of the CB, along with a noticeable increase in the beam's stiffness. This increase in stiffness led to a 21% reduction in the deflection of the beam compared to the CB.

According to [21], beams reinforced with the NSM technique had an ultimate load capacity that had 12–18% greater than beams reinforced with the EB technique.

The NSM steel bars technology might be utilized as a suitable method in the early stages of damage, as demonstrated in [22], even though the EB-CFRP sheet had more suited for badly damaged corbels. Additionally, the advantage of the NSM technique over the EB system in increasing the stiffness of strengthened beams had demonstrated by static and dynamic tests [23,24].

Ten 6.4 m long RC beams were tested by Cho et al. [25] in order to examine how concrete strength and steel reinforcement ratio affect the strengthening impact of a prestressed NSM FRP system. They found that the load capacity of beams strengthened with prestressed NSM FRP can be increased by 106 %. As the concrete strength increased and the reinforcing ratio decreased the load capacity improved even more. According to Lee et al. [26] the post-tensioned system's strengthening impact was noticeably enhanced. In contrast, even with the use of sandblasted CFRP bars, the pre-tensioned system without anchors had a notable decrease of pre-stress. This indicated that in such a prestressing system, the anchor is essential.

I.A. Sharaky et al. [9] assessed eight beams to examine the performance of beams reinforced utilizing the NSM technique employing various types of FRP. According to the findings, the CFRP, GFRP-reinforced beams rose by 166.3%, 159.4%, respectively, in comparison to the control beam (CB). Furthermore, CFRP-bar reinforced beams demonstrated greater stiffness than GFRP-reinforced beams. Additionally, it had shown that the concrete cover separation (CCS) failure mode controlled the ultimate capacity load. In [27], the impact of the interaction between the NSM strips and the main reinforcement of the strengthened members had examined. The findings indicated that installing NSM-GFRP strips in one groove side by side had a lower interfacial stress than installing them in two separate grooves. Additionally, deepening the grooves to install the NSM-GFRP strips near the stirrups could postpone cover separation, raise the ultimate load by approximately 1.5 times compared to installing them near the bottom surface of the beam. Additionally, El-Gamal et al. [28] discovered that the final capacity of the strengthened beam could be improved by more than 85% by doubling the FRP area. Additionally, GFRP-retrofitted beams might had an initial stiffness increase of 58–71%, an energy absorption increase of 35–96% when compared to CB, according to experimental results in [29]. The NSM bar could be installed at the side cover of the RC beam, however this would had a reduced load-carrying capacity, flexural rigidity, according to [30,31], which also indicated that the bottom cover had the sole location for this installation.

Wei sun et al. [32] developed an anchored system to fully NSM-FRP bond, increase the FRP tensile strength up to rupture. While, R.M. Reda et al. [11] bent the end of GFRP-NSM bars by different angles equal to 0o, 45o, 90o to delay the failure of the separation of the cover and the NSM-bar debonding. The results showed that the end anchors improved the CCS, increased the ultimate load capacity by 201 percent over the CB. By using EB U-wrap FRP, altering the failure mechanism to NSM-FRP bar rupture, Rahulreddy [33] improved the ultimate capacity and the bond strength of NSM-FRP bars. In addition to using mechanical interlocking grooves [34,35] or by use anchored technique with the prestressed [36,37] could delay the CCS in addition enhancing the carrying load. In contrast to conventional face-to-face connections, Hesham M.A. Diab [38] showed that the usage of NSM-FRP rods in conjunction with embedded through-section (ETS) anchors produced higher ductility. Several anchorages have been used to reduce these kinds of debonding failures. In order to increase the load capabilities, Wu et al. [39] employed three anchorages: U-shaped steel hoops, an expanded end, and grooves filled with low modulus resin. The U-shaped steel hoops demonstrated the greatest increase in load capacity, according to the results. Zhang et al. [40] tested eleven RC beams to show how successful a FRP U-jacket is for postponing debonding failures in NSM-beams. They explained that FRP U-jackets angled 45° to the beam axis outperformed their vertical equivalents. Zhang's group suggested an additional anchorage (dubbed the "embedded FRP anchor") that consists of a spike component implanted in the concrete substrate and a sleeve that warps the FRP bar. The embedded FRP anchor improved the ultimate load by up to 35 % [40].

On the other hand, A few investigations have been carried out to look at how the bonding patterns of NSM reinforcement affect the strengthened RC beams' performance. Eight RC beams with varying unbounded region lengths in the mid-span zone were evaluated by Seo et al.[41], who discovered that a longer unbonded length resulted in a reduced load capability. Five T-beams reinforced in flexure using a partially bonded NSM system, with the unbonded length ranging from 0 to 2100 mm, were tested by Choi et al.[42]. They showed that the partially bonded system increased the deformability of strengthened beams and changed the failure mechanism from FRP rupture to concrete crushing.

The flexural behavior of the NSM beams had analyzed using Finite element (FE) analysis in addition to the previous experimental studies [43–46]. Due to the fact that the CCS or slippage of the NSM bar cannot be anticipated to occur in a perfect bong model, it had concluded that the application of the debonding behavior in the FE model had required [47,48]. Numerous review articles had offered comprehensive insights into the performance of RC beams that had enhanced using the EB technique [49–52]. Nonetheless, there had only a limited number of reviews that focus on NSM elements [53–56]. The aforementioned review publications had all centered on particular elements that influence the NSM and EB methods. Thus, the goal of this work was to gather and assess the existing research on RC beam reinforcement employing both reinforcement method. Details on the strengthening materials, such as FRP, metallic composites, epoxy characteristics, factors affecting both procedures, ductility evaluations, the failure modes of the reinforced elements associated with each method had all included in the review. Along with outlining the present shortcomings of EB, NSM technique strengthening methods, the study also offered suggestions for improving both strategies in the future.

2. Strengthened materials

The Materials The oldest, most basic method for development, retrofitting had to attach repair material to the beam's soffit. In contrast to the NSM approach, a variety of materials had used for exterior strengthening

2.1. Steel

During the previous century, one of the first techniques in the field of structural upgrading was the employment of steel plates for the flexural strengthening of reinforced concrete structures [57]. Since the 1960s, the usage of steel plates has expanded to many nations because to its simple, quick method, which may be less expensive than demolishing the building. The mild steel plates used for exterior reinforcing had attached to the concrete beams' soffit using mechanical connectors (bolts) and/or strong glue. Nevertheless, poor corrosion resistance had one of the primary issues with steel plates that had subsequently noticed. Raithby MacDonald, Calder's exposure tests [58,59] show that the steel-epoxy interface experiences a critical amount of corrosion, which results in localized debonding, a decrease in strength. Furthermore, steel had a density of about 7800 kg/m^3, making it a somewhat heavy material. Steel plates had therefore difficult to handle on-site due to their critical weight, which complicates their usage as a reinforcing material.

2.2 FRP

In recent years, FRP materials have garnered a lot of interest because of its advantages over steel plates, which include increased strength-to-weight ratio, convenience of on-site handling, and shipping. The density of Fibers generally ranges from 1200 to 2100 kg/m^3 [60]. This indicates that FRP was between 85% and 73% lighter than steel, requiring less equipment and fewer on-site employees. In the middle of the 1980s, studies on the use of FRP for flexural strengthening got underway. The three most widely used forms of FRP were CFRP, GFRP, and aramid fiber reinforced polymer (AFRP) [61]. Still, CFRP was chosen for strengthening applications because it was stiffer and had a higher compressive strength than the other two types. ACI 440.2R-08 [60] outlined three distinct forms of FRP utilized for external strengthening: wet layup, prepreg, procured. The particular use on concrete structures, together with aspects pertaining to their handling, transportation on the job site, dictate which of the three types of FRP had best. Additionally, the various FRP varieties could be mixed, utilized as a hybrid to produce a gradual failure pattern like that of ductile materials like steel. In RC constructions, the idea of hybrid FRP had first presented as a possible substitute for conventional tension steel [62]. However, hybrid FRP has been researched to lessen the loss of ductility in strengthened beams as the use of FRP materials for strengthening applications has increased recently [63]. Structures made of reinforced concrete with EB using both FRP and steel plates are shown in Figure 1.

2.3 Hybrid steel-FRP

The decreased stiffness of FRP had a negative impact on the ductility of FRP-RC beams [66], since steel mostly increases the RC beam's pre-yield stiffness [67,68]. Hybrid bars had developed by combining the advantages of steel, FRP bars to address steel's corrosion issue. These hybrid bars maintain beam rigidity due to their high modulus of elasticity, while also incorporating the properties of fiber bars that could endure high stress levels as shown in Figure 2.

(a)

(b)

Figure 1. The application of traditional strengthening materials figure: (a) Using steel plate [64], (b) FRP plates bonded to R.C slabs [65]

Figure 2. Hybrid steel-GFRP bars [63]

2.4 Mechanical properties of strengthened materials

As shown in Figure 3 at the start of its stress-strain curve, steel usually exhibits a linear elastic phase when it responds to applied loads in a predictable manner. Steel reaches a yield point when tension rises, then it moves into a yielding plateau, which allows for considerable plastic deformation without causing stress to rise in tandem. Steel could absorb energy, undergo plastic deformation thanks to this property, which serves as a warning before collapse happens. In contrast, up to their ultimate tensile strength, FRP materials behave linearly elastically; nevertheless, they do not have the yielding plateau that steel does. Rather, FRP materials usually had a brittle failure after abruptly reaching their maximum stress. This implies that FRP lacks the warning indicators that steel does prior to failure, which could be a crucial factor in structural applications.

On another note, as shown in Figure 4, The hybrid steel-FRP bars' stress-strain curves had split into two phases by the yielding point of the inner steel core, the breaking point of the exterior fiber materials. Therefore, in contrast to carbon and glass fiber rods, which exhibited linear behavior until failure, the stress strain curves of steel-GFRP and hybrid steel-CFRP bars had bilinear. Before the inner steel bar yielding, the outer FRP layer and the inner steel bar share the load. Once the inner steel bar yields, the bonding stresses had less than the shear forces at the point of contact between the steel, the adjacent FRP. As a result, delamination begins, the weight had completely transmitted to the F.R.P until the fibers had finally cut [69].

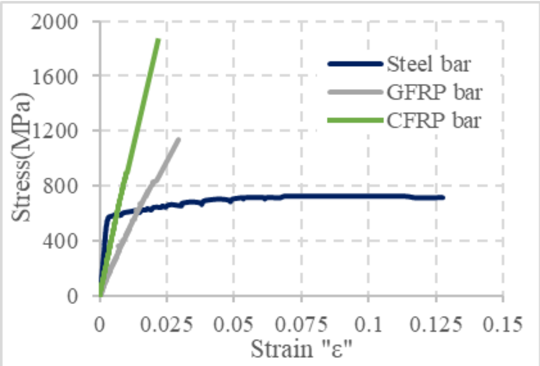


Figure 3. FRP Properties Compared with Steel[63]

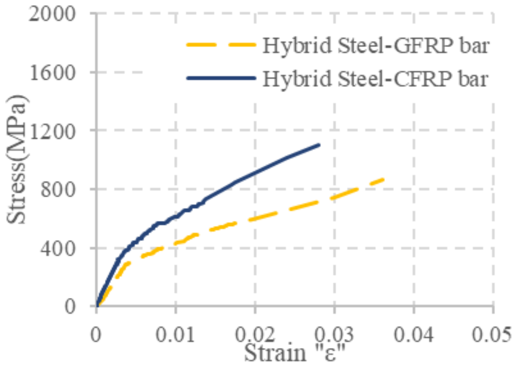


Figure 4. Properties of hybrid Steel-FRP bars [63]

3. Strengthened materials

For RC structures, the two most commonly used methods for strengthening are EB and NSM techniques. Numerous reviewed studies have examined the performance of RC beams that have been reinforced using the EB method.[52,70,79–88,71,89,90,72–78]. Nevertheless, the NSM approach has not received much attention in research [51,53–56,91–93]. or both methods [50,94,95]. As a result, this section will compile and analyze the majority of recent research focused on strengthening beams through the both methods.

3.1 EB Technique

The tension side of the RC beams or slabs is connected to the steel or FRP sheets through the EB method (Figure 1b). The EB approach has proven to be successful in enhancing. Behavior of RC structures in the past. Steel plates were bonded to the surfaces of RC structures many years ago in order to strengthen and repair them [96]. FRP laminates, which had robust, lightweight, corrosion-resistant, had recently been used to repair [97–99]. Numerous research had conducted to use E.B-FRP laminates to improve RC constructions [25, 39 – 45]. The EB process had used to bond one or more plates or laminates to the tensile surface of the beam [100]. Single, double, triple layers of CFRP laminates had utilized to enhance the reinforcement of RC beams in the study referenced in [108]. There had two W-shaped, one U-shaped edge strips in the CFRP laminates. The results showed that as the number of CFRP laminate layers grew, so did the flexural stiffness, yield load (Py), ultimate load (Pu). Beams that featured end anchoring, had low ratios of FRP reinforcement exhibited the most critical improvements in flexural strength. Additionally, the FRP systems absorbed the tensile force as the steel bars gave way, CFRP laminates tended to improve the beam capacity. Furthermore, the ultimate capacity of two beams had determined by testing them under static flexural pressures [109]. CFRP plates had used to strengthen one of the two beams, but the other had left unreinforced. When CFRP reinforcement had added, the mid-span deflection decreased by 36% to 40%, the Pu increased by about 77%.

3.1.1. EB-Metal plates

The aluminum alloy (A.A) plates served as external bonding reinforcement for flexural support in [110] for RC elements. The strength gain varied from 13% to 40% when compared to the CB. Then, in [111], as A.A plates had orientated at a 45° angle, they critically boosted beam shear capacity, which resulted in a 39% increase in the load capacity of the reinforced RC beams as compared to the CB. Additionally, in [112], E.B-A.A plates had utilized to strengthen the beams through two different anchorage methods. The beam strengthened with EB-A. A plate showed a 32% rise in load capacity, but the bolted A.A plates only produced a 24% improvement over the C.B.

3.1.2. EB-FRP sheets or laminates

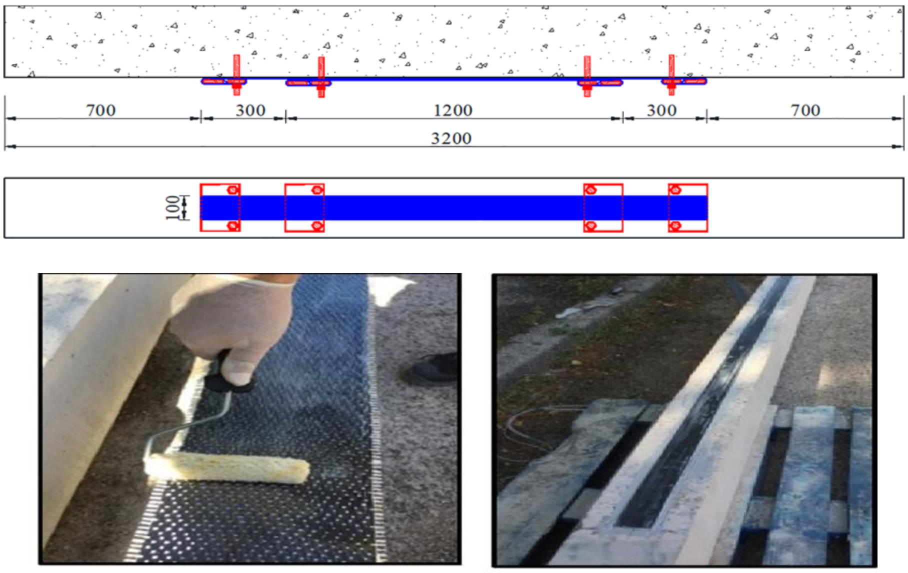
EB-CFRP plates or sheets had employed in several prior studies to enhance the stress levels in RC beams [100,101,114–123,102,124–127,103–106,108,109,113]. In [113], the flexural strength of continuous RC beams reinforced externally with CFRP plates or sheets was evaluated (Figure 5). The results shown that EB-CFRP strengthening could raise the yield, ultimate loads of continuous RC beams by approximately 59.1%, 49.8%, respectively, in both positive, negative bending moment zones. Furthermore, the CFRP sheet's modest weight allowed it to increase beam efficiency more than the addition of several sheet layers. The ultimate load increased by 41–125% when RC beams had strengthened flexural utilizing EB-CFRP sheets in [114] as opposed to their CB capacity. On the other hand, by testing a short beam with varying volume percentages of steel fibers (0–1.0%) but no strengthening, Yin, Wu [115] illustrated the improvement in the toughness of RC structures. Additionally, a number of FRP beams reinforced with identical volume fractions of steel fibers were evaluated to show how Fiber strengthening affected the beam's toughness. The results confirmed that there was a discernible increase in the FRP stress transfer duration, peak loads, and debonding onset. On the other hand, The CFRP plates had secured in [126] by applying two layers of U-wrap sheets with fibers aligned perpendicularly, one layer in the longitudinal direction, one in the transverse direction.

In textiles, composites, AFRP had a synthetic fabric that works incredibly well. Although AFRP had more expensive than GFRP, it offers many benefits, including superior strength, high flexibility. Its density had also 40% lower in additional heat resistance [104]. In [105], Examined were twenty-two RC beams strengthened with externally unidirectional AFRP sheets while submerged in saltwater. After 360 days, the maximum strength increase had 8.5%, while in other scenarios, it did not exceed 6.5%.

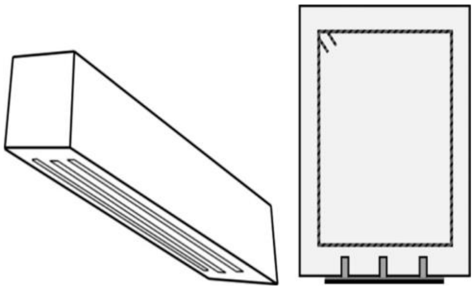
Furthermore, compared to the un-strengthened beam, the flexural stiffness increased with the number of layers when the AFRP sheets were placed to the beams [116]. When comparing basalt fibers (BF) to glass and carbon fibers, BF emerges as a more cost-effective and environmentally friendly option with superior insulation properties. [117]. Sim et al. [118] investigated how, depending on the amount of BF layers, BF reinforcement increased the ultimate and yield strength of the beam samples by up to 29%. Additionally, the BF achieved their maximum capacity prior to failure when one or two layers of BF were utilized. FE simulations indicated in [119] that Beams reinforced with basalt-EB have a higher flexural capacity than beams reinforced with FRP or steel.

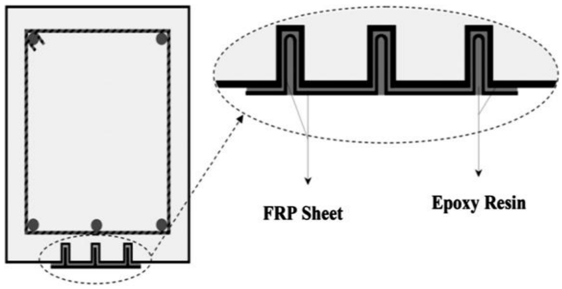
The strength, ductility of many fiber types had successfully combined in the hybrid FRP (HFRP) composites. The reaction of RC beams that had enhanced with HFRP laminates had investigated in [120], It has been studied how well beams strengthened with both hybrid Carbon and glass laminates perform. The maximum capacity of the improved RC beams was 10.3% higher than that of the CB. As a result, in [122], updating the R.C elements with CFRP/BFRP sheets increased the beam's ductility in addition increased its carrying capacity by about 28–75% in accordance with the CB.

To compare the use of fiber versus steel as EB strengthened material, Ayman et al. [128,129] tested seven cantilever slab divided into three groups over the control slab. The first group consisted of two beams strengthened with RC jacket with and without shear connector, the second group consisted of two beams strengthened with GFRP layers with varying lengths of reinforcement in the slab, and the last group included two specimens strengthened with steel plates using different fixation methods either with epoxy or bolts. According to results, the jacket strengthening approach significantly affects all measured responses. As for the second group, failure always occurs due to the debonding of the GFRP layers. But, for the slabs strengthened with steel plates, they were completely ineffective due to the early separation of the steel. These results were also confirmed using FE programs [129].



a) EB-CFRP plates or sheets [113]**.**





b) EBROG [113]

c) EBRIG [113]

Figure 5. Strengthening with E.B C.F.R.P reinforcement [113]

According to [101], The load-bearing capacity of side external bonded (S-EB) RC beams increased by 100% to 160% with reinforcing ratios of 0.0071 and 0.005. In [127], soffit bonding outperformed S-EB strengthening as a strengthening technique in terms of flexural strength, property enhancement. However, it has been demonstrated that utilizing EB-wrapped GFRP composites to upgrade beams is a crucial way to increase their flexural capacity [123]. Flexural strength, ductility and cost-criticalness had all increased by adding two layers of GFRP textiles to the strengthened beams' tension face, half on each side below the neutral axis.

Comparing the grooved method (Figure 5b, c) with the U wrapping-EB technique without any surface preparation, the final long-bearing capacity had critically increased by using either end-bonded reinforcement on a groove (EBROG) or embedding end-anchored reinforcement in a groove (EBRIG). Specifically, For one, two, three EBROG layers, it specifically enhanced capacity by 139%, 148%, and 99%; for one, two, or three EBRIG layers, it improved capacity by 142%, 186%, 155% [124]. A novel method had put out by Moradi et al. [125] that included hole drilling along the beam webs, grout-filled FRP reinforcements.

In this manner, Walid et al. [130] studied the behavior of reinforced lightweight concrete beams made of lightweight expanded clay aggregate (LECA) strengthened with EB-GFRP layers under flexural. A set of beams consisting of 44 beams, each 700 mm long with a cross-section of 100×100 mm, were cast and divided into four series. The first series contains 4 beams as control specimens, while the second consists of twelve beams that were strengthened with glass fibers layers before the loading process. The third group includes twenty beams that were loaded up to 80% of their maximum load before the strengthening process. Finally, the fourth series consist of sixteen beams that were immersed in a 10% sulfate sodium for six months before testing. The findings indicated that reinforcing lightweight concrete beams with GFRP layers significantly enhanced their overall load-bearing capacity with lower deflection. Additionally, beams that were loaded to 80% of their pre-repair load levels exhibited behavior comparable to that of strengthened beams prior to loading.

3.1.3. EB-Steel meshes

Because of its high tensile strength, modulus of elasticity, hardwire steel-fiber (H.S.F, Figure 6) Because of its high tensile strength and modulus of elasticity, hardwire steel-fiber (HSF, Figure 6) serves as an excellent alternative for external reinforcement, providing additional advantages over FRP, such as enhanced stiffness, bonding, and strength performance[131]. Additionally, HSF composite sheets are easier to pre-stress and are more affordable and lighter than traditional FRP laminates. The efficiency of polymer mortar composites and steel wire meshes (SWM) in fortifying RC beams was investigated by Xing [132]. The findings showed that compared to CB, all reinforced beams were more rigid and able to support more weight. In order to improve the RC beams, [133] CFRP sheets, SWM, a combination of the two had used. When the load capacity increased relative to CB, the experimental beams failed because the SWM ruptured or the CFRP laminates de-bonded. Galvanized steel mesh (G.S.M.) sheets with varying cord densities could be used to provide external reinforcement for R.C. beams. The G.S.M. sheets might be affixed to the RC structures using epoxy adhesives. Meshes with low cord-density had the only ones that function critically with cement mortar. G.S.M documents [134]. When G.S.M sheets had utilized for external bonding to strengthen R.C beams, their ultimate flexural capacity increased by 41.8% to 51.4% [134].

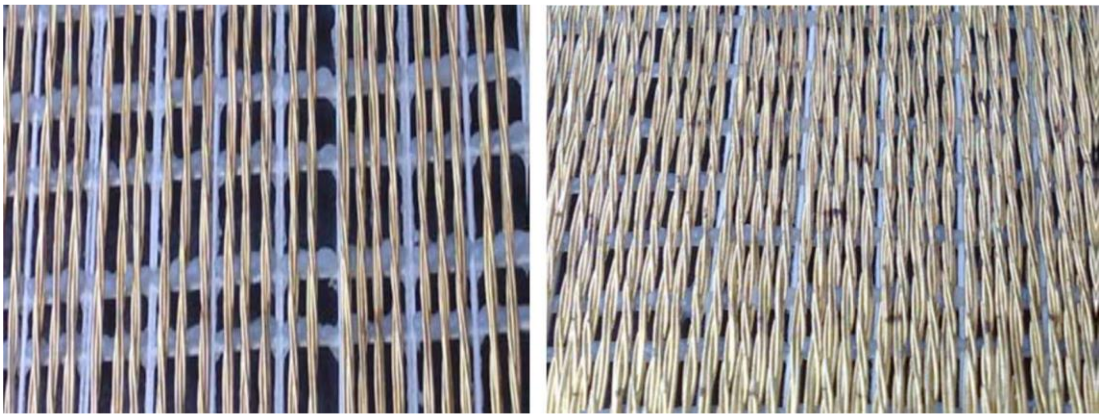


Figure 6. hardwire steel-fiber sheets [131].

3.1.4. Fabric-reinforced cementitious matrix (F.R.C.M)

Recently, TRM, or F.R.C.M systems, had emerged as a critical alternative to traditional reinforcing materials in construction [80]. Additionally, compared to epoxy resin used in FRP systems, F.R.C.M performs better on concrete substrates. Since ultra-high-performance fiber-reinforced concrete (UHPFRC, Figure 7) had better at preventing heat, fire, its bond with the mortar matrix of this system had stronger.

Because of this system's superior heat and fire resistance, the mortar matrix forms a solid connection with UHP-FRC [135]. In contrast to conventional FRP, FRCM makes use of continuous, highly-strengthened fibers embedded in a matrix. Numerical techniques were used to test and analyze the flexural reinforcement of whole RC beams utilizing UHPFRC strips [136]. UHPFRC layers were used to improve two beams, and steel bars were added to two more beams. It was discovered that adding steel bars to the layers could result in an 89% improvement in load-bearing capability. Giese et al. [137] found that the ultimate load growth for 2, 3, or 4 layers was 31%, 54%, and 72%, respectively. A new method for upgrading RC beams with a bonded and cast steel-bar-reinforced mortar layer (RML) was investigated by Alharthi et al. [138]. For beams with bonded steel RML, an increase of up to 113% above the CB was obtained, making this approach suitable for RC elements without concrete cover (CC) and with narrow widths.

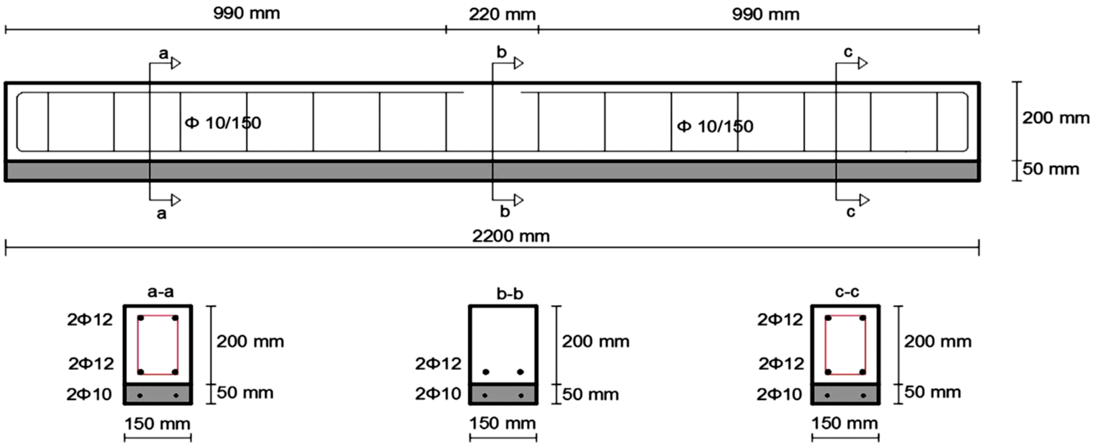


Figure 7. Strengthening using UHPFRC [135].

3.1.5. EB-Hybrid-bonded FRP technique (H.F.B-FRP)

Preventing debonding could be achieved by using H.F.B-FRP, which uses a steel plate as a permanent mechanical fastener held in place using rods and nuts (Figure 8) [139]. Zhou et al. claim that [140], Comparing this technology to the U-jacketing strengthening method, the capacity of the beams had enhanced by up to 2.13 times. Additionally, it successfully prevented FRP debonding issues. Zhang et al. claim state that [141] FRP debonding failure had the recommended method for the H.F.B-FRP combination because it had more ductile. Because it offers dependable, quick, and economical flexural reinforcement, the mechanical fastening technique (M.F) has been suggested as a good substitute for EB techniques [142]. [143] investigated the failure envelope of R.C beams reinforced using a hybrid technology that blends EB/MF methods with reduced-size of FRP strips. The shear force of the modified beam was over 65% higher than that of the CB. Lastly, [144] suggested a mixed anchoring method for FRP sheets that combined E.B, ending anchorage. These had secured to concrete using pre-planted bolts after being self-locked into slotted plates. Either the FRP ruptured or the concrete had crushed as a result of this approach, which also increased ultimate strength, failure ductility.

3.1.6. EB-precast thin layers

Hamdy M. Afefy et al.[145] reinforce a double-spanned, full-scale RC beam with precast thin layers. Precast was included into the concrete cover to reinforce both positive and negative zones with 20 mm thickness and 150 mm width. Four concrete beams were put to the test, two reference beams were un-strengthened, while the other two were. The first beam was strengthened using form of plain type without any reinforcement, while the other was strengthened using an embedded ductile smooth steel sheet extended along the entire strip of 2mm thickness and 100mm breadth. The experimental findings demonstrated that the strengthening system significantly enhances the load-carrying capability and failure mode. In comparison to the CB, the adoption of a plain precast layer increased the ultimate load by 6% and improved the moment redistribution ratio by 33%. The precast layer's rupture failure was replaced with delamination without slippage in the embedded steel sheet and matrix when the strengthening system was applied to the reinforced precast layer. This allowed the precast layer to reach its maximum tensile capacity. Additionally, there was a 36% increase in maximum deflection and a 34% and 41% increase in yielding and ultimate loads, respectively.

Figure 8. Flexural strengthening using H.F.B-F.R.P [139].

3.1.7. Factor affecting the EB technique

The following discusses the variables influencing the E.B technique, links them to research done to look at how they affect the flexural characteristics of members that had strengthened by EB.

- The FRP characteristics, area

The stress transfer lengths and ultimate loads were enhanced in [109] by increasing the volume fraction of steel fibers and utilizing multiple layers of FRP in the EB approach. Furthermore, in [127], The flexural strength of beams reinforced with two layers of side-bonded CFRP laminates was as much as 93.4% greater than that of the CB. It was discovered that the more CFRP layers added, the higher the final strength of continuous beams composed of reinforced high-strength concrete (HSC). In contrast to natural flax FRP (N-FRP) plates, it was proposed in [113] that GFRP, CFRP, and steel plates might have a greater effect on the beam's final lateral load-carrying capacity [146,147]. Deng, Xiao [116] discovered that bearing capacity rose in proportion to the amount of prestressed A-FRP layers, Nevertheless, the number of A-FRP sheet layers had not always directly correlated with this increase. The biggest benefits in terms of strength, affordability, environmental concerns had found to be found in four layers of N-FRP laminates, which had a sectional area 6.67 times that of CFRP laminates [148]. Concurrently, greater cracking stresses had noted as N-FRP thickness rose [149].

- The bonded length

According to Chen et al. [146], jute-F.R.P had more likely to rupture than CFRP, flax-FRP due to its shorter length. When paired with the right type of end anchorage, it was shown that RC beams strengthened with CFRP plates that enclose at least 25% of their shear span had an effective strengthening technique that lowers expenses and material consumption [126].

- The F.R.P sheet width

The side E.B. (S-EB) reinforcement for the RC beams loses criticality when the centroid of the CFRP sheets approaches the section's neutral axis because the fiber's total depth and moment arm both decrease [131,146]. On the other hand, in [127], The ultimate loading capacities of 50 mm, 100 mm, 150 mm wide beams reinforced with carbon fiber sheets increased by 39.7%, 66%, 87.2%, respectively compared to the CB.

- The environmental critical

A year of immersion in a 35 g/L NaCl solution had no discernible effect on the load capabilities of A.F.R.P-strengthened beams. Additionally, the biggest average growth (up to 8.5%) had recorded by specimens submerged for 360 days [106]. According to [147], Dry heat had used to further boost the beam load since it increased the bonding polymer's cross-linking density.

- Anchorage systems

Since the beams' lack of anchorage caused the plate ends to de-bond, anchorages play a crucial role in the failure process. The EB with end anchorage, on the other hand, created localized debonding between the anchors. The U-wrap with end anchors seemed to be the most critical arrangement in [150]. In [149], The ultimate loads rose by 13%, 21%, respectively, when the sisal-FRP strengthening had bonded with end anchors for reinforcing the RC beams using polyester and epoxy resin. Additionally, bolting could greatly improve the ductility of the beam in [112]. However, the bonded A.A plate's load capacity had greater than that of the bolted, bonded A.A plate due to the presence of drilled holes. The holes caused the cross-section area to diminish, which lessened its contribution under stress, as highlighted in [144], preventing end debonding, limiting the development of intermediate crack debonding.

- Epoxy

The importance of selecting the right epoxy for FRP strengthening has been shown, especially in maritime environments. A-FRP sheet affixed to the tension side of a concrete beam using polyoxy-propylenediamine hardener/epoxy resin demonstrated higher flexural strength and ductility than either a modified amine/epoxy resin blend or an amine saturant/solvent-free epoxy at room temperature [151]. However, the environmental advantages of natural fibers had nullified by excessive epoxy resin [148]. Sisal-FRP with epoxy resin outperformed sisal-FRP with polyester resin in terms of mechanical properties [149]. This led to a 36% increase in ultimate load over the CB. On the other hand, beams reinforced with NFRP, epoxy had a maximum load that had 68% higher than the CB.

- Cost

The considerable amount of epoxy glue employed in the composites limits the cost advantage of natural fibers over carbon fiber [148]. Among the several natural and synthetic fibers, unidirectional flax showed the greatest cost-criticalness and significant benefits [146]. In addition, Salih et al. [65] conducted a number of experiments to strengthen and repair beams with varying degrees of flexural and shear damage utilizing a variety of repair/strengthening methods, including mechanical steel stitches (MSS), steel plate (SP), and carbon fiber-reinforced polymer and the cost of every kind of strengthening was determined. It was founded that the MSS method practicality, economic feasibility.

3.2 EB Technique

By enhancing the flexural and shear strengths of RC elements in structures, NSM-FRP has gained popularity. Using this technique, the FRP reinforcement is bonded into prepared concrete cover grooves (Figure 9). The NSM-FRP technology has several uses in reinforcing concrete structures and has many benefits over the EB-FRP technique [152,153]. The biggest advantage is focusing on the surface preparation tasks required to apply NSM reinforcement. The NSM is categorized based on the location of the grooves where the bottom-near-surface mounting of the strengthening bars is placed. (BNSM, Figure 10a) [11,46][154] and side-near-surface mounted (SNSM, Figure 10b) [155].

According to the BNSM approach, in slits created inside the bottom cover of the concrete using cement mortar or epoxy, longitudinal steel bars must be placed next to FRP or steel reinforcement [18–20] [67–70]. Conversely, using the SNSM method, the grooves had located on the beam's side concrete cover [4] [21–23] [71-72]. The BNSM outperforms the EB-FRP component in terms of bond performance, protection, surface preparation [100,166,167]. Furthermore, in comparison to the EB technique, the BNSM technique improved ductility, raised failure limits [27–29]. Consequently, the BNSM approach had critically chosen for RC strengthening since it appears to had benefits over the EB approach [100,171]. Despite the BNSM-FRP approach's benefits, it's vital to be aware of some disadvantages, like the debonding of strengthening materials, the separation of concrete covers before the BNSM materials reach their maximal tensile strength or concrete compression failure [31-32], [74]. The ductility of beams had critically reduced by the BNSM method. [18,19,169,170,176,177].

Table 1 Studies on RC beams strengthened with EB technique

Author	Method and epoxy	Samples parameters	Pu (%)	Deflection (mm)			Failure mode	Ductility index	
				δy (mm)	δu (mm)	δf (mm)		μΔult ($\delta u/\delta y$)	% Dec
Salama et al. [127]	(Bottom or side-bonded) of the CFRP sheets and V-wrap 700 epoxy adhesive	Bottom sheets, 1 ply	62.0	8.0	18.3	18.4	SC-F	2.28	16.8
		Bottom Sheet,2Plies	92.0	8.7	15.3	15.3	S-F	1.77	35.6
		Side Sheets, 1 plie	66.0	7.0	14.7	15.2	SC-F	2.09	23.8
		Side Sheets, 2 plies	84.4	8.8	12.9	13.1	SC-F	1.68	38.8
		SSB, 1 Ply 50 mm	39.7	7.6	14.4	14.8	SC-F	1.89	31.1
		SSB, 1 Ply150 mm	87.2	9.8	16.5	16.8	SC-F	1.47	46.4
		SSB, 2 Ply 50 mm	58.8	7.6	13.1	13.3	S-F	1.69	38.4
		SSB, 2 Ply150 mm	93.4	8.9	15.1	15.9	SC-F	1.74	36.7
Chen et al. [146]	Two types of FRP: flax and jute	2-layer CFRP	32	11.61	28.13		S-F + Fr	2.42	21
		2-layers—jute fabric	17	8.98	18.33		Fr	2.04	33
		3-layers -jute	0	9.83	12.88		Fr	1.31	57
		4-layers-bidirectional flax	18	9.78	26.15		Fr	2.67	13
		8-layer unidirectional flax	40	11.61	35.01		S-F+Fr	3.02	2
Huang et al. [147]	FFRP	2Ø8 mm- 4 layers	67	2.7	17.2	19.23	SFr	6.5	+ 160
		2Ø8 mm- 6 layers	105	4.0	23.4	24.74		5.9	+ 136
		2Ø12 mm- 4 layers	15	5.2	19.3	22.13		3.7	+ 48
		2Ø12 mm- 6 layers	21	5.4	21.9	22.34		4.0	+ 60
	FFRP applies 80% of Py of the CB	2Ø8 mm- 4 layers	71	2.4	16.9	17.90		7.1	+ 180
		2Ø8 mm- 6 layers	113	3.3	22.8	23.89		7.0	+ 180
Abdallaa et al [172].	3 mm thick AA-plates oriented at 90° and 45°, Sika	oriented at 90°	19	5.74	5.74	5.75	SH	1.00	–
		oriented at 45°	39	6.29	8.23	9.57	SH	1.16	–

Table 1 (continued)

Author	Method and epoxy	Samples parameters	Pu (%)	Deflection (mm) δy (mm)	δu (mm)	δf (mm)	Failure mode	Ductility index μΔult ($\delta u/\delta y$)	% Dec
Rasheed at al. [110]	2 mm thick AA plates or 3 mm thick AA plates, with single and double- end CFRP sheet U-wraps by Sikadur-330 with SikaWrap-300C for CFRP sheet	2 mm AA Plates	15.3	7.13	28.19	34.75	IC	3.95	+ 13
		2 mm AA Plates	13.3	6.23	22.85	27.08	IC	3.67	+ 5
		2 mm AA Plates U-wraps	24.8	6.15	20.44	34.53	IC	3.32	5
		2 mm AA Plates 2U-wraps	21.4	7.18	48.15	48.15	IC	6.71	+ 90
		3 mm AA Plates	40.0	7.20	25.16	25.92	IC	3.49	0
		3 mm AA Plates 1U-wraps Anchorage	29.2	6.65	21.37	29.55	IC	3.21	9
		3 mm AA Plates 2U-wraps Anchorage	26.2	6.82	24.71	37.56	IC	3.62	+ 4
Hawileh et al. [131]	HSF width= 40,70,100,120 mm and Sikadur 30LP	1-layer Med-density steel sheet	44.0	10.3	17.82	18.3	SC-F	1.73	13
		2-layer med-density steel sheet	56.4	9.32	11.51	12.2	SC-F	1.23	38
		1-layer of high-density steel sheet	47.8	11.2	15.8	16.15	SC-F	1.41	29
		2-layer of high-density steel sheet	62	8.62	12.1	12.1	SC-F	1.40	30
		2-layers of high-density steel sheet	41.6	9.31	14.25	14.3	SC-F	1.53	23
		2-layers of med-density steel sheet	29.3	10.5	12.85	14.14	SC-F	1.22	39
		2-layers of med-density steel sheet	33.4	10.4	12.18	13.12	SC-F	1.17	41
		1 layer of CFRP	57.3	8.59	18.55	19.39	SC-F	2.16	38
		1 layer of GFRP	30.8	7.40	20.69	23.21	SC-F	2.80	20
		1-layer GFRP / CFRP	83.0	7.80	15.75	20.10	SC-F	2.02	42
		1 GFRP/ CFRP/ GFRP	98.0	8.86	14.11	26.90	S-C	1.59	55
Zhou et al. [144]	epoxy resin (Good-bond JN-C3P)	CFRP sheets	9.47		25.48		IC		-
		1 CFRP sheets + hybrid anchored	24.2		56.56		FR		-
		2 layers CFRP sheets + 2 plies hybrid anchored	45.2 6		51.76		SC-F		-

3.2.1. Flexural strengthening with NSM-FRP bars

Beams updated with NSM had an ultimate load that was 12–18% greater than beams updated with E.BRs when the same amount of CFRP had been employed [19], as shown in (**Figure 11**). In [28], the flexural behavior of R.C beams reinforced with NSM-FRPs had examined utilizing either carbon or glass with two different approaches (NSM or hybrid). Furthermore, experiments were carried out to ascertain the effects of the proportion of tension steel reinforcement, the quantity of fiber (one or two bars). The findings showed that the ultimate capacity increased by almost 85% when the amount of FRP had doubled (**Figure 12**). Additionally, the ductile response of the improved NSM-GFRP beams was good. However, Kotynia [21] came to the conclusion that the performance of the FRP-concrete bond was impacted by the internal steel reinforcement. According to Almusallam et al. [46], It might be possible to successfully recover the load capacity of RC beams with corroded steel reinforcement by using GFRP bars or NSM steel with sufficient end anchorage. [9] states that yielding loads increased by 29% and 50%, respectively, in CFRP and GFRP strengthened RC beams, whereas ultimate loads increased by 60% and 66%, respectively.

Additionally, the NSM technique critically increased the stiffness and load capacity of RC beams, depending on the strengthened material. However, increasing the number of strengthened bars from one to two resulted in a 7.5% increase in maximum loads, a 25.6% increase in yield. Furthermore, the inclusion of two NSM-GFRP bars increased the beams' yielding and maximum loads by 11.7% and 13%, respectively, in comparison to beams reinforced with a single GFRP bar (Figure 13). Regardless of whether mortar or resin had used as a filler, CFRP rods had found to be extremely critical in enhancing the flexural strength of RC beams by Al-Mahmoud et al. [156]. There had a debonding from the groove in the CFRP rod with mortar strengthened beam.

Furthermore, as Sakar et al. [178] had shown, GFRP rods had an efficient NSM strengthening technique that raises the ductility, load capacity of RC components during cyclic loading. Four upgrading techniques were introduced in [179].: NSM-CFRP bars, NSM stainless steel bars, EB-CFRP sheets, and E.B-steel-reinforced polymer (SRP) sheets. According to the findings, the flexural system's premature debonding and delamination failures had successfully avoided by the ductile flexural response that external FRP transverse strengthening offered.

Figure 9. N.S.M F.R.P strengthening technique [63]

[180] demonstrated how the reaction of the larger RC beams was impacted by the prestressed NSM-CFRP system. It had found that the more prestressing forces applied to the RC beam, the greater its strength and the ultimate load

at which it split. Additionally, crack resistance had increased by using post-tensioned NSM enhancing systems. The pre-tensioned NSM-strengthened RC beams with two bars also shown increases in maximum loads, steel yielding, and concrete cracking of roughly 17.8%, 8.4%, and 2.8%, respectively, as compared to single bars. Nonetheless, a slight prestressing effect on the deflection was seen at yield load and cracking. However, prestressing critically affected the final deflections. Only 50% of the C.F.R.P rupture strength should be prestressed into the R.C beams, per the recommendation. Similarly, prestressed N.S.M F.R.P reinforcement of R.C beams increased their yielding, cracking loads as the prestressing levels increased in [181], despite having no effect on the ultimate loads.

3.2.2. Flexural strengthening with NSM-FRP strips

Gil et al. [182] looked at the critical of post-tensioning strengthening with prestressed, non-prestressed NSM-BFRP laminates in the concrete gaps. Despite the CB's 63% higher ultimate load, neither type's deflections had affected. Cruz et al. [183] studied beams reinforced with NSM-CFRP strip bonded with stiff, flexible adhesives. Based on the findings, using flexible adhesives rather than stiff ones reduced the load-carrying capability by less than 19%. As a result, it also increased residual load capacity (61% augmentation), ductile failure.

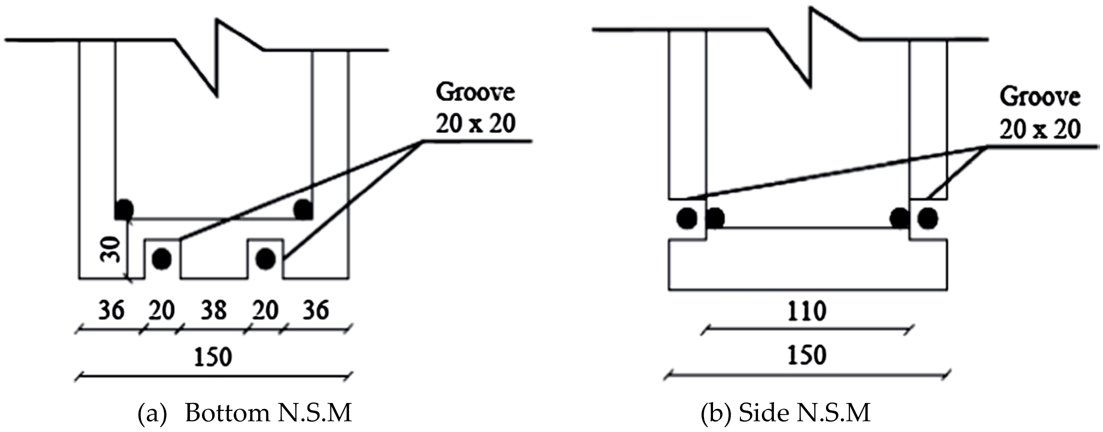


Figure 10. Bottom N.S.M, side N.S.M positions [154].

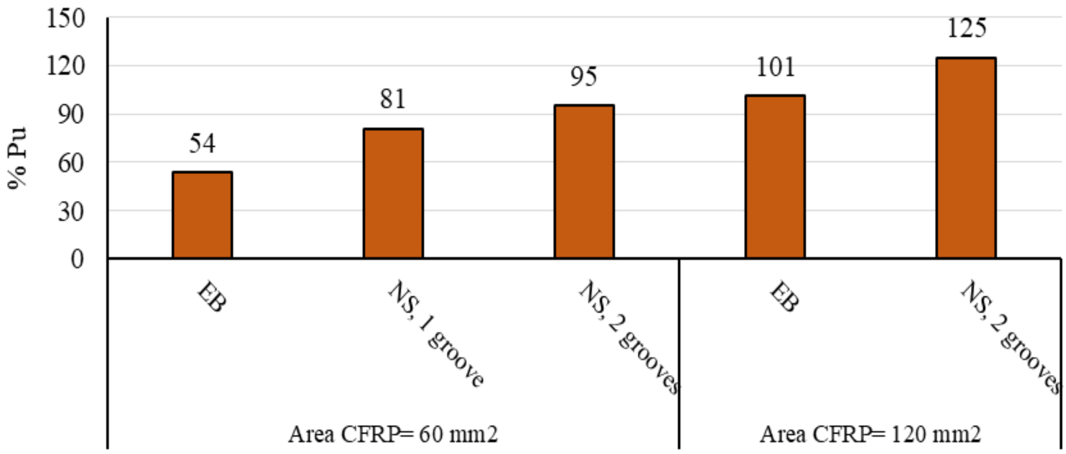


Figure 11. The load efficiency of RC beams strengthened by NSM, EBR techniques [19].

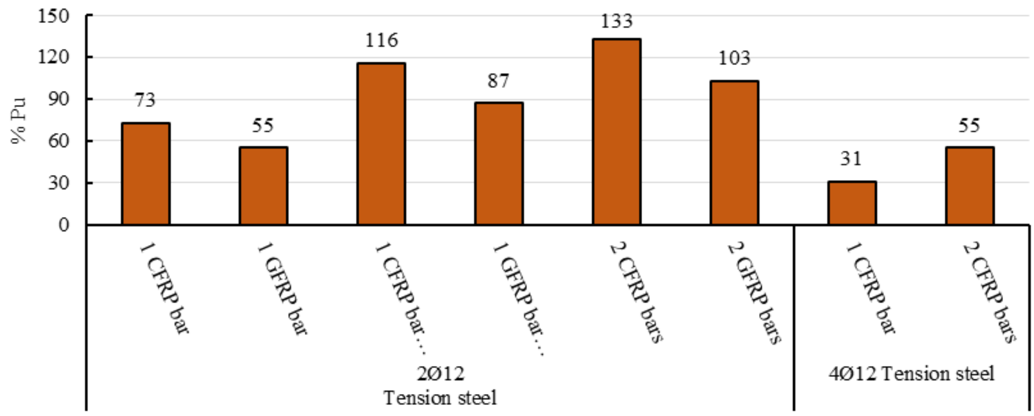


Figure 12. The amount of the FRP strengthening effect on the R.C beam load efficiency [28].

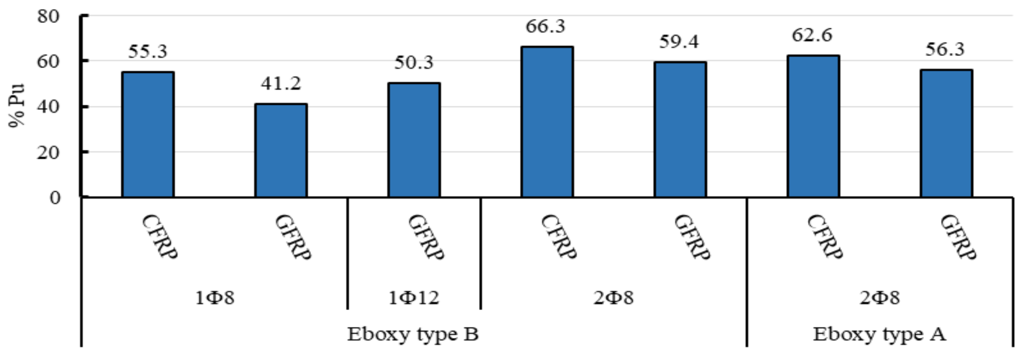


Figure 13. The effect of NSM-CFRP, and GFRP bars numbers on the beam load efficiency [9].

In [184], EB and NSM methods were employed to reinforce one-way RC slabs. When NSM strips were used instead of EB strips, Comparing the slab to the CB, the load capacity increased by around 51.7%.

3.2.3. Flexural strengthening with SNSM FRP bars

Pullout, early debonding had examples of non-traditional failure modes that could be avoided with side NSM (SNSM) strengthening in [185]. In addition, increasing the CFRP bar length raised both the beam failure load, the CFRP strain (Figure 14). Additionally, CFRP rods that had placed near internal steel reinforcement, embedded in resin worked better than those that had placed in mortar or above the steel reinforcement. Additionally, Zhu et al. [186] has assessed the SNSM-CFRP approach's performance on large-scale RC beams. The flexural capacity of the upgraded beams had increased by either decreasing the CFRP spacing or raising the degree of prestressing [187].

The use of BNSM and SNSM-GFRP bars to reinforce GFRP R.C beams had investigated by Ahmed, colleagues [30]. According to the results of their investigation, SN.S.M G.F.R.P bars showed greater ductile failure than BN.S.M bars.

3.2.4. Flexural strengthening with EB, BNSM metal bars

EB-CFRP sheets, EB-steel-reinforced polymer (SRP) sheets, and NSM stainless steel bars were used to strength the RC beams [179]. The results showed that external FRP transverse strengthening prevented early debonding and delamination failure of the flexure system by exhibiting a ductile flexural response. In [188], high-strength A.A bars enhanced the flexural stiffness of the beams while decreasing their ductility in comparison to the unenforced ones

(Figure 15). According to Imjai et al. [189], the pre-cracked post-tension metal strapping (PTMS) strengthened beams' capacity was only 8% greater than their CB. Conversely, the increased flexural increase provided by the FRP bars allowed the SNSM to enhance the beam's capability to 55%.

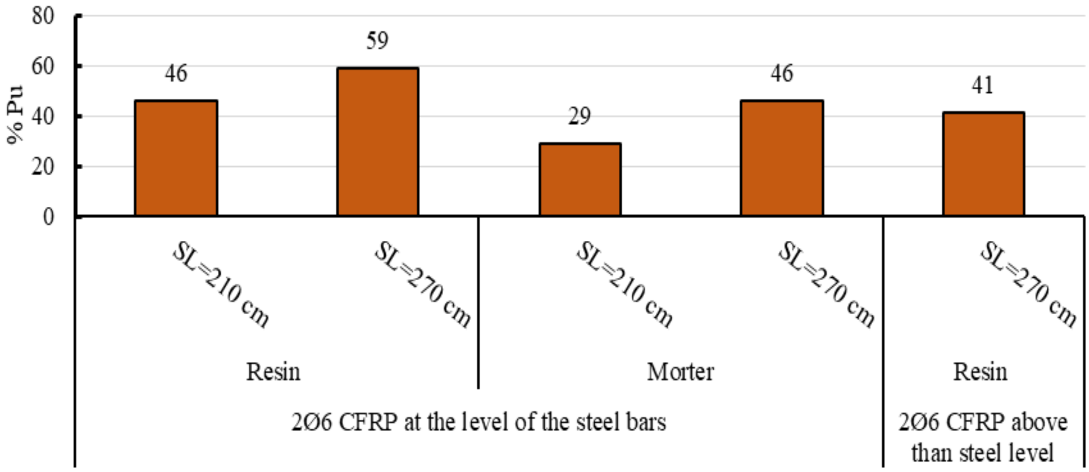


Figure 14. Effect of bars length, position on the beam efficiency [185].

3.2.5. Flexural strengthening with NSM hybrid steel-FRP bars

A. Ali et al. [63] investigated the critical of using hybrid steel-GFRP, and hybrid steel-CFRP bars as strengthened bars. These bars boost the load of reinforced beams by 90.6%, 94.3%, respectively, according to the CB. Doubling the area by using two hybrid bars instead of one increased the beams' capacity to 106.90 kN, 109.20% kN, respectively, by augmenting the load capacity by 101.70%, 106% above the CB (Figure 16).

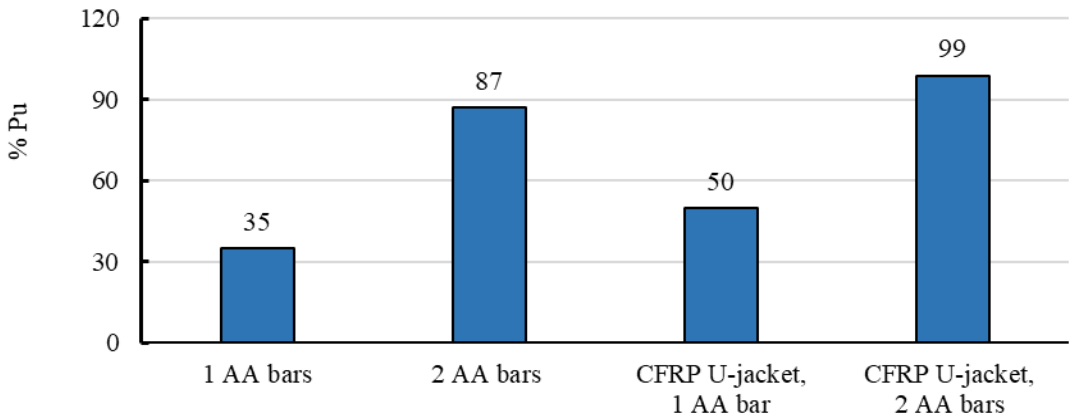


Figure 15. The % Pu by increasing the number of the A.A bars, C.F.R.P U-jacket [188].

3.2.6. Shear strengthening with N.S.M F.R.P bars

In [190], With an a/d (shear span to depth ratio) of 0.85, N.S.M strengthening of the beams raised the load capacity from 7.35-20.56%. The range of the load increment for beams with an a/d=1.136 had 8.13 to 15.45% (Figure 17). According to the findings in [191], the shear-strengthened RC beams demonstrated higher load efficiency than its CB, irrespective of the major stirrups area, NSM shear strengthening forms. Compared to the CB with the same steel area as stirrups, the beam strengthened in shear by had a slightly higher load efficiency. In addition, in terms of increasing the load capacity, stiffness of RC beams, using the reinforced high-strength concrete layer (R.H.S.CL) as NSM shear strengthening had more successful than employing NSM bars. In [31], RC beams with steel or GFRP bars as the primary reinforcement had strengthened using NSM GFRP or steel bars. The R.H.S.CL layers additionally use steel bars or GFRP that are linked together in side grooves to strengthen the beams' shear strength. The GFRP-bar reinforced beams were found to be less rigid and to have a lower shear efficiency when compared to steel-bar reinforced beams under tension. However, steel RC beams strengthened in shear using internal stirrups or NSM reinforcement (or both) had a shear efficiency that increased by 142.8–211.7% in comparison to GFRP-RC beams without any shear reinforcement. Comparing the steel-RC beams strengthened in shear using internal stirrups or NSM reinforcement (or both) to the identical beam without shear reinforcement, however, revealed that the shear capacity increased by 153.5–279.9%.

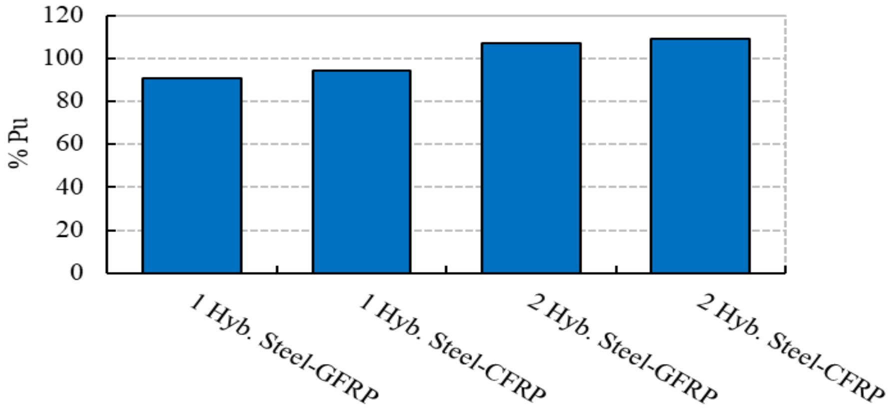


Figure 16. The % Pu by changing the number, the type of the hybrid bars [63]

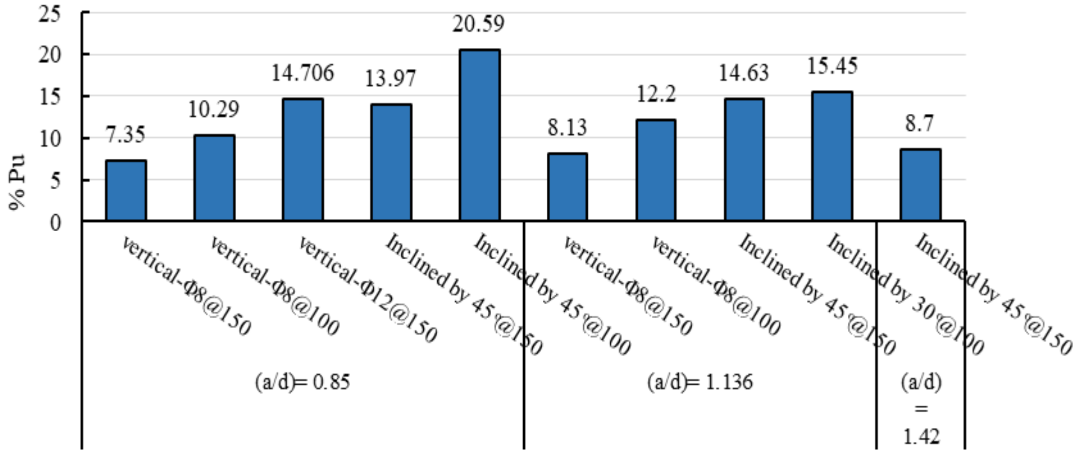


Figure 17. The load efficiency of the beams with a/d ratio [190].

3.2.7. Factors Affecting the NSM Method

- Type of N.S.M FRP material

Compared to those reinforced with GFRP bars (141.2%-159.4%), the CFRP-strengthened beams achieved loads ranging from 155.3% to 166.3% [9]. Even though CFRP bars supported more weight, also the brittle behavior of the CFRP-strengthened beams had greater [28]. Using the NSM-A.A system improved the reinforced beams' flexural performance by more than 35% [188]. When compared to the control corroded slab in [192], the slabs reinforced with two or four NSM–basalt FRP (BFRP) bars showed improvements in yield load of 32–42%, ultimate loads of 45–50%, respectively. Ys, CC failed. Given that Ys, CC failed, the slab capacity should be slightly impacted by the NSM bars' material (GFRP or BFRP). Along the same lines, to compare beam strengthening using different materials, strengthening the beam with the same reinforcement area of steel, GFRP, and CFRP resulted in an increase in the beam’s load capacity by 60.6%, 78.7%, and 81.1%, respectively [63]. When compared to GFRP bars, CFRP bars' greater stiffness may postpone the internal steel's yielding, maintain the beam's stiffness above that of NSM and GFRP bars following internal steel yielding, and tend to enhance the yielding load capacity [187]. However, when using hybrid steel-FRP bars either glass or carbon fiber by A.Ali et el. [63], the maximum load capacity of the beam is only increased slightly by about 4 to 6% compared to beams strengthened with fiber bars alone. On the other hand, the beam’s ductility is significantly improved.

- The amount N.S.M reinforcement

According to [28], In comparison to the CB, the maximum recorded crack width decreased by around 8% and 28%, respectively, when one or two G.F.R.P. bars were present. Despite the negative impact on deflection, the application of a high reinforcement area significantly boosted energy ductility, flexural capacity, and pre-yield stiffness [9,46,193,194]. Specifically, depending on the groove depth, the ultimate load rose by 19 to 74.5% when two GFRP strips had placed in a single groove rather than attached in separate grooves [195]. Using NSM-CFRP strips spaced out over two grooves rather than one could boost the ultimate load, reduce crack widths [19]. The hybrid technique of NSM and EB beams has lower capacities than NSM beams with two bars [80]. Compared to NSM beams with two bars, the NSM and EB hybrid method showed lower capacities [82]. The basalt-fiber strengthening efficiency had critically impacted by the inner steel area [184,196]. Slabs with a smaller primary reinforcement area had the highest load efficiency [184,196]. The shear capacity of the beam improved by 6.85% when the diameter of the vertical strengthening bars had raised from 8 mm to 12 mm [190]. When the diameter of NSM-GFRP bars was raised by 50%, the specimens experienced the same type of failure, with a 75.2% increase in failure load [67]. Furthermore, Shabana [197] strengthened the RC beam using one and two NSM CFRP bars, and it was founded that doubling the fiber reinforcement area does not significantly increase the beam’s maximum load capacity due to the concrete cover separation failure. However, a significant increase in ductility was observed. This is completely consistent with what Ali [63] presented when strengthening beams using two NSM-hybrid steel-FRP bars instead of one bar and the beam carrying capacity only increased by 5% only. However, the yielding load was increased by 32%, which led to a noticeable improvement in the beam’s ductility.

- The N.S.M bonded length

For flexural retrofitting, lengthening the bonded lengths of CFRP plates might improve their criticalness in strengthening, rebuilding concrete [86]. It had demonstrated that extending the carbon fiber rods by 60 cm increased their criticalness as reinforcing materials by preventing peeling off or delaying debonding failure [185]. In addition, the beam's ultimate strength and ductility increased when the FRP bars' and strips' bond lengths increased and the clear distance decreased [177]. This backs up the idea that short CFRP lengths might affect how well it works, heals. Both the NSM efficiency, the beam capacity rose until the bond length (Lb) reached a threshold value. After that, as Lb increased more, the growth rate decreased [156,166,177,198]

- The positioning of the NSM bars

In comparison to those with vertical bars, the R.C beam load capacity increased by 9.33% when the shear-strengthening NSM bars had positioned in an inclined configuration [190]. Nevertheless, the yield, ultimate load-carrying capacities of the C.F.R.P-strengthened beam had marginally lower than those of the main tension steel because the C.F.R.P rods generated extra tensile stress above the steel bars' level [185].

- Anchorage system

The FRP bars could be surrounded by a fire protection board to ensure that anchoring had maintained in the presence of high temperatures [199]. According to studies, the use of these mechanical anchorages had increased the beams' overall load-carrying capacity by 6% to 12% [188]. The use of mechanical interlocking grooves in [200] marginally increases the load-bearing capacity while having no influence on the strengthened beams' ductility.

- Epoxy

Sharaky et al. [9] used two kinds of epoxy resin (A, B) in their experiment. POLYFIXER EP (ROBERLO) had type B, MBRACE ADHESIVE HT (B.A.S.F) had type. A comparison of the average properties of the two resins revealed that Type A had a modulus of elasticity of 5761 MPa, a compressive strength of 70.2 MPa, and a tensile strength of 18.9 MPa. Type B, had 8000 MPa, 95.5 MPa, 23 MPa respectively. Since failure was controlled by the separation of the concrete cover, the results showed that the type of epoxy used had little effect on the yielding, ultimate loads. When flexible adhesive was used instead of mortar filler for post-tensioned N.S.M. strengthening, the results showed improvements of 16% on uncracked series and 28% on fractured beams. In addition, CFRP continued to contribute after the adhesive's maximum load-carrying capacity, which led to a residual load capacity after failure that had about 40% greater than that of steel reinforcement [183]. The bond efficiency of the CFRP, steel bars used in the embedded through-section approach had critically decreased at 90 °C (90, 94%, respectively) in [201]. On the other hand, the kind of epoxy had no effect on the rigidity of the reinforced slabs but had a minor impact on their ability to support loads [196].

4. Conclusions and Future Work

1. In the flexural strengthening of RC beams, the NSM FRP strengthening method is more effective than the EB FRP method. As, it was observed that the NSM beams' ultimate load was 12–18% greater than the EB-reinforced beams. Also, NSM CFRP strips outperform NSM FRP bars of various sectional forms (like round bars and square bars) because of the former's higher perimeter-to-sectional-area ratio.
2. Concrete cover separation (CCs) is a common failure mode in beams strengthened with NSM-FRP reinforcements. Unfortunately, the NSM bars are not used optimally, as the separation occurs before the strain in the strengthened bars reaches the rupture strain. On the other hand, EB-beams mostly fail due to delamination, and IC debonding.
3. In comparison to straight bars, strengthening with end-anchored bars or using FRP U-jacket was particularly efficient in postponing the CCs failure and improving the ultimate load with percentage range 25%: 30%. This is because, in addition to serving as shear dowels at the epoxy-concrete interface, the end anchors supplied a clamping effect. However, end anchoring had little effect on the efficiency of the EB/NSM when the failure mode had IC, CS, or FRP rupture.
4. When compared to the completely bonded bar, un-bonding the NSM CFRP bar reduced the effective pre-yield stiffness by about 11.0% but had no influence on the ultimate carrying capacity. Therefore, the epoxy required for bonding the reinforcement bars can be conserved by not using it along the entire length of the NSM-bar.
5. The NSM-CFRP strips, with their high perimeter-to-area ratio, had the highest efficiency among all other NSM FRP shapes (round bars, square bars), the NSM reinforcing approach performed better than the EB strengthening method for strengthening RC beams in flexural loads.

Table 2. Studies on RC beams strengthened with NSM technique.

Authors	Method and filling	Specimen designation		%Pu	Δy (mm)	Δu (mm)	Failure mode	$\mu_{\Delta u}$= Δu/ Δy
AI-Issawi et al.[202]	(a/d) ratio	*a/d*=0.85, Ø8 mm CFRP, vertical inclination	150 mm spacing	7.35				
			100 mm spacing	10.29			SH	
		a/d= 0.85, Ø12 mm CFRP	150 mm spacing vertical inclination	14.70				
		a/d= 0.85, Ø8 mm CFRP, inclined by 45°	150 mm spacing	13.97			S-Cs	
			100 mm spacing	20.59				
		a/d = 1.136, Ø8 mm CFRP, vertical inclination	CB	-			SH	
			150 mm spacing	8.13			S-Es	
			100 mm spacing	12.2			SCS	
		a/d = 1.136, Ø8 mm CFRP, 150 mm spacing	Inclined by 45°	14.63			F	
			Inclined by 30°	15.45			S-Cs	
		a/d = 1.42, inclined by 45°, 150 mm spacing	CB	-			SH	
			Ø8 mm CFRP	8.7			S-Cs	
Zhang et al. [203]	BFRP and GFRP bars with various bonded length (BL)	Ø8 mm BFRP, C30 MPa	BL =100 mm	4		12.72	S-Es	
			=200 mm	-		10.35	F-C	
			= 300mm	12		13.85		
			= 400 mm	14.5		17.01		
		Ø8 mm GFRP, C30 MPa	=100 mm	7		16.03	S-Es	
			=200 mm	3		14.37	F-C	
			= 300mm	9		17.58		
			= 400 mm	8		18.52		
		Ø10 mm GFRP, C30 MPa	=100 mm	7.7		6.05	S-Es	
			=200 mm	6.11		7.92	F-C	
			= 300mm	17.65		9.96		
			= 400 mm	25.0		14.62		

Table 2 (continued)

Authors	Method and filling	Specimen designation		%Pu	Δy (mm)	Δu (mm)	Failure mode	$\mu_{\Delta u}$= Δu/ Δy
Zhang et al. [203]	BFRP and GFRP bars with various bonded length (BL)	C40 MPa	Ø10 mm GFRP	2.88		19.86		
		C50 MPa	= 400 mm	13.85		15.37		
		Ø8 mm BFRP, C30 MPa	=500 mm	-		28.33		
			=600 mm	-		20.79		
		Ø8 mm GFRP, C30 MPa	=500 mm			24.19	Fr	
			=600 mm			22.48		
		Ø10 mm GFRP, C30 MPa	=500 mm			29.77		
			=600 mm			26.43		
		C40 MPa	Ø10 mm GFRP			32.81		
		C50 MPa	=500 mm			29.8		
Hong and Park [204]	prestress levels of CFRP-NSM plate -with and without transverse grooves (TGs)	1 plate		42	13.3	50	F-c	
		1 plate, Prestressing force 10%		73	12.4	62.1		
		1 plate, Prestressing force 20%		79	12.1	52.8		
		1 plate, Prestressing force 30%		85	12.7	59.0		
		1 plate, Prestressing force 50%		85.6	13.7	49.6		
		1 plate, Prestressing force 20%+TGs		91.6	12.9	43.8		
		1 plate, Prestressing force 50%+TGs		96.1	14.2	46.7		
Sharaky et al. [205]	BBRACE ADHESIVE (BASF)	1bar CFRP, d = 8mm		55.3		31.7	S-Es	
		2bar CFRP, d = 8mm		66.3		20.3	CCs	
		1 bars GFRP, d = 8mm		62.6		22.0	Fr+Es	
		2 bars GFRP, d = 8mm		41.2		59.7	F-C	
		1bar GFRP, d = 12mm		50.3		35.3	S-Es	
		2 bars CFRP, d = 8mm		59.4		42.4	CCs	

Table 2 (continued)

Authors	Method and filling		Specimen designation	%Pu	Δy (mm)	Δu (mm)	Failure mode	$\mu_{\Delta u}$= Δu/ Δy
Abdallah et al.[185]	SNSM-2Ø6 CFRP rods	Resin Filling	Strengthening length/beam length=0.94	59	15.5	50.4	F-C	3.25
			Strengthening length/beam length = 0.65	46	15.5	22.9	Peeling off	1.48
		Mortar Filling	Strengthening length/beam length=0.94	45.6	15.7	38.2	S-Es	2.43
			Strengthening length/beam length=0.56	29.3	15.8	16.2		1.03
		Resin Filling	Strengthening length/beam length=0.94	41.1	13.6	40.4	F-C	2.97
El-Gamal et al. [28]	2Ø12 tension steel NSM		1Ø10 CFRP bar	73	11	22	F	
			2Ø10 CFRP bars	133	11	26		
			1Ø10 GFRP bars	55	9	61	S-Cs	
			2Ø10 GFRP bars	103	11	54	Fr	
	NSM and EB		1Ø10 CFRP bar + 1Ø10 CFRP sheet	116	12	24		
			1Ø10 GFRP bar + 1Ø10 CFRP sheet	87	11	22		
	4Ø12 tension steel NSM		1 CFRP bar	31	10.5	28	F	
			2 CFRP bars	55	14	25		
Almusallam et al. [206]	2Ø10 steel main bars		1Ø10 steel NSM bar	3		37.14	S-Cs	7.27
			1Ø14 steel NSM bar	41.9		39.51		6.31
			1Ø10 GFRP NSM bar	19		38.75	Fr	7.57
	1Ø10 steel main bars		2Ø10 steel NSM bar	12.8		41.66	S-Cs	7.44
			2Ø14 steel NSM bar	94.9		32.18		4.08
			2Ø10 GFRP NSM bar	26.2		43.91	Fr	8.53

Table 2 (continued)

Authors	Method and filling	Specimen designation	%Pu	Δy (mm)	Δu (mm)	Failure mode	$\mu_{\Delta u}$= Δu/ Δy
A.Ali et al. [63]	NSM steel bar,GFRP bar, CFRP bar, hybrid steel-GFRP bar, and hybrid steel-CFRP bar	1∅12 mm steel bar	60.6	18.8	81.2	CC	4.31
		1∅12 mm GFRP	78.7	20	65	Cs	3.26
		1∅12 mm CFRP	81.1	23.4	36.3	CCs	1.56
		1∅12 mm Hybrid steel-GFRP	90.6	20.6	86.0	Cs	4.19
		1∅12 mm Hybrid steel-CFRP	94.3	21.1	47.5	SH	2.25
		2∅12 mm Hybrid steel-GFRP	101.7	22.4	36.4	CCs	1.63
		2∅12 mm Hybrid steel-CFRP	106.0	--	23.3	CCs	--
Yu et al. [188]	NSM 7075 AA bars	1 ∅16 AA bars	35	11.2	50.09	IC	2.88
		2 ∅16 AA bars	87	10.03	49.06	CCs	2.85
		1∅16 AA bars + CFRP U – jacket	50	11.04	61.80	S-Cs	5.6
		2 ∅16 AA bars + CFRP U – jacket	99	10.35	47.21	CCs	3.82
Deng et al. [207]	CFRP-NSM for UHPC pre-stressed concrete prisms (CFRP-PCPs)	BL= 2200 mm+ 0% Prestress CFRP	59.9		39.2	S-Cs	4.36
		BL= 1000 mm+ 0% Prestress CFRP	7		80.08	F	-
		BL= 1400mm+ 30% Prestress CFRP-UHPC	45.8		75.22	S-Es	-
		BL= 1800mm+ 30% Prestress CFRP-UHPC	56.6		41.43	S-Cs	-
		BL= 2200 mm+ 30% Prestress CFRP- UHPC	67.9		36.33	S-Cs	3.54
		BL= 2200 mm+ 30% Prestress CFRP- Epoxy resin	51.8		32.74	S-Es	-
		BL= 2200 mm, 50% Prestress CFRP- UHPC	55.9		33.5	S-Cs	2.65
Ebead and El-Sherif [208]	FRCM-NSM, 0.5% reinforcement ratio	(PBO)	57.1		28.1	SF	5.73
		CFRP-FRCM	48.4		16.1		3.21
		GFRP-FRCM	31.4		22.9	Fr	5.56
	FRCM-NSM, 1.27% reinforcement ratio	PBO-FRCM	83.5		26.2	SF	3.60
		CFRP-FRCM	84.3		17.5		2.45
		GFRP-FRCM	70.4		21.0	Fr	2.87

Table 2 (continued)

Authors	**Method and filling**	**Specimen designation**	**%Pu**	**Δy (mm)**	**Δu (mm)**	**Failure mode**	**$\mu_{\Delta u}$= Δu/ Δy**
Shabana et al. [197]	2Ø10 CFRP-NSM bars fully and partially 90° end-hooked	1-fully bonded straight bar	56.6	12.7	28	CCs	2.2
		2-fully bonded straight bars	57.3	14.94	15.6	CCs	1.04
		2-fully bonded end-anchored bars	97.9	13.8	20.8	CCs	1.51
		2 partially bonded end-anchored bars 700 mm un-BL	96.6	13.6	25.3	CCs	1.86
		2 partially bonded end-anchored bars 900 mm un-BL	76.2	12.2	20.2	SH	1.66
Attia et al. [209]	(GFRP) or steel -NSM, and U-jacket	3 layers GFRP	22		20.2	F	3.59
		60 mm width of GFRP, folded into 3 layers	19		18.1	F	2.98
		steel plate of 4 mm thickness	37		12.7	F	2.78
		recovering the U- section with steel fiber	14		14.4	F	2.85
		recovering the U- section with 3 strips of GFRP	28		18.6	F	2.93

Author Contributions: A. Ali: Conceptualization, methodology, writing original draft, revised editing, validation, formal analysis, data curation. **I. A. Sharaky**: Conceptualization, methodology, writing original draft, revised editing, validation, formal analysis, data curation, editing. **A.H.H. Khalil**: Conceptualization, methodology, writing the first draft, revised edits, validation, formal analysis, data curation, editing. **Mohammed M. Attia:** Conceptualization, methodology, writing the first draft, editing it after it had revised, validation, formal analysis, data curation, editing. All authors have read and agreed to the published version of the manuscript."

Funding: This research received no external funding

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