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Review Article

# Shear Strengthening of RC Beam Using FRP Composite in Various Techniques: A Review

**Rafal A. Hadi** [1]•, **Raid A. Daud** [2] •

*1,2, Department of Civil Engineering, Al Nahrain University, Baghdad-Iraq.*

•*These authors contributed equally to this work*

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## Abstract

This research reviews existing literature on RC beams strengthened techniques for shear. Research indicates that fiber-reinforced polymers (FRP) are best utilized and effective materials to enhance RC beams. These materials have corrosion resistance and exceptional strength. The strengthening of reinforced beams by FRP depends on the nature of fiber, arrangement, materials, and manner of strengthening. The current article analyzes the properties, advantages, and applications the FRP composites. In addition to the mechanisms of failure, properties, and behaviors of FRP-strengthened reinforced beams undergoing shear with various strengthening techniques such as EB, NSM, and ETS.

**Keywords:** *Shear Strengthening, NSM, EB, ETS, Failure Modes.*

**Corresponding author:** Provide the corresponding author information and publisher here. E-mail address: rafalalgburi95@gmail.com

## 1. Introduction

Rehabilitating Civil Engineering structures is the most challenging assignment for engineers. Rehabilitation and repair of reinforced concrete (RC) structures is crucial due to many factors, including environmental (corrosion of the steel reinforcement within the concrete which can crack and spall the concrete, also repeated freezing and thawing reducing strength and durability of concrete), structural damage ( cracks which affects the load-carrying capacity of the structure and spalling which reduces the cross-sectional area of the concrete and cause damaged to reinforcement) and high future loads (if a structure was not originally designed for these higher loads, it may require strengthening to safely support them.) and changes in codes design (design codes and standards evolve to incorporate new knowledge and better practices, structure that built before might not meet current requirements)

Strengthening RC beams can increase durability, enhancing their service life and capacity also offering stress mitigation from torsion, shear, bending, damage, fatigue, and vibration under specified instances. Strengthening is also often carried out to improve beam strength to satisfy current specifications and to repair deteriorated RC beams [1].

Damaged beams or undamaged modified with FRP materials are common due to their non-corrosive features, excessive tensile strength, stiffness, low weight, resistance to chemicals, minimal thermal transmission, as well as ease of implementation [2-8].

Surface preparation is critical in obtaining an effective strengthening reaction between FRP and concrete. The bond between concrete and FRP materials is critical for conveying stress from RC structures to the bonded FRP [9, 10].

Research continues to improve existing shear-strengthening technologies and develop new ones. Traditional shear-strengthening methods include external bolting, external bonding (EBR), and external prestressing. Steel were then changed by FRP materials due to their lightweight and high-yield strength [11-14]. Additional research resulted in the discovery of the (ETS) method. That effectively addressed the drawbacks of previous shear-strengthening technologies. The ETS approach involves creating holes across the section of the beam, the bars are inserting, and bonding them to the concrete using appropriate epoxy.

This paper offers a concise overview of current FRP-based enhancing and upgrading methods for reinforcing beams.

## 2. Fiber Reinforced polymer (FRP)

Steel plating was once thought to be the most efficient approach to strengthen RC beams. However, it is costly, difficult to apply, has low fatigue resistance, prone to corrosion, and adds dead load to the structure [15]. FRP offers advantages such as non-magnetic properties, simplicity of application, non-corrosiveness, and a good ratio of strength-to-weight, making it the ideal material for repairing and rehabilitating deteriorating RC structures due to its unique properties [16, 17, 18, 15]. FRP was initially used in civil engineering to strengthen and adapt existing structures by external bonding. In the 1980s, researchers focused on the properties of FRP in civil engineering applications. They identified three key fibrous materials:

glass, aramid, and carbon, which may strengthen elements of the structure [19, 20, 21]. Table 1 displays typical material characteristics for CFRP, GFRP, and AFRP [22].

**Table 1.** Some Typical Properties of Carbon, Glass, and Aramid Fibers [22].

| Type of Fibre | Thickness (mm) | Ultimate Tensile Strength (MPa) | Elastic Modulus (GPa) | Ultimate Tensile Elongation (%) |
|---|---|---|---|---|
| Carbon | 0.10-0.25 | 2100-6000 | 215-700 | 0.2-2.3 |
| Glass | 0.06-0.30 | 1900-4800 | 70-90 | 3.0-5.5 |
| Aramid | 0.10-0.30 | 2900-4100 | 70-130 | 2.5-5.0 |

Fiber-reinforced polymer materials can't serve as reinforcements for compression zones in construction projects due to their smaller compressive strength (20%-50%) [23]. Because of their brittle character and lower plasticity, FRP reinforcements before collapse exhibit linear elastic properties and have a small elasticity [24].

Strengthening materials are often chosen based on the materials used in the current construction, strength demands, climate variables, accessibility, and affordability. The ideal usage of several FRP components as strengthening materials has been described, but not compared to one another.

CFRP is less preferable than BFRP because BRFP exhibits significant strain handling at failure [25].

GFRP is very sensitive in alkaline circumstances because of its high silica content, while CFRP is impermeable to any type of alkali [26-28].

But CFRP was preferred over other types of fibers such as GFRP and AFRP in enhancing concrete's expansion and strength due to its excellent modulus of elasticity. Despite CFRP being widely applied and providing greater stiffness than glass fibers that use little epoxy [29], CFRP is more expensive than GFRP [26]. Enhancing works. S.A.A. Mustafa & H.A. Hassan [30] noted that beams strengthened with CFPR performed better than those strengthened with GFRP once cracks had formed, up until fracture.

Combining two types of FRP (CFRP & GFRP) are revolutionary building products that satisfy strength criteria. These building products exhibit excellent ductility, and the ability to deform and shatter resistance while remaining affordable. They have good resistance to the impact of Glass fiber and possess excellent strength and tensile of carbon fiber. [31-33].

However, CFRP-strengthened beams fail quickly once they reach their maximum point, but RC beams strengthened with GFRP remaining strength to an extended period after the peak.

GFRP has excellent energy retention properties and therefore is suggested for application in seismic

Combined usage of carbon and basalt fibers is advised for strengthening building parts that will be exposed to severe temperatures.

As a result, selecting the type of FRP is critical because it needs careful consideration and additional investigation. Furthermore, the choice of FRP is affected by structural component variances, loading properties, and climatic conditions.

## 3. Strengthening Applications.

Jacobian Strengthening RC beams improves fatigue, flexural, earthquake, shear, explosion resistance, and impact. After a given time of loading, beams should be strengthened to prevent structural damage. In this paper, the focus will be on the studies that dealt with shear strengthening only because shear failure usually comes unexpected and severe. Therefore, it is preferable for the beam to fail in flexure rather than shear [37], and these studies include studies that focused on the strengthening procedure for the RC beam directly after the casting (strengthening before testing) and the studies that dealt with the strengthening procedure after exposing the RC beam to certain ratios of damages (strengthening after testing).

## 4. Techniques Used to Strengthen RC Beams

RC beams can be strengthened using several approaches by FRP composite. EB FRP strengthening can include multiple layers on the beam in various arrangements, including U-wrapping, side bonding, and complete wrapping. In the near-surface method, bars are inserted into cuts made on the tension zone of the beam's surface and coated with layers of concrete of appropriate thickness. Proper anchoring of fiber ends improves FRP's overall strength and mitigates debonding. The ETS approach involves creating holes across the beam's section, entering bars, and filling holes with acceptable adhesive to bond bars with the surrounding concrete. These different techniques have previously been used to strengthen reinforced concrete beams [34-36].

### 4.1 EB Shear Strengthening Technique

The EB FRP strengthening approach improves shear strength in RC beams, although its efficiency varies depending on the type and direction of FRP reinforcements [82], longitudinal tensile steel, the percentages of FRP, concrete strength, and internal steel reinforcement [83]. Several studies have shown that FRP-based shear-strengthening systems are effective. The study by A.A. El-Ghandour [84] was conducted on a reinforced beam of 2m in length wrapped in a u-shape by a carbon fiber sheet of dimensions 50mm x 0.176 mm x 187.5 mm width, thickness, and space, respectively the reinforced beam's load capacity has risen by 32.4%. The strengthened beam has deformability 114.7% greater than the control beam also failure pattern is shifted to shear compression. M. Hussein et al. [85] employed carbon fiber to enhance a reinforced beam damaged in shear. They used external prestress force to close shear cracks in the cracked beam. Wrapped in a U-shape using a one-layer carbon fiber strip. The external force was eliminated following resin drying. That repaired beams' capacity rose by 57%. While researcher [86] utilized a U-wrapped system of strips CFRP 200mm wide and 275mm spaced and a U-wrapped system of strips GFRP 100mm wide and 200mm spaced to enhance shear on a 2.2m effective span of the RC beam. Anchors consisting of 10mm bars diameter of glass and carbon fibers. The anchored beam with a carbon fiber bar exhibited a 75% improvement in load compared to the reference beam. After the ultimate loading, the strengthening beams by carbon fiber failed in flexural, but beams strengthened by glass fiber in both non-anchored and anchored configurations failed in shear. Another study found that utilizing mechanically fastened hybrid FRP in shear-strengthened beams improved their ultimate load by 82.2% compared to specimens that reinforced without a stirrup unstrengthened within shear region [87]. However, the present of stirrups in beam was improved its load by roughly 69% when following the same strengthening. This data suggests that the stirrups affect the strengthening of EB FRP. Since the proper usage of EB FRP capability is impeded by the addition of a steel stirrup within the beam [89]. This is due to the strengthened beam's inability to achieve its maximum limit when critical shear cracks intersected through steel stirrup [88].

Islam, G. S.et. al.[38] Investigate the shear strengthening efficiency and types of failure of damaged rectangular cross-sectional beams strengthening by externally bonded using unidirectional CFRP composites to assess the effectiveness of CFRP strand and continuous sheet, results showed that shear strengthened beams produced results similar to or better than the reference specimen according to the type of carbon fibers material and the process of strengthening. The deflection of damaged beam strengthening by carbon fibers decreased by 23-8% and the amount of load regained by the beams ranged from 4-20%, compared to the reference beam at ultimate load.

Hussein, M., et. Al [39] proposes a modern strengthening technique and compares its results with other techniques by preparing seven beam specimens for shear failure. One beam was strengthened immediately on the cracked concrete on the outside, two beams were strengthened by applying a transient compressive force parallel to the depth of RC beam in the damaged shear region to fix shear fractures before applying CFRP-strengthening strips. The force remained maintained until the CFRP epoxy adhesive was completely cured [proposed technique]. One of the specimen was repaired without applying external compressive load, two beams were repaired with an injection of epoxy prior to strengthening with carbon fiber sheets, and one specimen was treated as reference without strengthening. The results showed that all strengthened beams increased their maximum capacities by 49-57%. The proposed crack-repair technique demonstrated a higher ultimate load compared to the resin injection method. This was verified for repaired beams with preloading values ranging from 85 to 95 percent.

## 4.2 NSM Shear Strengthening Technique

The EBR approach has been proven to greatly improve the shear capacity of concrete beams, according to multiple studies. Intensive laboratory testing has made externally bonded FRP laminates popular and effective for shear and flexural strengthening during the last 20 years. However, such a method is unable to fully use the tensile strength of FRP components because of early separation from the surface of concrete. When using FRP components in this technique, it's necessary to evaluate the impact of thaw/freeze cycles and variations in temperatures, because of the direct impact of weathering factors on their strength. Additionally, EBR mechanisms are prone to fire and work of destruction [37]. NSM acts as a more successful option for strengthening RC beams using FRP bars, steel plates, and steel bars, to the structural members' surfaces [40] and is considered a possible technology for upgrading structurally defective RC structures due to its simplicity of implementation. The NSM technology protects FRP composites against deterioration and harmful effects from the environment [41,42]. Several articles have been published on the application of this strengthening method [43-49]. Investigation indicates that this technique improves the ductility and shear strength of RC beams [44,45]. Thamrin, R. [50] reported that beams strengthened with steel plates had a 17% to 50% greater shear capacity than reference beams, according to the location of the plates (the higher shear strength was observed when glued the steel plate in the center of the beam) and longitudinal reinforcement ratio (inversely proportional). According to Rizzo and De Lorenzis [51], NSM FRP strengthening greatly increased the capacity of the shear of RC beams even when just a small number of stirrups in the shear was included. Jayaprakash et. al. [52] found that the bidirectional carbon fiber strip enhancing approach improves the shear strength in RC rectangular beams. The study found that CFRP strips serve as shear stirrups, identical to steel reinforcement. Hassan and Rizkalla [53] studied the effectiveness of various methods of strengthening and FRP types for reinforced concrete elements. NSM CFRP strips outperformed EBR CFRP strips in terms of efficiency by three times. And in its study [54] observed that using NSM CFRP strips significantly improves the strength, stiffness, debonding loads, and bond properties of RC beams. Abdel-Kareem, A. H. [37] investigated the shear strengthening of reinforced beams utilizing (NSM) GFRP rods and strips. In various spacings, connections, and end anchors. The study found that strengthened specimens performed better in the form of deflection, initial load of crack, and maximum load relative to the reference beam also when comparing the shear capability of RC beams strengthened wit h NSM to those EB with glass fiber sheets with similar content of FRP. The NSM method was found to be better than EBR for strengthening of shear. Deng et al. [55] investigated the shear resistance of reinforced beam strengthening with NSM CFRP in pre-stressed concrete prisms by experimental and analytical methods and when compared to the reference beam, a 65.23% to 103.45% increment was observed due to using NSM CFRP.

## 4.3 ETS Shear Strengthening Technique

The two previous techniques EBR and NSM are the most often utilized for enhancing the shear of RC beams. Early separating of strengthening materials steel plate or fiber sheets, which occurs before the material reaches its ultimate tensile strength, is a typical failure in EBR shear-strengthened beams [56]. While the NSM method minimizes separating failure by a certain amount. Typically, they fail because the concrete covers fracture at the area of the steel shear reinforcement [57, 58]. Numerous investigations are continuing to improve existing techniques of shear-strengthening and develop novel strategies. Additional studies resulted in the discovery of the embedded through-section method that effectively addressed the drawbacks of traditional techniques for shear strengthening. This procedure entails creating apertures throughout the beam's section, inserting the bars, and gluing them to the concrete using adequate glue. The ETS technique is not subject to the debonding failure found in traditional techniques (EBR and NSM). In the ETS technology, the surrounding concrete enhances confinement and bond performance and stresses distributing between the concrete and the embedded bar [59]. Chaallal et al. [60] compared the three techniques external bonded, near surface, and deep embedded. The performance of these techniques was evaluated to enhance shear stresses. Figure 1 depicts the shear strengthening designs for the three techniques EBR, NSM, and ETS implemented in the present study.

The test results showed that ETS specimens outperformed other strengthened specimens with regard to deflection and ultimate load at failure. The ETS method improved RC beam behavior by raising ductility and ultimate load capacity. Mofidi, A. [61] performed an investigation on nine specimens of reinforced beams to verify shear strengthening using the ETS FRP technique adopting certain variables such as: (1) the transverse reinforcing steel inside the specimen, (2) the coating of FRP rod's surface, (3) the diameter of FRP rod, (4) the spacing of ETS FRP rod. Test results confirmed even with modest internal transverse steel reinforcement, the ETS FRP technique successfully improves the shear strength of reinforced beams, the close spacing of the transverse reinforcement significantly reduced the performance of FRP shear strengthening, as for the CFRP bar coating, the plain bars were more efficient in strengthening and transferring shear with epoxy compared to the sand-covered CFRP bars, narrow spacing between ETS FRP bars improved significantly the shear strength and for the influence of the FRP bar diameter in the ETS technology, it had a direct effect (the application of large diameters resulted in an improvement in shear efficiency using FRP). Moradi, E. [62]. Verify the ETS approach for strengthening four beams reinforced in shear with FRP strips, as illustrated in Figure 2. And evaluated the results with three beams strengthened by EB technique.

Research findings indicated that all strengthened beams had a higher load effectiveness than the control specimen, but, the samples reinforced with EB technique showed less improvement due to the separation failure of FRP except the specimen with a fully wrapped design as the result was almost the same. Steel stirrups contributed less to strengthening the beams' shear capacity than the control specimen.

Breveglieri et al. [63] compared steel and carbon fiber bars in RC beams using ETS method. The results are displayed in Figure 3, the beams strengthened with carbon fiber bars are referred to as 4S-C180- 90 and 4S-C180-45 and the specimens strengthened with steel bars are referred to with 4S-S180-90 and 4S-S180-45

We can see from the displayed figure the shear efficiency of the CFRP bars, whether for the sample (4S-C180- 90) or (4S-C180-45). Sogut, K. [64] studied the a/d ratio of T-beam specimens strengthening in shear using CFRP ETS. This study found that using higher values of a/d ratio from reduced shear strength by 27% for control specimens and 23% for strengthened specimens. Decreasing a/d ratio results in reduced shear strength from 37.2% to 29.6%. The results of 1.9 and 3 a/d ratio for strengthened specimens (S/1.9, S/3) and unstrengthened specimens (U/1.9, U/3) were showed in figure

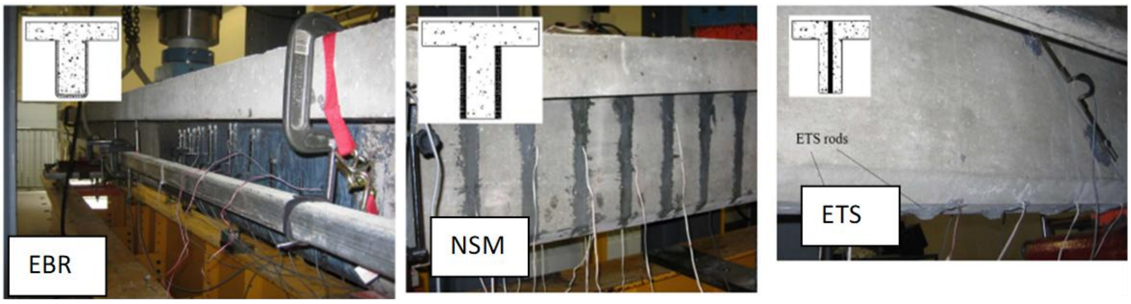


**Figure 1.** Design of shear strengthening using FRP bars/sheets in a) EBR b) NSM c) ETS [60]

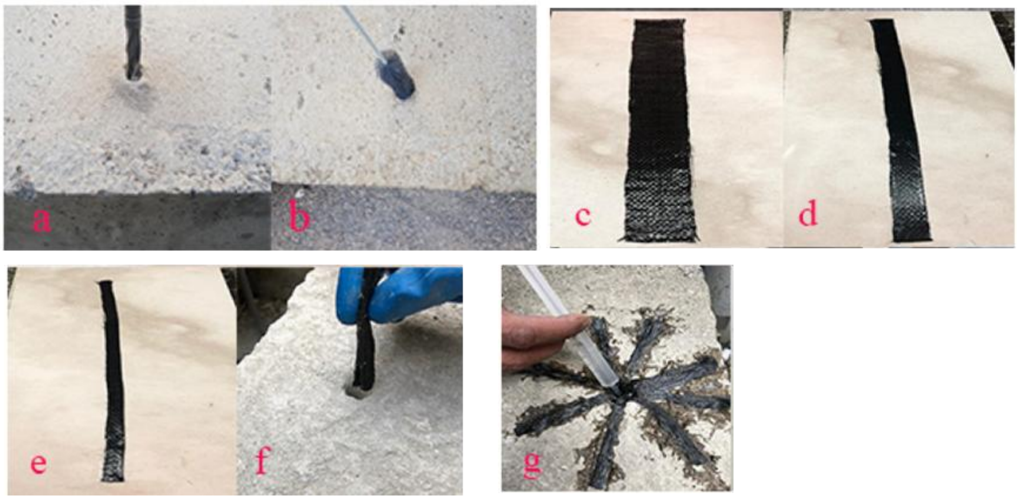


**Figure 2.** The procedures for strengthening using the ETS technique [62]

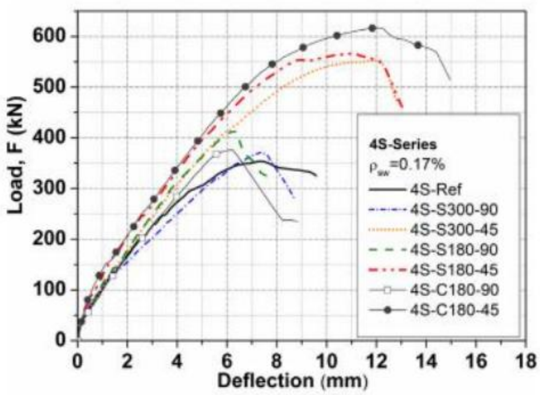


**Figure 3.** Comparison between steel and carbon fiber reinforcing bars Breveglieri et.al [63].

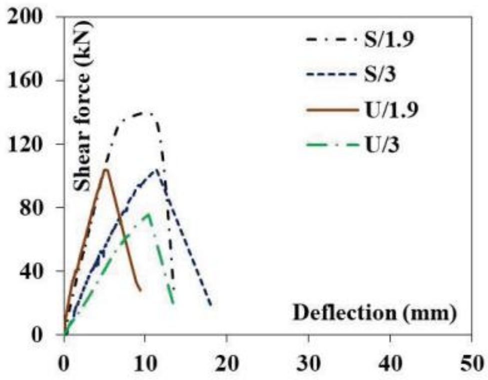


**Figure 4.** the effect of the a/d ratio for strengthened and unstrengthened specimens [64]

## 5. Failure Modes:

Possible failure points (Figure 5 [65]) are regions with insufficient connections between all components, which can cause the entire system to fail if one component fails. The mode of failure of enhanced elements can be used to determine the effectiveness of strengthening efforts. It is anticipated that most strengthened structures will experience ductile failure, utilizing their maximum strain capacity. Typical failure mechanisms and related behaviors deserve a comprehensive discussion.

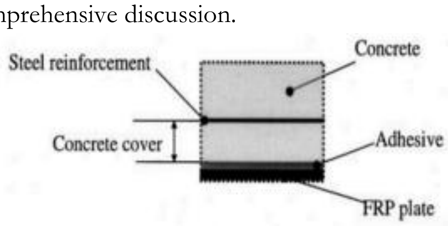


**Figure 5.** Possible failure points of strengthening RC with FRP [65]

### 5.1 Debonding Failure:

A frequently cited drawback is the occurrence of debonding during the loading of strengthening RC structures with FRP, as reported in [66]. This mechanism of failure is particularly prevalent when wrapped FRP in a U-shape when using EB strengthening method, side-bonded, encompassing premature debonding modes such as separation of plate end or concrete cover, and debonding caused by flexure and shear [67]. The majority of brittle debonding failure mechanisms occur at the bonding area of the FRP and concrete. Except for the splitting of concrete cover, which occurs mostly at the internal steel level. To avoid prematurely debonding failure, a variety of temporary anchorages have been used, involving wrapped FRP strips in U-shaped, mechanically attached, and anchors by FRP bars [67].

Metallic clamping anchors inhibit debonding by allowing the continuance transfer of loads between FRP and concrete, thereby enhancing bond strength [68]. The prevalent failure in NSM systems is typically attributed to separation of concrete cover [69]. As a result, the mode of failure is determined by the integrity of the concrete cover as well as the bond created between concrete and NSM strips. The sleek surfaces of NSM strips may diminish the adhesion of NSM strips with adhesives leading to fissures in the resin layer, which is influenced by the onset of gradual deterioration at the FRP adhesive surface [70].

Several researchers [73, 74, 75-77, 78, 79, 80] have revealed that debonding is the predominant failure mechanism on the tension area of RC beams strengthening with a plate. The preferred failure modes should include ultimate yielding and steel rupture before crushing of concrete as displayed in Figure 6 [75], this can be achieved by adjusting the ratio of steel-reinforcement and fibers materials when designing RC.

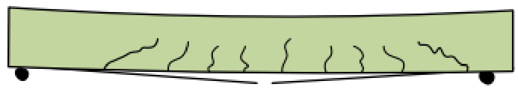

**Figure 6.** rupture of FRP and yielding of steel failure [75]

To address the final form of failure, [81] recommends using an adhesive layer between the CFRP sheet and the concrete. Apply carbon fiber diagonally reduces the separation of the longitudinal CFRP sheet, improves the ductility of the beam, and enhances the strength of carbon fiber sheets attached to the tension face of the RC beam as seen in Figure 7.

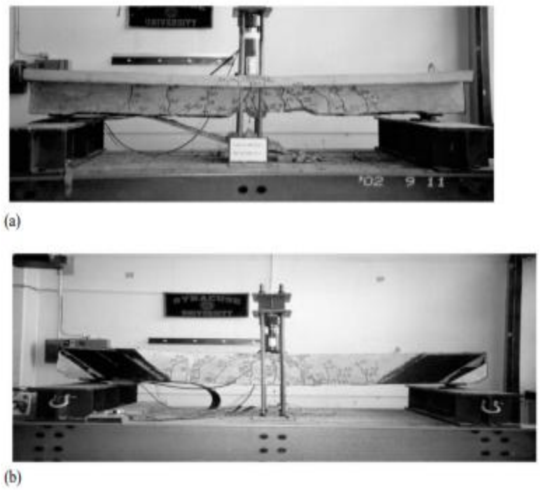


**Figure 7.** Failure modes of a) CFRP sheets on the tension face of the beam b) CFRP sheets on the tension face of the beam with anchors by 45° CFRP [81]

### 5.2 Rupture of FRP:

The prevalent mode of failure observed in RC beams enhance with complete wrapping is the rupture of FRP following localized debonding. This outcome can be attributed to the efficient utilization of strain [67]. The combination of high concrete-adhesive bonds, optimal stress utilization, and lower fiber quality in concrete of high compressive strength reinforced with steel may result in the rupture of fiber as the maximum failure mechanism. FRP rupture occurs when the wrapped side of the structural element in a shear region partially with FRP strips resulting in severe diagonal shear cracks under long-term loading. The FRP rupture appears in an abrupt direction, along with the orientation of the fiber [71]. When a beam is wrapped with one sheet of carbon fiber rather than two of them, the highest FRP rupture occurs horizontally. Multiple layers of FRP can limit strain usage and brittle rupture at levels lower than their efficient stress. Anchors can successfully avoid early fractures by distributing bond stress across the span of the beam.

### 5.3 Failure Mechanism Due to Anchorage Type/Pattern:

A study conducted by [72] revealed that proper anchors may avoid debonding failure and enhance the strength of glass fiber-strengthened beams in partially wrapped [72]. The anchorage increases the strain before failure occurs in the FRP, and this is evident from the research presented by [67], which demonstrated reduces the level of slip and an increase in resistance of about 95% when using appropriate types of anchors. With the inclusion specific method of anchorage, the debonding decreases, thereby mitigating the distribution of stress throughout the area of the anchor. However, fractures can occur in FRP anchors when used in addition to FRP wrapping.

Adhesive the strips on the sides of the beams when strengthening, following the Near-surface method, may allow for more efficient exploitation of FRP than gluing it to the bottom surface of the beam [69]. This is because in bottom NSM strip-strengthened beams, failure typically occurs by splitting the cover of concrete within the area anchored.

## 5. Conclusion:

The following paper provides a comprehensive review on shear zone strengthening of RC beams with fiber components. The study included the different techniques used in strengthening (EB, NSM, ETS) as well as common failure mechanisms (debonding, FRP rupture, anchorage failure). The study can be concluded in the following points:

1.Applying FRP to strengthening RC beams enhances strain endurance by prolonging both their lifespan and strength.
2.In specific conditions such as strength development and preventing debonding failure, the NSM process outperforms EB strengthening methods.
3.Wrapping RC beams with EB FRP layers at 90° or 45° and adding connections improves their shear abilities.
4. The ETS shear strengthening technology surpasses traditional EBR and NSM techniques in terms of shear-strengthening effectiveness, inclined ETS bars offer superior performance compared to vertical ETS bars. This superiority arises from their extended resisting bond length and optimal orientation perpendicular to the shear cracks' inclination. Increasing the spacing of ETS bars reduces the ETS method's efficiency, and the same effect was observed when increasing the percentage of shear stirrups.
4.The use of FRP can effectively restore RC beams that have been pre-damaged and cracked due to shear force. The FRP system is very effective in repairing and retrofitting beams, capable of extending the structural service life to a safe limit, despite the repaired beams potentially failing below FRP's ultimate stress level.
5.The failure mechanism of a strengthened beam depends on its overall technique, material quality, and stress conditions. Preventing premature debonding can improve the strength and longevity of fiber-strengthened beams.

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