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Overview of sustainable GFRP-concrete beams' shear behaviour

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Abstract: Integration of Glass Fiber Reinforced Polymer (GFRP) in concrete beams presents a promising approach for developing sustainability as a substitute for traditional steel reinforcement. Many empirical and analytical studies are presented in this paper, emphasizing the shear performance of Reinforced Concrete (RC) with GFRP. This work aims to focus on the benefits, challenges, and design considerations associated with GFRP in RC beams. This review is based on findings of the latest investigations, which have explored factors like the ratio of span to depth (a_v/d), the longitudinal reinforcement ratio, concrete compressive strength, the bar diameter and spacing of stirrups. The information taken during the study indicated that GFRP may be utilized as a substitute for steel reinforcement due to their corrosion-free, lightweight, and high tensile strength, which can develop durability. The employment of GFRP increases shear capacity, which may reach 80 % more than beams that did not have stirrups, depending on the bar diameter and spacing between stirrups. On the other hand, GFRP mechanical properties significantly decrease when exposed to high values of pH, which are greater than 10. In addition, challenges such as reduced modulus of elasticity and brittle failure modes are observed, which require careful design considerations. This paper also reviews the number of analytical methods to assess the shear capacity of GFRP-concrete beams.

Keywords: Sustainable performance, Beams of reinforced concrete, Shear capacity, non-corroding reinforcing, GFRP.

1. Introduction

Since the turn of the 20th century, the shear capacity of RC elements has been the focus of numerous discussions and controversies [1]. Shear forces are internal forces that act on structural elements in a perpendicular direction to their longitudinal axis. When these forces exceed the capacity of the materials, a shear failure can occur. This type of failure is often distinguished by diagonal cracks, which are typically angled at 45◦ to the beam's axis [2]. Design of shear resistance depends upon factors like material properties, cross-sectional geometry, as well as the presence and type of reinforcement [3-11]. The shear failure is more frequent than flexural failure and typically happens without any prior warning [12]. Thus, the design of shear strength should be more accurate and adequate.

Steel stirrups are used to resist shear stress according to ACI 318-25 [13]. The corrosion problem reduces the steel's lifespan [14&15]. The costly maintenance of RC members damaged as a result of steel corrosion is one of the important challenges that owners have to take into consider [16&17]. However, alternative reinforcing materials like FRP are the result of recent innovations. FRP is commercially ready in the form of bars, sheets and grids used in concrete members to fulfill several desired properties [18-21].

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The tensile strength, modulus of elasticity, and alkaline resistance of Carbon Fiber Reinforced Polymer (CFRP) are the highest compared to other types of FRP. On the other hand, GFRP is more economical than any other type of FRP [22-24]. At the same time, the elastic modulus for the GFRP bars is about 1/5 compared to the steel modulus [25]. The behaviour of the GFRP bar is linear during the tensile strength test and exhibits brittleness at failure, as shown in Figure (1).

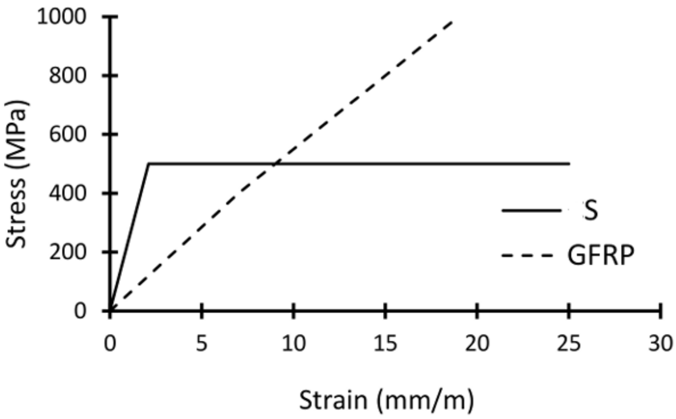

Fig. 1 Stress-strain curve for GFRP and Steel [26].

GFRP bars have a lot of sustainable advantages over steel, such as 85% lower CO_2 emissions, higher durability, and lower lifecycle costs due to corrosion resistance [27]. Their high-strength, lightweight properties allow for material saving and reduced environmental impact across a wide range of construction applications.

Despite much research having been conducted in the last 10 years to assess the performance of GFRP-RC beams, several significant gaps remain. First, current shear design models (e.g., ACI 440.1R-15 and CSA S806) are predominantly derived for steel-reinforced concrete and may be improperly for GFRP's linear behavior, reducing modulus of elasticity and bond properties. Second, research on the long-term durability of GFRP under shear cracking, environmental exposure (alkalinity, moisture, temperature, humidity), and cyclic loading is limited. Third, the new GFRP arrangement can significantly develop shear capacity; therefore, more research is required to improve these designs and check their effectively by finite element modeling. Additionally, practical challenges such as optimal detailing of GFRP stirrups, size effects in large-scale beams, and the effective of hybrid reinforcement systems require further investigation to facilitate wider adoption in construction.

This review aims to (i) provide an inclusive review of the works conducted in this field, giving a higher consideration to the recent findings, (ii) explain limitations in current models, evaluating the influence of GFRP properties (e.g., bar type, stirrup configuration), (iii) highlight innovative solutions (e.g., hybrid reinforcement, advanced composites). The review will suggest recommendations for developing practical applications by bringing together research from around the world. That will help to make GFRP more safety and effective in shear-critical structural members.

2. Comparison between types of FRP and steel bars

Steel and FRP are common materials used as reinforcement in concrete structures. Each one has advantages and disadvantages, so structural demands, environmental conditions, and financial constraints are taken into account when making a decision to choose between them. Table (1) shows the main differences between steel stirrup and types of FRP [13, 28-42].

Table 1 The main different properties between steel, GFRP, CFRP, and AFRP bars [13, 28-42]

Property	Steel bars	GFRP bars	CFRP bars	AFRP bars
• Materials composition	Carbon steel	Glass fiber + polymer resin	Carbon fiber + polymer resin	Aramid fiber + polymer resin
• Tensile strength (MPa)	483-1600	483-690	600-3690	1720-2540
• Modulus of elasticity (GPa)	200	35-51	120-580	41-125
• Yield stress (MPa)	276- 517	NA	NA	NA
• Yield strain, percent	0.14-0.25	NA	NA	NA
• Density (gm/cm^3)	7.9	1.25-2.1	1.5-1.6	1.25-1.4
• Corrosion resistance (durability)	Poor	Excellent	Excellent	Excellent
• Cost	Low	Moderate	Very high	High
• Application to concrete	Standard placement, welding, and can be used with Near Surface Mounted (NSM)	Installed same steel bars, but needs anchors and non-weldable	Installed same steel bars, but needs anchors and non-weldable	Installed same steel bars, but needs anchors and non-weldable
• Alkali Reaction	Creates a passive oxide layer and corrodes when the pH falls	Alkali attack susceptibility as a high pH concrete	Highly resistant to alkalis	Resistant to alkalis
• Acid/Salt Resistance	Exposed to corrosion in salts and acids	Resistant to acids and salts	Resistant to acids and salts	Resistant to acids and salts
• Applications	Widely used in conventional RC and seismic-resistant structures and high-rise buildings	Suitable for corrosive situation (marine structures)	Suitable for corrosive situation (marine structures)	Suitable for corrosive situation (marine structures)
• Design codes	Governed by several methods such as ACI 318-25 and CSA A23.3-04, [13&37]	Governed by several methods such as: ACI 440.11-22, JSCE-97, Said, ISIS-2007, and CSA S806-12 [38-42]	Governed by several methods such as: ACI 440.11-22 [38]	Governed by several methods such as: ACI 440.11-22 [38]

3. Shear transfer mechanisms in concrete beams

RC beams are governed by a number of critical parameters that determine their shear capacity and behaviour, which in turn influence the shear transfer mechanisms. Key mechanisms are shown in Figure (2) [43] and include:

- The compression zone offers primary resistance to shear forces in uncracked concrete [44&45].
- Residual tensile stress in concrete is the shear strength at concrete-to-concrete interfaces [43].
- Dowel action is the second mechanism that allows longitudinal reinforcement to resist shear forces at crack interfaces. The dowel action is influenced by the amount and types of longitudinal reinforcement [46].
- Aggregate interlock is a primary mechanism for resisting shear. Studies suggest that it can contribute up to 70% or more of the total shear strength in such beams [47]. The existence of shear reinforcement, reduces the impact of aggregate interlock on shear resistance.
- Shear resistance of shear reinforcement, which varied depending on the type (steel, GFRP, CFRP, and AFRP) and amount of it.

Understanding these mechanisms is vital for predicting shear failure and enhancing the RC building design.

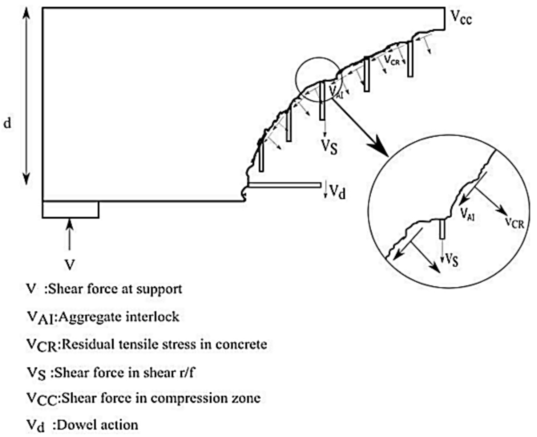

Fig. 2 Reinforced concrete beams' shear transfer mechanisms [43].

4. The analytical approach

ACI 440.11-22 [38] recommended that the GFRP-RC beam shear strength (V_{cf}) be specified in Eq. (1) when the FRP is used as longitudinal reinforcement.

$$V_{cf} = \frac{2}{5}\sqrt{f_c'}\ b_w c \qquad (1)$$

where f_c' is the concrete compressive strength in MPa; b_w is the web width in mm, and c is the depth of the neutral axis in mm.

The ACI 318-25 [13] method which is utilized to evaluate shear capacity of steel stirrups, is usable to evaluate the shear strength when shear reinforcement represented by FRP as shown in Eq. (2).

$$V_f = \frac{A_{fv}\, f_{fv}\, d}{s} \qquad (2)$$

where V_f is shear strength supplied by FRP stirrups in N; A_{fv} is the FRP stirrups' area provided in distance s in mm^2; f_{fv} is level of stress in FRP for shear design in MPa; d is the beam's effective depth in mm; and s is the distance from center to center between FRP stirrups in mm.

Eq. (3) represents the level of stress in FRP shear design (f_{fv}) according to ACI 440.11-22 [38]. The reasons for the limitation of the tensile strength are: to decrease the shear crack width, to protect the concrete shear strength and to prevent the part of the FRP stirrups that is bent from failure.

$$f_{fv} = 0.005\, E_{fv} \le f_{fb} \qquad (3)$$

where f_{fb} is FRP bent portion strength in MPa as shown in Eq. (4) [48]; E_{fv} is FRP stirrups elastic modulus in MPa.

$$f_b = \left(0.05\left(\frac{r_b}{d_b}\right) + 0.3\right) f_{fu} \qquad (4).$$

where f_{fu} is FRP ultimate tensile strength; r_b is FRP stirrups bending radius, and d_b is the diameter of the stirrups bar.

ACI 318-25 [13] recommended the availability of the smallest quantity of steel shear reinforcement ($A_{sv,min}$) when the ultimate shear force (V_u) overtake $ØV_c/2$ to avoid the sudden shear failure in members. The same recommendation is applied when shear reinforcement is represented by FRP, as shown in Eq. (5).

$$A_{fv,min} = 0.35\frac{b_w\, s}{f_{fv}} \qquad (5)$$

where $A_{fv,min}$ is the minimum shear reinforcement.

A variety of equations are employed to assess the shear strength of GFRP-RC beams, with several of these outlined in Table (2).

Table 2 Shear strength according to [38-42].

Analytical method	V_{cf}	V_f
ACI 440.11-22 [38]	$V_{cf} = max\begin{cases} \frac{2}{5}\lambda_s\sqrt{f_c'}\ b_w c \\ 0.0664\,\lambda_s\sqrt{f_c'}\ b_w c \end{cases}$ λ_s is the size effect factor $\lambda_s = \begin{cases} \sqrt{(2/(1+d/254)\ )} \le 1.0 & A_{fv} \le A_{fv}, min \\ 1 & A_{fv} \ge A_{fv}, min \end{cases}$	$V_f = \frac{A_{fv}\, f_{fv}\, d}{s}$ $f_{fv} = max\begin{cases} 0.005\, E_{fv} \\ \left(0.05\left(\frac{rb}{db}\right) + 0.3\right) f_{fu} \\ f_{fu} \end{cases}$
JSCE-97[39]	$V_{cf} = \beta_d\, \beta_p \beta_n f_{vcd} b_w \frac{d}{\gamma_b}$ β_d is the size effect factor, β_p is the factor of tensile reinforcement stiffness, and β_n is the factor depended on the axial force on cross-section. $\beta_d = \left(\frac{1000}{d}\right)^{\frac{1}{4}} \le 1.5$ $\beta_p = \left(\frac{1000\rho_f E_f}{E_s}\right)^{\frac{1}{4}} \le 1.5$ $\beta_n = 1$ in the absence of any axial force $f_{vcd} = 0.2\sqrt[3]{f_c'}$ supplied that $f_{vcd} \le 0.72$ N/mm^2 $\gamma_b = 1.3$	$V_f = \left[\, A_{fv}E_{fv}\, \epsilon_{fwd}\, (\cos\alpha_s + \sin\alpha_s)/s\right] \frac{z}{\gamma_{bs}}$ α_s =angle generated by shear reinforcement and the axis of the member z is the distance between compression and tensile resistance forces, $z = \frac{d}{1.15}$ γ_{bs} =1.15 $\epsilon_{fwd} = 0.0001\left(f_{mcd}'\left(\frac{\rho E_f}{\rho_w E_{fv}}\right)\right)^{\frac{1}{2}}\left[1 + 2\left(\frac{\sigma_n}{f_{mcd}'}\right)\right]$ ρ_w is the shear reinforcement ratio $, \rho_w = \frac{A_{fv}}{b_w s}$ $f_{mcd}' = \left(\frac{h}{0.3}\right)^{-\frac{1}{10}} f_c'$ h=Height of the section

Said [40]	$V_{cf} = 0.037\left(\frac{\rho_f\, E_f}{\beta_1}\right) b_w\, d$ ρf is the FRP tensile reinforcement ratio $\rho_f = \frac{A_f}{b\, d}$ $\beta_1 = 0.85 - 0.007(f_c' - 28) \geq 0.65$	$V_f = \frac{A_{fv}\, f_{fv}\, d}{s}$ $f_{fv} = 0.00096\sqrt{f_c'\left(\frac{\rho_f\, E_f}{\rho_{fv}\, E_{fv}}\right)}\, E_{fv} \leq f_{fb}$
ISIS-2007 [41]	$V_{cf} = 0.2\,\lambda\sqrt{f_c'}\, b_w\, d\,\sqrt{\frac{E_f}{E_s}}$ λ =Factor for reducing mechanical properties of lightweight concrete	$V_f = \frac{A_{fv}\, f_{fv}\, d_v}{s}\cot\theta$ $f_{fv} = max\begin{cases}\epsilon_{fwd}\;\; E_f \\ \frac{\left(0.05\left(\frac{rb}{db}\right) + 0.3\right) f_{fu}}{1.5}\end{cases}$ $\epsilon_{fwd} = 0.0001\left(f_c'\left(\frac{\rho E_f}{\rho_w E_{fv}}\right)\right)^{\frac{1}{2}}$ d_v=0.9 d ɵ= the shear plane's angle of inclination, which is assumed equal to 45°
CSA S806-12 [42]	$V_{cf} = 0.05\,\lambda k_m k_r\sqrt[3]{f_c'}\;\; bd_v$ Such that $0.11\sqrt{f_c'}\, bd_v \leq V_c \leq 0.22\sqrt{f_c'}\, bd_v$ $k_m = \sqrt{\frac{V_f\, d}{M_f}} \leq 1,$ where $\frac{V_f\, d}{M_f} = \frac{a}{d}$ k_r=1+$(E_{fv}\rho)^{\frac{1}{3}}$	$V_f = \frac{0.4\, A_{fv}\, f_{fv}\, d_v}{s}\cot\theta \qquad f_{fv} \leq 0.005\, E_{fv}$ $\theta = 30° + 7000\epsilon_l$ Such that $30° \leq \theta \leq 60°$ $\epsilon_l = \frac{M_f d_v + V_f + 0.5N_f}{E_{fv}\, A_{fv}}$ N_f= axial load, which is normal to the cross section of member

5. Review of literature on shear performance of RC beams using GFRP

This literature overview displays several studies that have utilized GFRP as a shear reinforcement in RC beams. Many parameters were studied, such as the ratio of shear span to the depth (a_v/d), the amount and the type and spacing of stirrups, arrangement of shear reinforcement, etc.

5.1 Effect of reinforcement ratio (longitudinal and transverse reinforcement)

GFRP-RC beams were examined by Said et al. (2016) [40]. The variations among the nine beams were the stirrups spacing and the longitudinal reinforcement ratios of GFRP. Results from Non-linear Finite Element (NFE) analysis were compared with the empirical findings. Findings indicate that employing GFRP as stirrups increased shear capacity by 41% - 82% with stirrup spacing varied from 215 mm to 100 mm, compared with beams that had no stirrups. The GFRP-RC beams' strength was enhanced with an increase in the main reinforcement ratio.

Johnson & Sheikh (2016) [49] studied ten large beams with 400mm width, 650 mm depth, and 3640 mm length, which were reinforced using GFRP. Three-point bending was used to test the beams, which varied in shear reinforcement ratio, and GFRP bar type (milled-surface and sand-coated). Results showed that GFRP stirrups significantly enhanced shear capacity with strains exceeded 1% at failure, well above the strain limits prescribed by design codes. Beams with GFRP stirrups exhibited less brittle shear failures than expected, with wide shear cracks providing warning before failure. There was no fundamental difference in the shear strength between milled-surface or sand-coated stirrups. Higher shear reinforcement ratio led to a rise in shear capacity, improved ductility, and better cracking control, but shear cracks remained a concern, especially at service load levels.

Mahmoud & El-Salakawy (2016) [50] performed both practical and numerical analyses to study the shear performance of GFRP stirrups in RC continuous beams. Seven large-scale continuous specimens supported over two spans were tested: one steel-RC beam and six GFRP-RC beams, as shown in Figure (3). Variables included the diameter of GFRP stirrups (4.8-12.7) mm and the spacing of stirrups (115 and 150) mm, which produced different shear reinforcement ratios (0.21-1.1) %. The test results displayed that shear failure near the interior support was observed for all beams, with significant moment redistribution observed. Increasing the transverse reinforcement ratio by larger stirrup diameters did not result in a substantial increase the shear capacity. However, reducing stirrup spacing was more effective. The failure shape of the tested beams depended on the shear reinforcement ratio. The CSA/S806-12 [40] code provided a better estimation of shear strength compared to ACI 440.1R-06 [55]. ATENA software was employed to develop an NFE model to accurately characterize the shear behaviour of RC beams. The NFE model demonstrated a high degree of agreement with empirical results.

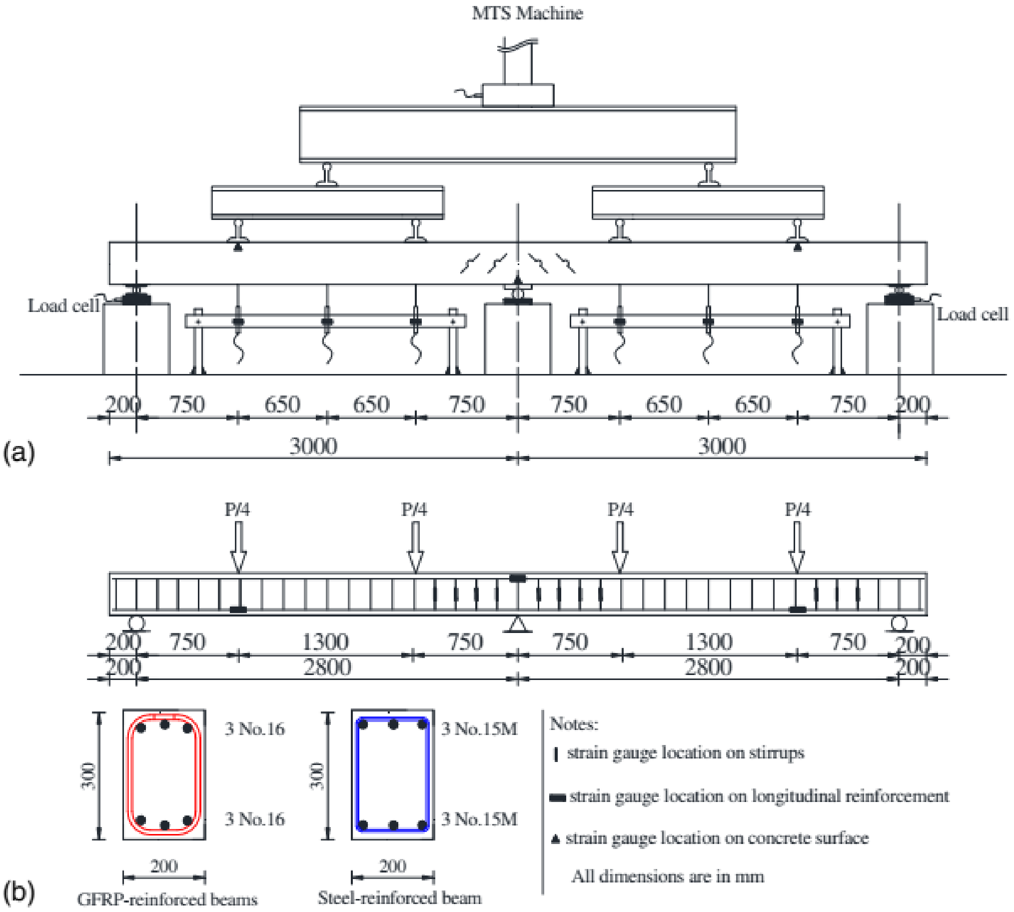

Fig. 3 Details of specimens, (a) test set up; (b) reinforcement details and cross section of beams [50].

Krall & Polak (2019) [51] focused on the efficiency of GFRP stirrups in RC beams. The research involved casting 12 beams with different ratios of longitudinal reinforcement, stirrup size, and spacing arrangement. The beams performed three-point bending testing with a constant a_v/d equal to 2.5. The researcher concluded that raising the longitudinal reinforcement ratio from 1.82 % to 2.51% caused in an approximate 30% enhancement in shear strength for RC beams without shear reinforcement. Whereas RC beams failed at similar applied loads when longitudinal reinforcement ratios varied, but the shear reinforcement ratios remain the same. Increasing the stirrup size and reducing its spacing enhanced the shear capacity of RC beams with GFRP. However, these measures reduced as the shear reinforcement ratio increased.

Shear failure in GFRP-RC beams was examined by Szczech & Kotynia (2020) [52] using five real-scale, simply supported T-section concrete beams. The variations of the study were bar diameter of longitudinal reinforcement (25 and 28) mm, bar diameter of transverse reinforcement (8 and 12) mm, and GFRP stirrups spacing (120, 250, and 270) mm with a constant a_v/d ratio (2.9). After testing the specimens, the failure mode of beams with GFRP stirrups showed more complex crack patterns with multiple diagonal shear cracks developed as the load increased. That is due to the high strain of GFRP compared to steel. Higher transverse reinforcement ratios resulted in more cracks with smaller widths, indicating better crack control. Increasing the shear reinforcement ratios caused to enhance of shear strength by 72% -198% compared to specimens without stirrups. Also, a 33% enhance in the shear strength was observed when the longitudinal reinforcement ratios increased. The strain measurements on GFRP stirrups showed that higher transverse reinforcement ratios led to higher strain values, indicating greater utilization of the stirrups.

Looking into the possibility of employing GFRP instead of conventional steel reinforcement, Issa et al. (2024) [53] studied the contribution of GFRP to the shear capacity of RC beams. All beams were reinforced with GFRP stirrups, with the exception of one, which was reinforced with steel stirrups. The variations were the spacing of GFRP stirrups (50, 75, and 100) mm. Test findings displayed that reducing the GFRP stirrups' spacing from 100mm to 50mm caused an 11% rise in shear capacity and helped restrain crack widening. Whereas, the shear strength was stable when the stirrups' spacing varied from 100mm to 75mm.

5.2 New arrangement of shear reinforcement

Eight large-scale GFRP-geopolymer concrete beams were prepared by Maranan et al. (2018) [54]. The study aimed to examine the impact of the arrangement of the shear reinforcement (GFRP stirrups and GFRP spiral), as shown in Figure (4), and spiral pitch (75,100 and 150) mm on the beam shear performance. It was observed that strength and deflection capacity have been raised by 20% and 120%, respectively, when the spiral reinforcement was employed compared to the conventional stirrups. That was attributed to the spiral's inclination, which was near perpendicular to the shear cracks. The enhancement due to the close-spiral pitch was the main factor in developing the shear strength and the confinement of concrete beams compared to the wide-spiral pitch.

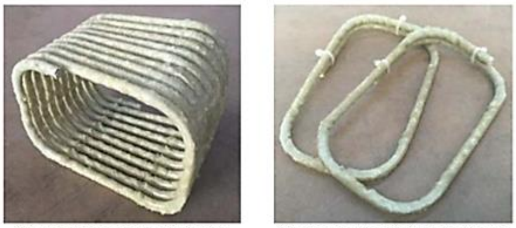
(a) Continuous spiral stirrups (b) Conventional closed stirrups

Fig. 4 GFRP shear reinforcement [54].

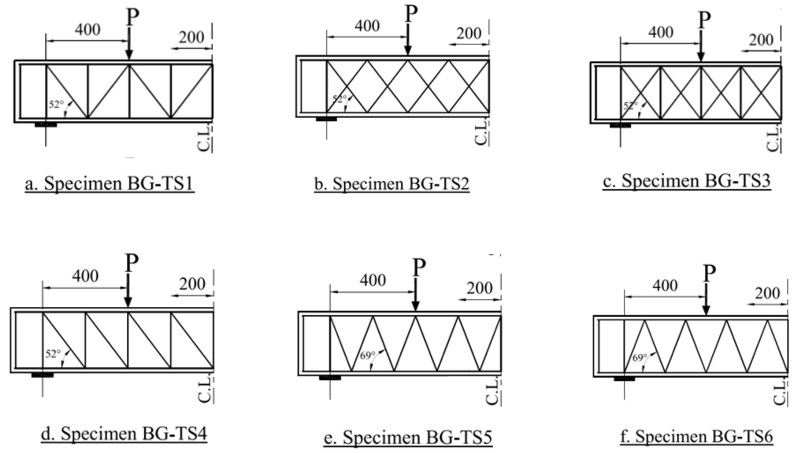

Fig.5 Various embedded GFRP trusses [55].

Moubarak et al. (2023) [55] investigate the performance of GFRP trusses integrated into RC beams as a new shear reinforcement technology, as presented in Figure (5). The results indicated that shear strength was enhanced by 56%–80% compared to the specimen without stirrups and by 29%–50% when compared to the beams with only vertical GFRP stirrups when embedded GFRP trusses were used. Beams with embedded GFRP trusses exhibited shear-compression failure, while the specimen without stirrups failed in shear-tension failure, as shown in Figure (6). That means that the trusses helped delay the creation of significant shear cracks because the direction of bars is almost perpendicular to shear creacks .

Control beam - Specimen BC

Specimen BG-TS1

Specimen BG-TS2

Specimen BG-TS3

Specimen BG-TS4

Specimen BG-TS5

Specimen BG-TS6

Fig.6 Mode failure of tested beams [55].

5.3 Impact of a_v/d ratio and type of shear reinforcement

Maranan et al. (2017) [56] studied in another work how geopolymer-RC beams with GFRP bars behave when subjected to shear stress. Six beams with $a_v/d = 1.8$ (deep beams) and one with $a_v/d = 4.7$ (slender beam) were studied. One of the deep beams was without shear reinforcement, and another parameter of the deep beams was the type of shear reinforcement (steel and GFRP). The findings showed that GFRP stirrups in deep beams significantly enhanced shear and deflection capacity by about 200%. Web shear cracks in deep beams and flexural shear cracks in the slender beam were observed. Brittle shear with diagonal strut compression failure was observed in deep beams that had GFRP stirrups, and diagonal strut tension failure in the beam, which did not have stirrups. While the concrete was crushed in the flexural compression zone, which caused the failure in the slender beam. Strains in GFRP stirrups were higher than in steel stirrups, indicating enhanced strain resistance. In addition, shear capacity estimation provided by ACI 318-08 Strut and Tie Method (STM) [57] was more accurate, while the CSA S806-12 STM [42] was overly conservative.

Li et al. (2022) [58] designed and tested six RC beams with dimensions of (150×300×2400) mm. This study examine the impact of stirrup type (steel and GFRP) and a_v/d (1.5, 2, and 3) on the shear strength of RC beams. The researcher found that the shear capacity of the tested beams decreased and the diagonal crack width increased as the a_v/d and spacing of the stirrups increased. Also, beams with GFRP stirrups showed slightly wider cracks and a 12.5% decrease in shear capacity when compared to steel stirrups. That is because the elastic modulus for GFRP is lesser than steel.

A study by Sobeh et al. (2023) [59] focused on the shear capacity prediction of RC deep beams with GFRP bars using a verified numerical model. NFE models GFRP_RC beep beams with 300mm width, 1200 mm depth, and 5000 mm length were tested to study the effects of a_v/d (1.0 and 1.5). The results exhibited that the suggested numerical model showed accurate predictions regarding shear strength. Increasing a_v/d reduced shear strength more significantly in beams with lower compressive strength and larger stirrups spacing. At the ultimate load, a 0.4 % strain in the horizontal shear reinforcement (GFRP) was lesser than that in the vertical stirrups, which was 0.7%. This evidence suggests that the vertical stirrups are subjected to higher tensile stresses during loading.

5.4 Effect of fiber in concrete mix

Gomes et al. (2023) [60] investigated how GFRP-RC beams behave with basalt fiber under shear stress. The study focused on four beams: without stirrups or fiber (B00), with GFRP stirrups only (BS0), with 0.5% basalt fiber only (BOF), and with both GFRP stirrups and fiber (BSF). Three-point bending was used to test the specimens with a constant a_v/d (2.54). The displacement of RC beams with fiber and/or stirrups was reduced, and the post-cracking rigidity of these beams was higher in comparison to beams that did not have shear reinforcement, as presented in Figure (7). Failure modes were basalt fiber rupture in B0F and BSF, whereas stirrup rupture in BS0. The combined use of fiber and stirrups in specimens of B0F and BSF caused a 23% enhancement in shear capacity compared to beams with only stirrups (BS0) and a 38% increase compared to beams with only fiber (BOF).

Erfan et al. (2025) [61] investigated how adding steel fiber to the concrete mix may improve the shear performance of beams with GFRP. Shallow wide-RC beams of 200mm depth, 600mm wide, and 2100mm length were tested. It was showed that utilizing steel fiber with the concrete mix by 1.5% caused to increase in the shear load failure by 14% when compared to beams without steel fiber. Whereas, the effect of steel fiber in the concrete mix with GFRP stirrups caused to increase the mid-deflection by 3%. This is because the ductility of steel fiber, which compensates for the brittle property of GFRP.

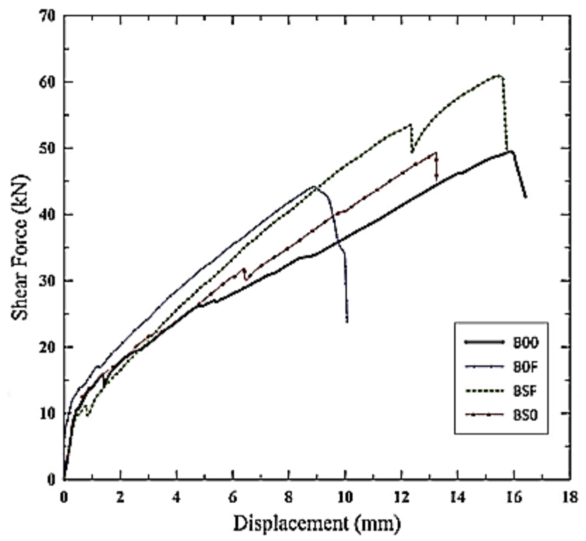

Fig. 7 Load-displacement relationship [60].

The summary of previous studied is stated in Table (3).

Table 3 the summarized of literature overview.

Parameter of study	Authors	Note
Effect of reinforcement ratio (longitudinal and transverse reinforcement)	Said et al. (2016) [40]	The increase of GFRP longitudinal and transverse reinforcement ratios could develop the shear strength of RC beams.
	Johnson & Sheikh (2016) [49]	Higher shear reinforcement ratio led to a rise in shear capacity, improved ductility, and better cracking control, but shear cracks remained a concern, especially at service load levels. The strain in GFRP stirrups at failure exceeded 1%.
	Mahmoud & El-Salakawy (2016) [50]	Raising the shear reinforcement ratio by larger stirrup diameters did not major increase the shear strength.
	Krall & Polak (2019) [51]	The rise in longitudinal reinforcement ratio from 1.82 % to 2.51% caused a 30% development in shear capacity for RC beams without shear reinforcement. Whereas RC beams failed at similar applied loads when longitudinal reinforcement ratios varied, but the shear reinforcement ratios remain the same.
	Szczech & Kotynia (2020) [52]	The failure mode of beams with GFRP stirrups showed more complex crack patterns as the load increased. Higher transverse reinforcement ratios resulted in more cracks with smaller widths.
	Issa et al. (2024) [53]	The reducing spacing of GFRP stirrups from 100mm to 50mm caused an 11% rise in shear capacity. Whereas, the shear strength was stable when the stirrups' spacing varied from 100mm to 75mm.

New arrangement of shear reinforcement	Maranan et al. (2018) [54].	The strength and deflection capacity have been raised by 20% and 120%, respectively, when the spiral reinforcement was employed compared to the conventional stirrups.
	Moubarak et al. (2023) [55]	The shear strength was enhanced by 29%–50% when compared to the beams with only vertical GFRP stirrups when embedded GFRP trusses were used.
Impact of a_v/d ratio and type of shear reinforcement	Maranan et al. (2017) [56]	Brittle shear with diagonal strut compression failure was observed in deep beams that had GFRP stirrups, and diagonal strut tension failure in the beam without stirrups. While the concrete was crushed in the flexural compression zone, which caused the failure in the slender beam.
	Li et al. (2022) [58]	The shear strength decreased, and the diagonal crack width developed as the a_v/d increased. Also, beams with GFRP stirrups showed slightly wider cracks and a 12.5% drop in shear strength when compared to the beams with steel stirrups.
	Sobeh et al. (2023) [59]	The suggested numerical model showed accurate predictions of shear strength. Increasing a_v/d reduced shear strength more significantly in beams with lesser compressive strength and larger spacing.
Effect of fiber in concrete mix	Gomes et al. (2023) [60]	The displacement of RC beams with basalt fiber and/or stirrups reduced, and the post-cracking rigidity of these beams was higher in comparison to beams that did not have shear reinforcement.
	Erfan et al. (2025) [61]	Utilizing steel fiber with the concrete mix by 1.5% caused to develop in the shear load failure by 14% when compared to beams without steel fiber. Whereas, the contribution of steel fiber with GFRP stirrups increased the mid-deflection by 3%.

6. Conclusions

This paper reviews how GFRP-RC beams behave when subjected to shear stress. The following conclusions are summarized:

- Using GFRP stirrups rather than steel stirrups achieves more durable beams as a result of excellent corrosion resistance; therefore, it is ideal for aggressive environments.
- GFRP reinforcement can effectively enhance the shear strength of the concrete beams. Increasing transverse rebars spacing or raising longitudinal reinforcement ratio can enhance shear capacity.
- The spacing and diameter of GFRP stirrups play a crucial role in shear performance. Proper stirrups size and spacing is required to optimize shear strength without over-reinforcing. In addition, reducing stirrups spacing is more effective in increasing shear strength than increasing stirrup diameter.
- Beams with less than or equal to the minimum transverse reinforcement fail by stirrups yielding, while those with higher than the minimum fail by concrete crushing.

- Basalt fiber significantly enhances the shear strength, stiffness, and ductility of RC beams with GFRP stirrup, especially when combined with minimal stirrup reinforcement.
- Increasing the a_v/d ratio generally reduces the shear cracking load, capacity, and post-cracking stiffness, resulting in a load-deflection response that is less preferable for beams with higher a_v/d ratios.
- Using the new configuration of GFRP, such as spiral reinforcement and embedded GFRP trusses, is an effective alternative to the conventional steel stirrups, significantly enhancing shear capacity and improving concrete confinement.
- The CSA/S806-12 code provides more accurate shear strength predictions and is more conservative than the ACI 440.1R-06.

7. Future work and practical recommendations

Further researches are needed to explore the behaviour of hybrid stirrups (steel and GFRP)-RC beams with the main parameters such as a_v/d, concrete strength, and stirrups spacing. Especially, the two materials (steel and GFRP) have different properties. Combining of green concrete with GFRP is a sustainable solution for concrete structures; thus, additional research is required to optimize the shear performance of green concrete with GFRP reinforcement.

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