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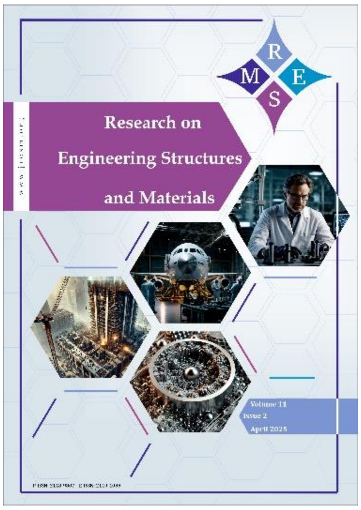

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Review Article

Review of improving the shear capacity of reinforced concrete beams augmented with fiber-reinforced polymer bars

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Abstract

The use of fiber-reinforced polymer (FRP) bars represents a promising technique for enhancing the shear capacity of reinforced concrete (RC) members. Epoxy may be utilized to affix FRP bars into vertical holes drilled in concrete to enhance the shear strength of reinforced concrete (RC) beams. This paper presents a comprehensive review of the Embedded Through-Section (ETS) technique using FRP bars to enhance the shear strength of RC beams. From the literature review, the slanted ETS bars were significantly more efficient than the vertical ones, owing to the greater potential resistive bond length provided by the former shape because the directions of the bars will be perpendicular to the hypothetical directions of the shear cracks. For equivalent shear strengthening ratios, the ETS technique demonstrated superior efficacy compared to externally bonded (EB) and near-surface-mounted (NSM) methods. The remarkable efficacy of the ETS approach is attributable to the superior bonding conditions afforded by the core concrete encasing these bars.

1. Introduction

Fiber Reinforced Polymer (FRP) composites used in reinforced concrete members have become one of the most promising technologies for repairing aging infrastructures during the last three decades. Reinforcement using Carbon Fiber Reinforced Polymer (CFRP) may be used in a variety of contexts, including both brand-new construction and renovation projects [1,2,3]. The many advantages of using FRP especially CFRP as an outside reinforcement for reinforced concrete (RC) beams have led to extensive research into their effectiveness. Most studies have focused on shear strengthening, which involves using CFRP products. While some studies have looked at the overall response of CFRP-reinforced beams, others have focused on the bond interface to see how it acts locally. Bond behavior at the interface, the source of many early failures, has been studied in an effort to pinpoint its causes [4,5]. FRP bars offer advantages like corrosion resistance, a superior strength-to-weight ratio, electrical non-conductivity, and durability [6,7].

There are many FRP forms used to strengthen reinforced concrete beams in shear such as: sheets, laminates, meshes, and bars [8,9]. The ETS method offers numerous benefits over existing methods, like externally bonded FRP sheets (EB FRP) and near-surface mounted FRP rods (NSM FRP). Unlike EB and NSM methods where the FRP relies on the concrete cover of RC beams, in the ETS method, the FRP relies on the concrete core of the RC beam, which offers a greater confinement and hence improves bonding performance [10].

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Ashour [11] presented the test findings of twelve concrete beams reinforced with glass fiber-reinforced polymer (GFRP) bars, which were subjected to a four-point loading method. All test specimens lacked transverse shear and compression reinforcement, and were categorized into two categories based on concrete compressive strength. The primary parameters examined in each group were the beam depth and the quantity of GFRP reinforcement. Two mechanisms of failure were identified: flexural and shear. Flexural failure primarily occurs due to tensile rupture of GFRP bars, either in the mid-span area or beneath the applied point stress. Shear failure is triggered by a significant diagonal crack in the beam's shear span. This diagonal crack extended horizontally at the level of the GFRP bars, signifying bond failure.

El Refai et al. [12] examined the shear effectiveness of concrete beams constructed using basalt fiber-reinforced concrete (BFRC) and reinforced with basalt fiber-reinforced polymer (BFRP) bars. Fourteen hybrid (BFRC-BFRP) beams devoid of stirrups were subjected to failure testing using a four-point loading configuration. The parameters examined were the volume fraction, Vf, of the incorporated fibers (0.75% and 1.5%), the reinforcement ratios of the BFRP bars (0.31%, 0.48%, 0.69%, 1.05%, and 1.52%), and the shear span-to-depth ratios, a/d, of the beams (3.3 for slim beams and 2.5 for short beams). The test findings indicated that the incorporation of 0.75% basalt macrofibres (BMF) enhanced the shear capacity of thin and short beams by 46% and 43%, respectively, in contrast to 81% and 82% when 1.5% BMF was utilized. The influence of including the BMF on the shear capacity of the beams decreased with increasing longitudinal reinforcement ratios.

In this study, a review was developed to deeply provide insight into improving the shear strength of reinforced concrete beams augmented with FRP bars this is because there are still gaps in our knowledge of long-term behavior under complicated loading scenarios and environmental circumstances, notwithstanding progress. In order to overcome these obstacles and guarantee the sustainability and dependability of RC beams strengthened in shear with FRP bars in a variety of applications, research is still concentrated on novel materials and hybrid bonding processes.

2. Review Methodology

In this study, a review of research published in reputable journals for the period from 2007 to 2025 was prepared, as this research encompassed a diverse range of experimental, analytical, and numerical studies. However, most of it was of the experimental type. The focus was on the effect of the spacing of steel stirrups, the strengthening technique, the embedment length of the FRP bar, and its angle of inclination on improving the shear resistance in reinforced concrete beams strengthened with FRP bars. Then, the necessary comparisons are made to reach useful conclusions.

3. Shear Failure Mechanism in Concrete Beams

A multitude of experimental and theoretical studies into the shear bearing capacity of reinforced concrete (RC) members had been undertaken. In concrete beams subjected to bending, which are longitudinally reinforced but lack stirrups, the shear failure mechanism exhibits considerable variation, particularly impacted by the percentage of main reinforcement, strength of concrete, member scale, and the shear span-to-depth ratio. This ratio considers the relationship between the moment of bending M and the shear force V acting concurrently in the same cross section, expressed as M/(Vd). For three- and four-points bending tests, it can be calculated as a/d, where a represents the distance between the applied load and the supports, and d denotes the effective depth of the cross section. Experiments documented in scholarly articles indicate that characteristics like concrete strength and reinforcement ratio exert predominantly quantitative influence on shear failure mode rather than qualitative ones [13]. Shear failure could be classified according to three types based on the ratio of shear span to effective depth:

- Diagonal tensile failure
- Diagonal compressive failure
- Splitting or true shear failure

3.1 Diagonal Tension Failure

Diagonal tensile failure happens when the shear span (a) to effective depth (d) ratio (a/d > 2.5. Diagonal tension failure may arise when the load and reaction are considerably separated, as seen in Fig. 1. The diagonal fracture arises from previous flexural cracking and gradually inclines under shear strain. As the diagonal fracture advances into the compressive zone, it meets resistance. The tensile fracture progressively expands at a moderate slope as the load increases, ultimately resulting in an abrupt failure at point 2. Beam failure is an alternate term for this category of failure. [14].

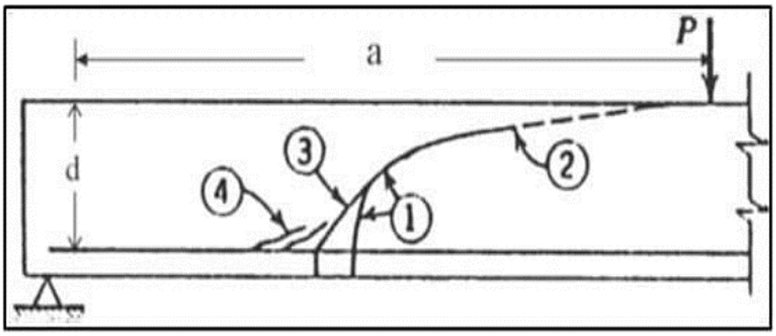


Fig. 1. Diagonal tensile cracks [15]

3.2 Diagonal Compressive Failure

Diagonal compressive failure transpires when the shear span (a) to effective depth (d) ratio is between 1 and 2.5, as seen in Fig. 2. In this failure mode, the specimen is capable of supporting an extra load subsequent to the emergence of the initial fully formed inclined tension fracture. The inclined cracking and bonding separation alongside the steel were constrained by vertical compression stresses throughout the response, and elevated shear over a brief span may trigger a 45º fracture (bending-shear cracking) the crack starts in the bending zone and progresses toward the compression zone (loading point). Such fissures impede the transmission of shear resistance to a lesser un-cracked depth, hence augmenting shear stress. Consequently, the beam functions as an Arch Action. The compression zone diminishes as the angled fracture propagates. Adjacent to the load point, it becomes insufficient to withstand the compressive force, resulting in crushing (shaded region depicted in Fig. 2) [16].

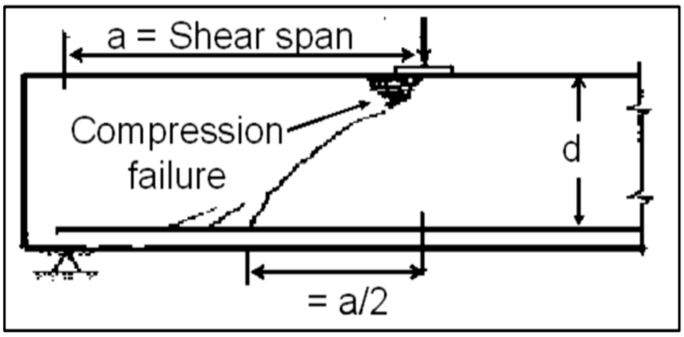


Fig. 2. Shear compressive failure [16]

3.3 Shear Failure in Deep Beams (a/d<1)

Splitting or full shear failure happens in deep beams if the shear span is narrow, namely when a/d < 1 as shown in Fig. 3. Conventional diagonal tension concepts are negated in this situation because shear is transferred as an angled thrust between the load and the reaction. In such cases, the shear strength is greatly increased. Splitting is the ultimate failure, albeit it might also fail during compression at the reaction, [16].

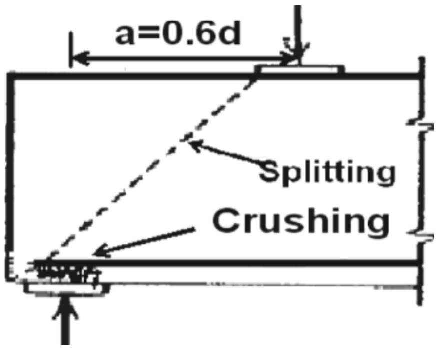


Fig. 3. True shear failure [16]

3.4 Factors Influencing the Shear Strength of Concrete

Numerous primary elements impact the shear strength of RC beams like [16], [17]:

- Concrete compressive Strength (f'c)
- Tensile steel ratio (ρ)
- Beam size
- Shear span to effective depth ratio (a/d)
- Shear reinforcement ratio (ρv)

4. Previous Studies on Embedded Through Section Technique (ETS)

To make RC beams stronger in shear, epoxy can be used to bond FRP rods to vertical holes drilled into concrete. So far, there haven't been many experiments done on how embedded through section (ETS) FRP rods may be used to make RC beams stronger against shear. An overview of experimental research on shear strengthening RC beams using ETS FRP rods is provided below:

4.1 Effect of Steel Stirrups

Chaallal et al. [18] reported the findings of a study that compared the efficacy of the ETS approach with that of the externally bonded (EB) and near-surface-mounted (NSM) techniques. T-beams with a length of 4520 mm are subjected to a total of 12 tests. (1) The effectiveness of the ETS approach relative to the EB FRP sheets and NSM FRP bar techniques; (2) the existence of inside steel; and (3) the ratio of internal stirrups is examined. The test findings verify the effectiveness of the ETS technique and illustrate that the shear behavior of beams reinforced with this method significantly surpasses that of samples strengthened using the EB and NSM methods. Table 1 shows the experimental program details, revealing a mean concrete strength of 25 MPa for the So and S1 set, and 35 MPa for the S3 group. The inside of flexural steel possesses a nominal yield strength of 471 MPa for the So and S1 series, and 651 MPa for the S3 groups. The shear reinforcement possesses a yield capacity of 540 MPa for So and S1, and 650 MPa for the S3 groups. Table 2 presents the outcomes of the experiment. For the samples strengthened using the EB and NSM techniques, the inclusion of transverse steel reduced the contribution of FRP to the shear resistance. In the specimens strengthened using the ETS method, the addition of transverse steel reinforcement did not considerably reduce the contribution of FRP.

Table 1. Experimental layout [18]

Beam ID/set	So set	S1 set	S3 set
Reference beam	So-CO	S1-CO	S3-CO
EB FRP method	So-EB	S1-EB	S3-EB
NSM FRP method	So-NSM	S1-NSM	S3-NSM
ETS FRP method	So-ETS	S1-ETS	S3-ETS

Barros et al. [19] evaluated the effectiveness of the ETS approach. An extensive experimental program involving 14 reinforced concrete beams was conducted, yielding the following results: (i) inclined ETS strengthening bars demonstrated superior effectiveness compared to vertical ETS bars, with shear capacity increasing as the spacing of bars decreased; (ii) shear-failure was transformed into flexural-failure; and (iii) shear capacity of the beams improved with reduced spacing between bars. The ACI 318-(08) and Eurocode-2nd-(2004) requirements for shear resistance were examined for potential applicability.

Table 2. Experimental outcomes [18]

Strength method	Series	Specimen	Load at Rupture (kN)	Total shear resistance (kN)	Resistance of concrete (kN)	Resistance attributable to steel (kN)	Failure Mode
	So	SO-CO	122.7	81.3	81.3	0.0	Sh-F
Reference	S1	S1-CO	350.6	232.2	81.3	150.9	Sh-F
	S3	S3-CO	294.0	194.7	96.2	98.5	Sh-F
	So	SO-EB	181.2	120.0	81.3	0.0	Sh-F
EB	S1	S1-EB	378.5	250.7	81.3	150.9	Sh-F
	S3	S3-EB	335.2	222.0	96.2	98.5	Sh-F
	So	SO-NSM	198.0	131.1	81.3	0.0	Sh-F
NSM	S1	S1-NSM	365.0	241.7	81.3	150.9	Sh-F
	S3	S3-NSM	380.0	251.6	96.2	98.5	Sh-F
	So	SO-ETS	273.0	180.8	81.3	0.0	Sh-F
ETS	S1	S1-ETS	397.0	262.9	81.3	150.9	F-F
	S3	S3-ETS	425.5	281.8	96.2	98.5	F-F

Sh-F = shear failure, F-F = flexural failure.

The experimental and analytical results exhibited a strong correlation. The experimental program consists of two groups, A and B, including beams with cross-sections of 15 cm by 30 cm and 30 cm by 30 cm, respectively, each with a full length of 245 cm and a 90 cm span length. Table 3 presents the general data regarding the beams in the two groups, where ρ_{sl} denotes the main steel reinforcement ratio (ρ_{sl} = As1 / d bw), with Asl representing the area of cross-sectional of the main steel bars, b_w indicating the width of web, and d signifying the effective depth. ρ_{sw} denotes the shear reinforcement ratio ($\rho_{sw} = A_{sw}/s_w\, b_w$), where A_{sw} represents the cross-sectional area of the two legs of the stirrup, and s_w indicates the spacing between stirrups. The ρ_{fw} presented in Table 1 represents the ETS strengthening percentage, defined by the equation $\rho_{fw} = A_f/(s_f\, b_w \sin\theta_f)$, where A_f denotes the ETS shear strengthening bar area, sf signifies the spacing of bars, and ɵf indicates the angle of inclination of the strengthening bars relative to the beam's longitudinal axis. Figure 4 illustrates the ETS reinforcement method utilized in this reference, whereas Figure 5 depicts the correlation between the load and the deflection of the section for groups A and B.

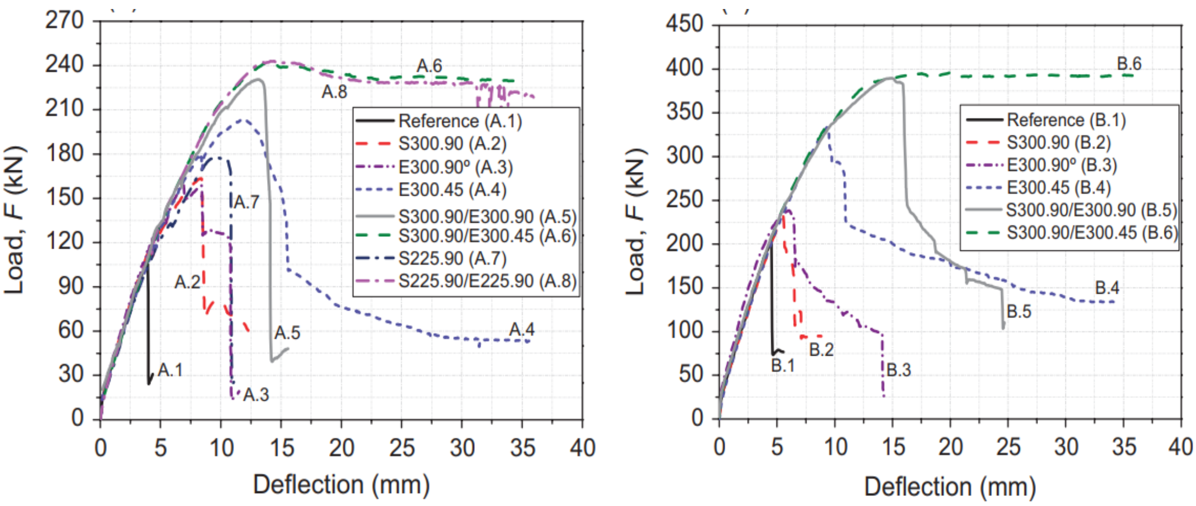
Table 3. General information on the beams [19]

	150× 300 mm^2				300 × 300 mm^2			
Beams ID	ρ_{sl} (%)	ρ_{sw} (%)	ρ_{fw} (%)	Batch	ρ_{sl} (%)	ρ_{sw} (%)	ρ_{fw} (%)	Batch
Reference	2.50	0.00	0.00	1	1.88	0.00	0.00	1
S3OO.90	2.50	0.13	0.00	1	1.88	0.06	0.00	1
E3OO.90	2.50	0.00	0.17	1	1.88	0.00	0.11	1
E3OO.45	2.50	0.00	0.25	2	1.88	0.00	0.16	2
S3OO.90/E300.90	2.50	0.13	0.17	1	1.88	0.06	0.11	1
S3OO.90/E300.45	2.50	0.13	0.25	2	1.88	0.06	0.16	2
S225-90	2.50	0.17	0.00	2				
S225-90/E225.90	2.50	0.17	0.23	2				

RC T-cross section beams reinforced in shear with ETS steel rebars and ETS CFRP bars were utilized in an experiment. The primary objective of the research in [20] is to evaluate the efficacy of the

ETS on samples with varying levels of internal stirrups (ρ_{sw} = 0, ρ_{sw} = 1, and ρ_{sw} = 0.17%), where ρsw denotes the shear reinforcement ratio ($\rho_{sw} = A_{sw}/s_w b_w$), with s_w indicating the spacing between stirrups. The efficacy of various ETS strengthening setups was also examined. The strong adhesion between the reinforcing ETS bars and the surrounding concrete enabled the ETS steel bars to begin yielding and allowed the ETS CFRP rods to attain elevated tensile stresses. This resulted in a substantial enhancement of shear strength, which was significantly affected by the angle of the ETS rebars and the quantity of stirrups. Based on the results, it can be said that the proposed method raised the load-carrying capacity of ETS bars in general, no matter what kind of material they were made of. Between 5% and 68%, more weight could be carried with the help of vertical ETS bars. Since the ultimate load went up from 53% to 136%, the angled ETS bars made sure that the strengthening worked better. The angled ETS bars were also better at making sure that the beams could bend more when they broke. The reason why inclined ETS bars work better is that they have a longer bonding length and are better positioned in relation to the angle of the shear failure cracking [20].

Fig. 4. ETS strengthening technique [19]



(a) (b)

Fig. 5. Correlation between the applied load and the deflection of the loaded part for series: (a) A and (b) B [19]

Chalioris et al. [21] are conducting studies to evaluate the efficacy of a novel retrofitting technique aimed at enhancing the structural performance of RC deep beams devoid of steel stirrups, utilizing CFRP bars as the only stirrups. Continuous loading experiments are conducted on five shear-critical beams with T-shaped and rectangular cross sections. The reinforcement strategy consists of (a) two normal U-shaped 2-link ropes attached within the flanged beam's web's perimeter utilizing a near-surface-mounted (NSM) approach, and (b) a vertical and a diagonal 1-link CFRP rope installed internally with the web of the RC beam via an ETS approach. The CFRP ropes' free lengths were securely fastened in both cases utilizing epoxy-bonded lap splices as NSM at (a) the upper and lower portions of the rectangular beam's web and (b) the upper portion of the T-beam's slab. The proposed reinforcing method improved strength and converted shear failure into flexural failure, signifying a favorable result. The findings from the experiments of this research were employed to validate the precision of an analytical method for predicting the capacity of shear-strengthened deep beams reinforced employing FRP ropes as transversal links.

Van et al. [22] reported the results of an experiment on RC beams augmented in shear using embedded-through-section (ETS) steel bars and (FRP) rebars, with and without an engineered anchoring method. The response of the beams, encompassing the relationship between load and deflection, fracture patterns, and failure mechanisms, are examined. The shear behavior of different strengthening methods is analyzed through contrasting ETS scenarios with traditional reinforcing techniques. The impact of various forms of ETS strengthening is examined using differing quantities of steel stirrups. The shear effect provided by the reinforcement bars is examined to evaluates the effectiveness of current models. A mean strain formula for ETS-FRP rebars is formulated from the original model. Comparing the findings of this article with existing literature demonstrates that the end-anchored significantly enhances the efficacy of shear strengthening. The following are the principal conclusions of this reference: The shear resisting force of the unanchored vertical ETS steel bars was less to that of the interior vertical steel stirrups, which employed closed form configurations. Nevertheless, the shear contribution of the unanchored diagonal ETS steel system was marginally more than that of the internal diagonal steel shear reinforcement. The data indicate that premature debonding of the ETS bars transpired due to inadequate bond length, leading to diminished shear strengthening efficacy.

4.2 Effect of the Embedment Length of FRP bar

Godat et al. [23] developed two-dimensional finite element models to examine the interaction between the CFRP bar and concrete at the interface during the pull-out tests. In the model, separate truss members are positioned beside the CFRP bar to link it to both sides of the concrete. The behavior of bonds is shown using the Cosenza–Manfredi–Realfonzo (CMR) bonding stress--slip model. Numerical simulations indicate that the interfacial profiles of CFRP bars and concrete may be utilized to find the optimal lengths for the CFRP rods. The work had been extended to test FRP shear-strengthened specimens utilizing the ETS approach through the creation of a 3-D finite element model. The appropriate constitutive examples have been employed to estimate the nonlinear behavior of steel bars, plain concrete, and CFRP rods. The results are presented regarding the maximum load-carrying capacity of the bars, the correlations between load and deflection, and the axial stresses in the CFRP bars. The finite element results are checked with experimental results, and they align closely.

Bui et al. [24] conducted tests, analytical assessments, and numerical simulations to study the bonding of (ETS) FRP rods to concrete and its impact on the structural behavior of beams reinforced in shear using ETS rods. A series of pullout experiments were done to determine the adhesion between ETS bars and concrete, including variables like embedment length and ETS stiffness. An exhaustive analytical technique is presented for delineating the ETS–concrete interface profile, using historical data. The suggested bonding model is utilized to develop a novel technique for finding the ETS shear capacity and determining the energy absorption capacity of reinforced beams. The findings show that the established bonding model effectively simulates the interface between ETS and concrete, and the approach for determining the shear involvement of ETS FRP bars via a bond-based mechanism performs favorably in comparison to alternative shear models. The interfacial ductility index and interfacial energy significantly influence the performance of well-strengthened components. Finite element (FE) calculations were conducted on beams reinforced with ETS bars, utilizing the suggested bonding approach. The comparison of FE modeling findings and experimental data demonstrates that FE simulation with the suggested bond model effectively analyzes shear-strengthened beams constructed with ETS bars.

4.3 Effect of Angle of FRP Bar

Breveglieri et al. [25] ran an experiment using T-RC beams that were strengthened with steel bars to see how well the ETS method could work for shear reinforcing of RC beams. The research looked at how the angle and shear reinforcement ratio of ETS forms affect the efficiency of shear strengthening. It also looked at how ETS bars and currently available steel stirrups work together.

The beams shear capacities, both with and without internal stirrups was increased by 109% and 136%, respectively. Shear resistance went up more with angled ETS bars than with vertical ones.

Al-Kaabi and Al-Fartosi [26] showed the experimental investigation results from reinforced concrete beams that were reinforced with a modified fiber-reinforced polymer (ETS) (FRP) technique. The ETS FRP rod technique could be used to enhance the load capacity of RC beams and increase their shear strength. Since ETS reinforcement is a new way to keep concrete structures from failing, this strategy allows for more confinement and better results. Seven rectangular RC beams with a span of 1500 mm are used in the tests. The impact of the angle of the CFRP rebars was taken into account when setting the parameters for this study. This study shows the findings of seven tests done on reinforced RC beams using the shear ETS method as part of an experimental study. The ETS method is used to make RC members better in terms of FRP. Using the results of this study, the suggested strategy was demonstrated to be accurate. Suggested that there is a good match between the experimental data and the model. Also, the most important results of this study are:

- The ETS FRP strengthening method has been shown to enhance the shear resistance of RC beams. For samples B200-2E10-V, B200-2E10-V, and B200-3E10-V, the shear increase was 23.96%, 23.96%, and 7.43%, respectively.
- It has been shown that putting CFRP rods inside RC beams makes the cross-section more rigid. This is because EST FRP-reinforced beams can handle higher loads than unreinforced beams.
- It was shown that implementing inclined CFRP rods is more effective than implementing vertical CFRP rods, because the shear increase for sample B200-E10-I was 32.2%. This is because the direction of the inclined rods is the opposite of the direction of shear.

4.4 Effect of the Strengthening Techniques

The interaction of ETS bars with preexisting steel stirrups, in addition to the effect of ETS's strengthening shear percentage and inclination with respect to shear strengthening effectiveness, were all evaluated by [16]. In this study, two mathematical methods for determining the impact of ETS on shear resistance were provided. The first model is based on observations and experiments, whereas the second model incorporates the method's underlying physical and mechanical concepts (mechanically-based approach). Both models' prediction abilities are compared using published experimental findings [27].

Moradi et al. [28] showed a new way to use FRP materials to improve the shear resistance of RC beams. This approach entails drilling openings across the beam web, introduce FRP reinforcement in these openings, and then fill them with grout, rather of gluing FRP strips to the outside of the element. Technical literature indicates that externally bonding and NSM FRP reinforcements effectively improve the shear capacity of RC components. Nevertheless, they are inefficient in situations when the concrete cover exhibits inadequate bond strength, as debonding may result in beam collapse before the whole capacity is utilized. In constructions where the beam is secured to the flooring, the application of FRP wrapping requires the drilling of holes in the floor for reinforcement. This makes the area where the floor and beam touch more vulnerable to shear. Experiments show that samples reinforced with the proposed method work as well as or better than beams with FRP reinforcements that are bonded on the outside. Furthermore, a comparison of the Applied Strengthening Material Index (ASMI) for samples indicates that the suggested approach exhibits a superior ratio of FRP shear involvement relative to the quantity of FRP utilized, in contrast to external bonding techniques.

Al-Mahmoud et al. [29] looked into whether the NSM technique could be utilized to strengthen in-shear RC elements with Carbon Fiber-Reinforced Polymer (CFRP) rods. Seven reinforced concrete beams with or without stirrups were tested in flexure. Rods made of (CFRP) with a diameter of 6 mm were used. The performance of a mortar and a resin is compared to see if it could be used as a filler substance with a surface-preconditioned CFRP rod. The results show that the NSM method is a very good way to make a reinforced concrete beam stronger in shear. Shear strengthening still works better when resin is used as the filler material rather than mortar, although the difference is not very noticeable. The tests' outcomes are contrasted with previously developed analytical models. The NSM method of strengthening reinforced concrete beams in shear with CFRP rods works very well. The shear strength of a single surface-conditioned CFRP rod was approximately 43.6% over that of beams strengthened only with stirrups. The epoxy resin served as the filling medium, resulting in a 34.6% increase compared to the usage of mortar. However, as noted by other writers, augmenting the quantity of NSM CFRP rods within the shear zone significantly enhances the shear capacity of the beams. The data indicate that epoxy resin outperforms cement, however the disparity is not substantial. The interface between the mortar and the surface-conditioned CFRP rod functions effectively, since the failure occurred at the junction of the mortar and the concrete substrate. To enhance the efficacy of the reinforcement, consideration might be given to enhance the texture of the groove surface in the concrete.

5. Shear Behavior of Concrete Beams with Internal FRP Reinforcement

Hamid et al. [30] presented the test outcomes of simply supported RC beams strengthened with steel or GFRP. Sixteen substantial concrete beams reinforced with steel stirrups were constructed and subjected to testing until failure occurred under consistent pressure applied at four locations. Fifty percent of the samples were reinforced longitudinally by GFRP rebars, whereas the remaining fifty percent were longitudinally reinforced with steel bars as control examples. The primary factors examined in the research were longitudinal reinforcement ratios, shear span-to-effective depth ratios, and stirrup ratios. These were utilized to examine the shear performance of GFRP reinforced concrete (RC) beams. Two forms of failure were observed: flexural and shear. Because FRP bars have a lower modulus of elasticity than steel bars, concrete beams reinforced with GFRP bars have a lower shear capacity. The shear span-to- depth and main reinforcement ratios have a major impact on the force's distribution within GFRP reinforced concrete samples. The test findings agreed closely with the projected values supplied by conventional codes and design standards, except for GFRP reinforced concrete beams that encountered shear failure.

Said et al. [31] performed an investigation on the shear performance of beams reinforced with laboratory-manufactured GFRP rebars and stirrups. In the laboratory, the rebars and stirrups are produced from locally available raw materials and a bipartite die mold. Ten beams, each measuring 12 cm in width, 30 cm in depth, and 155 cm in length, were manufactured and subjected to four-point loading until collapse ensued. The primary criteria were the GFRP web reinforcement percentage and the compressive capacity of the concrete, quantified by the quantity of GFRP stirrups (Ø8 at 215mm, 150, and 100mm). The deflection at mid-span, the load on the inclined crack, and the stresses in the GFRP reinforcing stirrups and bars were quantified and analyzed for each examined beam. The test findings indicated that the shear capacity of a stirrup-less beam improved by 41% and 82%, respectively, when web GFRP reinforcement of 8 @ 215 and 8 @ 100 was employed. As the concrete compressive strength increased from 25 MPa to 45 MPa and subsequently to 70 MPa, the shear strength augmented by 49% and 104%, respectively. The highest strain observed in GFRP stirrups was 0.0095. A unique approach for assessing the shear strength of FRP stirrups was introduced and corroborated by a comparison of the experimental results from this study with those of prior studies. The shear capacities of the examined materials were assessed utilizing nonlinear finite element analysis (NLFEA) and strut and tie models (STM). The experimental shear strength ratio to anticipated shear capacity (V_{exp}/V_{pred}) was 1.2 for NLFEA and 0.9 for STM.

Issa et al. [32] examined the shear capacity as well as behavior of RC beams strengthened with basalt fiber-reinforced polymer (BFRP) bars, as well as without stirrups. Six concrete beams measuring 200 mm × 300 mm (8 in × 12 in) and 300 mm × 200 mm (12 in × 8 in) were fabricated with and without BFRP stirrups. The main reinforcement ratios (ρf) for samples without shear reinforced (NSR) beams varied from 2.690 to 14.80 times the percentage of balance (ρfb). For shear-reinforced (SR) samples, the range varied from 1.690 to 6.880 times ρ_{fb}. For the NSR beams, two distinct shear span-to-depth (a/d) ratios (5.650 and 7.00) and three varying a/d ratios (1.50, 2.50, and 3.50) were examined. The experimental data are presented regarding fracture patterns, modes of material failure, load deflection, load-strain characteristics, and shear strength. For both SR- and NSR beams, the shear strength increased with the augmentation of BFRP reinforcement area, despite the a/d ratio being constant. Conversely, when the a/d ratio increased, the shear strength diminished. The studies assessed predictive models and code equations for their efficacy in forecasting the shear capacity of BFRP reinforced concrete beams. Standard conditions were employed to produce both conservative and non-conservative projections. The predictions depend on the variables. Table 4 delineates the beam categories and reinforcing parameters for BFRP RC-Beams, indicating that the NSR group beams possess dimensions of 300mm in width, 200mm in whole depth, and 2440mm in span, whilst the SR group beams exhibit dimensions of 200mm in width, 300mm in total depth, and 3050mm in span. Figure 6 illustrates the BFRP flexural bar and shear reinforcement type, while Figure 7 depicts the fracture pattern in the BFRP reinforced concrete beams. Figures 8 and 9 illustrate the load-deflection behavior of non-shear reinforced BFRP RC beams.

Table 4. Beam labels and reinforcement specifications for BFRP RC-beams [32]

		Flexural reinforcement of BFRP				Shear reinforcement		
Type	Beam number	Bar diameter (mm)	Number of bars	Depth d (mm)	ρ_f/ρ_{fb}	10 mm BFRP	#3 steel	Shear span to depth (a/d)
NSR	5-10N5	10	5	170	2.69	No	No	5.65
	5-13N5	13	5	170	4.49	No	No	
	5-16N5	16	5	170	7.15	No	No	
	6-16N7	16	6	170	8.58	No	No	7.0
	3-25N7	25	3	165	11.10	No	No	
	4-25N7	25	4	165	14.80	No	No	
SR	2-13SB1	13	2	275	1.69	Yes	Yes	1.5
	3-13SB1	13	3	275	2.54	Yes	Yes	1.5
	3-16SB1	16	3	270	4.03	Yes	Yes	1.5
	2-25B1	25	2	265	6.88	Yes	No	1.5
	3-16B2	16	3	270	4.03	Yes	No	2.5
	3-16B3	16	3	270.0	4.03	Yes.	No.	3.5

Note: No = without stirrups; S = steel stir.; B = basalt stir.; i.e., Steel and basalt stir. (SB) and a/d = 1.5 (1). NSR = No stirrups, SR = with stirrups.

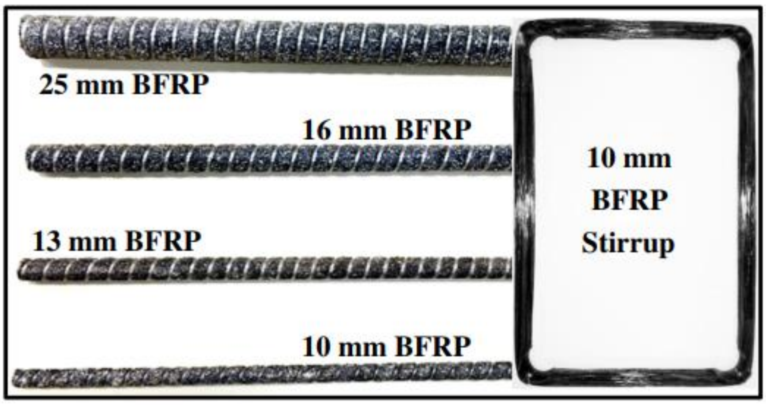
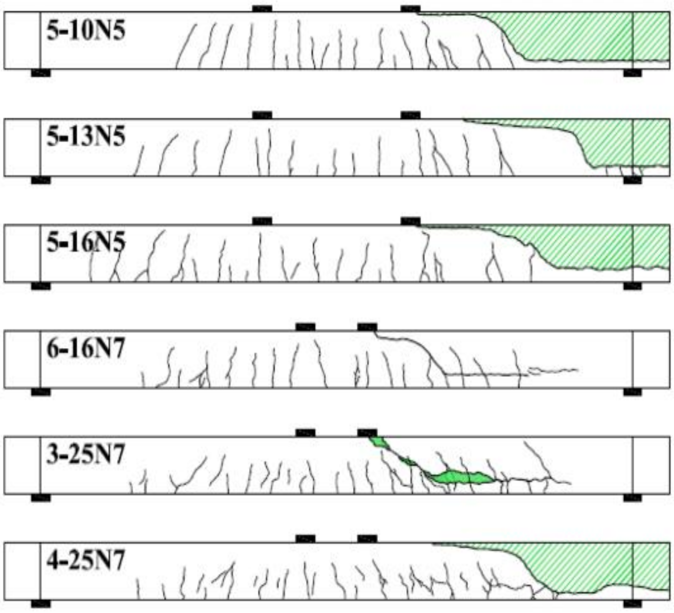
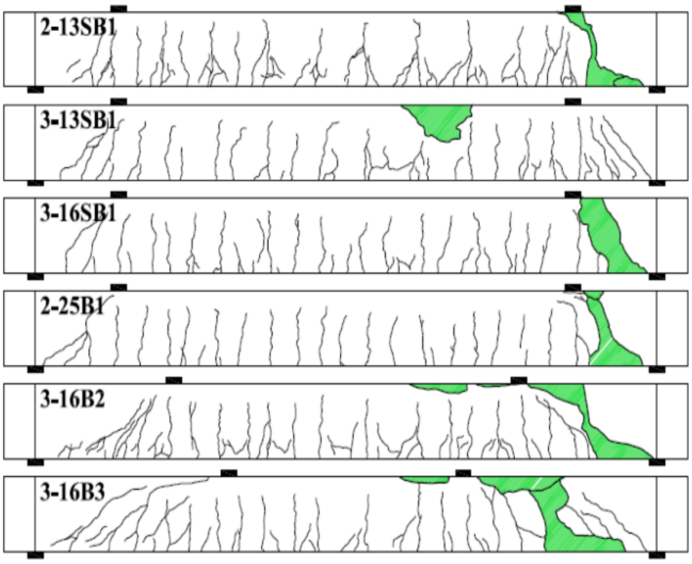


Fig. 6. BFRP flexure bar and shear reinforcement type [32]

Karayannis et al. [33] conducted experimental investigations on the behavior of seven RC beams have CFRP bars subjected to progressively increasing static loads. The load capacities, deflections, stiffness, fast local strength reductions, failure processes, and crack propagation are shown and analyzed. The bond properties of the anchoring distances of CFRP bars have garnered significant interest. The implementation of regional detention circumstances at the anchoring distances of CFRP bars appears to influence their cracking behavior in specific specimens. Furthermore, experimental data for CFRP beams and GFRP beams from contemporary literature are compared and analyzed. Herein are also comparisons between the experimental findings and the expectations based on ACI 440.1R-15 and CSA S806-12. The results of this study showed that: A generalization derived from the deflection curves is that each time a fracture emerges in the CFRP beams, a sharp reduction in load occurs immediately.



(a)



(b)

Fig. 7. Crack formation in the BFRP reinforced concrete beams: (a) beams without shear reinforcement; (b) beams with shear reinforcement [32]

Huang et al. [34] examined the ambient-cured Geopolymer Concrete GPC beams reinforced with basalt fiber reinforced polymer BFRP bars that were developed, cast, and subjected to static and impact stresses. The mechanism of damage and quantitative findings, including mid-span deflection, impact and response forces, were documented and examined. In comparison to typical rectangular stirrups, spiral stirrups improved the behavior of beams under the effect of impact and static loads, according to test data. Using the improved GPC material model, numerical models were created and calibrated using the impact test findings. The effect of GPC substance strength and the proportions of main and stirrup reinforcement on the behavior of impact-loaded beams was examined by parametric analysis. The utilization of steel bars as compression reinforcements was shown to enhance performance, as BFRP bars were prone to breaking under shear and compression when subjected to impact loads.

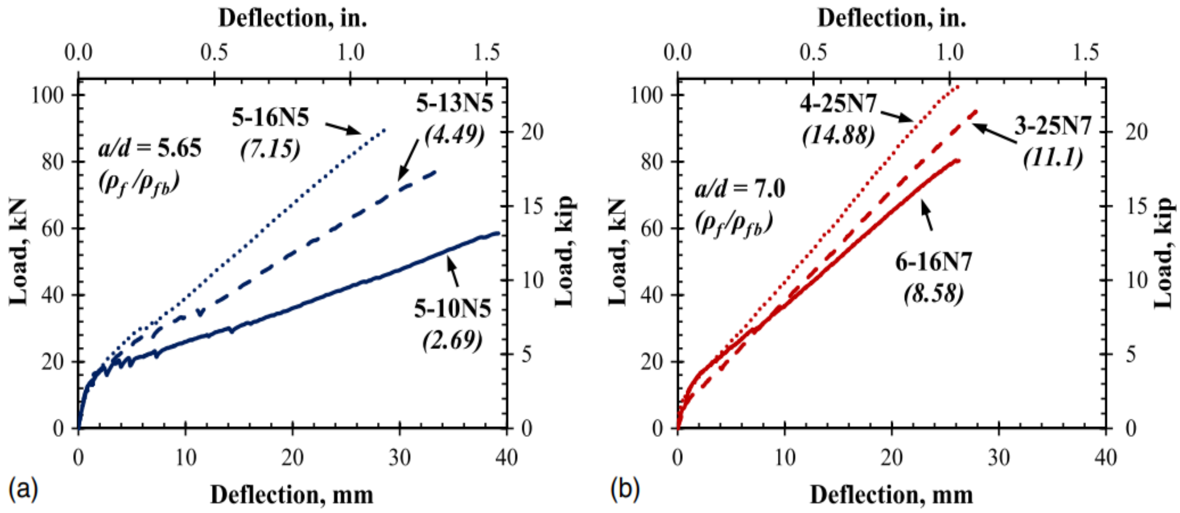


Fig. 8. Load deflection characteristics for non-shear reinforced member BFRP RC-beams: (a) a/d= 5.65; (b) a/d= 7.0 [32]

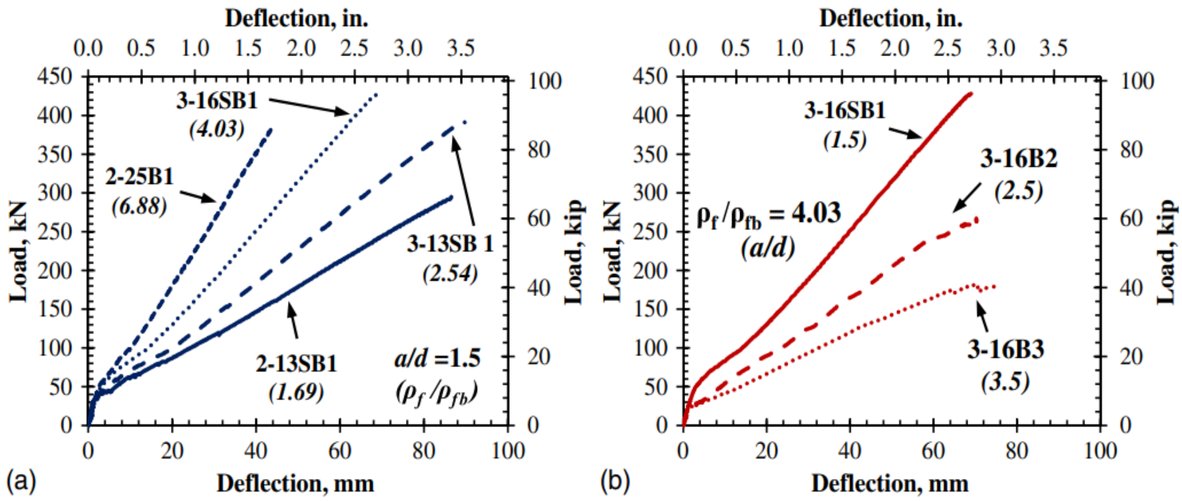


Fig. 9. Load deflection characteristics for non-shear reinforced member BFRP RC-beams: (a) a/d =1.5; (b) ρf /ρfb = 4.03 [32]

Fan et al. [35] conducted an investigation of the shear behavior of inorganic polymer concrete (IPC) samples strengthened with stirrups and BFRP bars, considering the influence of stirrup spacing (S = 8, 10, and 15 cm) and ratios of shear span to depth (1.50, 2.00, and 2.50). The results indicate that all BFRP-IPC beams experience shear failure due to the rupture of BFRP stirrups, leading to failures in both compression and shear. Ratio of shear span to depth exerts a greater influence on the shear behavior of BFRP-reinforced IPC samples than S, decreasing the shear capacity by up to 29.39%. The outcomes of the simulation align closely with the test data; however, the current design guidelines for FRP-reinforced concrete do not include this, resulting in forecasts that deviate from the trials by over 30%. Then, modified equations were made. These equations were used to estimate the shear strength of BFRP-reinforced beams, which matches experimental data well with an average difference of only about 5%.

Hassan and Yousif [36] demonstrated the shear behavior of tapering beams reinforced with BFRP bars via experiments and studies. Eight samples were evaluated to investigate the effects of varying inclination degrees and the incorporation of BFRP stirrups. The beams were categorized into two sets, each including four beams: reference straight specimen and 3 tapered specimens with varying taper angles. The initial batch lacked shear reinforcement, whereas the subsequent group was augmented with BFRP stirrups. The findings indicated that augmenting tapered angles diminished the shear capacity of BFRP tapered specimens devoid of stirrups, while enhancing it in beams equipped with BFRP stirrups.

Moussa et al. [37] examined the shear behavior of high-strength concrete (HSC) beams strengthened with CFRP bars. Thirteen HSC samples were exposed to static loading to failure, examining parameters including the shear span-to-depth (a/d) percentage, transverse reinforcement percentage, main reinforcement percentage, and the kind of main reinforcement (CFRP, hybrid CFRP-steel, and steel). Research suggests that shear failures in CFRP-reinforced high-strength concrete beams might manifest abruptly due to the brittle characteristics of both FRP and high-strength concrete. The incorporation of main steel bars with CFRP bars markedly improved the shear strength while maintaining a balance between ductility and durability.

6. Summary of Studies on Shear Strengthening of RC Beams

Table 5 illustrates a comparison among the research deals with RC beams enhanced in shear with FRP bars through number of samples, concrete type, FRP bars type and arrangement strengthening method, failure mode type, and percentage of enhancement in failure load.

Table 5. Summary of studies on shear strengthening of RC beams

Ref. No.	No. of samples	Concrete type	FRP bars type	Failure mode type	% of enhancement of shear capacity	Strengthening method
14	12	high strength	CFRP	Flexural for ETS and shear for the rest	19.23 - 61.5	EB *
20	19	Normal	CFRP	Shear	44.3-66.5	ETS
27	15	Normal	FRP	Shear	60-136	ETS
21	5	Normal	CFRP	Flexural or shear	6.5-29.8	ETS or NSM
22	11	Normal	GFRP	Flexural or shear	47-164	ETS
28	8	Normal	CFRP	Shear or failure of bonding	16.8-50.1	ETS or EB
24	9	Normal	GFRP	Premature or pullout	14.3-47.9	ETS
26	7	Self-compacting concrete	CFRP	Flexural or shear	1-13.2	ETS
29	7	Normal	CFRP	Flexural or shear	70-145	NSM

**ETS = embedded through section, NSM = near-surface-mounted; EB = externally bonded*

7. Conclusions

Reviewing the literature on increasing the shear capacity of reinforced concrete beams enhanced with fiber-reinforced polymer bars is the main goal of this work. The reviews' key conclusions are provided below:

- Because the bars' directions will be perpendicular to the hypothetical directions of the shear cracks, the slanted ETS bars have a higher potential resistive bond length than the vertical ones, making them noticeably more efficient.
- Because early debonding occurs in NSM strengthened members, ETS bars continuously gave the reinforced member better shear resistance than NSM retrofitted bars.
- Brittle abrupt shear failure modes may be changed to ductile flexural failure modes by using FRP bars for shear strengthening.
- The ETS approach outperformed the EB and NSM approaches in terms of effectiveness for equal shear strengthening ratios. The improved bonding conditions given by the core concrete encasing these bars are responsible for the ETS approach's exceptional effectiveness.

- Most researchers have used CFRP as a prominent FRP product because CFRP has high strength, stiffness, and weight savings.
- In general, GFRP-reinforced concrete beams exhibited linear behavior until failure, attributable to the minimal flexibility of the reinforcing bars. Furthermore, the failure occurred at significant displacements relative to steel reinforced concrete beams.
- CFRP and GFRP bars serve as non-corrosive substitutes for steel, with CFRP exhibiting much superior tensile strength and stiffness relative to GFRP. CFRP is optimal for high-load and long-span applications, but GFRP is more economical for common structural purposes, providing superior bonding capacity with concrete.

As recommendations for future research work:

- Studying the behavior of strengthened reinforced concrete beams with FRP bars under fatigue and cyclic loading.
- Effect of environmental conditions (moisture, temperature, chemical exposure) on concrete beams with FRP bars.
- Studying the behavior of strengthened reinforced concrete beams with FRP bars under the effect of fire.

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