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Effects of Using Longitudinal GFRP Reinforcing Bars on Shear Behaviour of RC Beams: A Review

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ABSTRACT

Traditional steel-reinforced concrete beams are prone to corrosion, necessitating frequent maintenance and repairs. Glass Fiber Reinforced Polymer (GFRP) bars present a promising alternative due to their superior corrosion resistance, high strength-to-weight ratio, and electromagnetic neutrality. This investigation aims to understand the performance characteristics and potential advantages of GFRP in structural applications, particularly in environments prone to corrosion. A series of experimental and analytical tests evaluated, and key parameters such as deflection, stiffness, crack width, and shear strength are analyzed. The results demonstrated that GFRP-reinforced beams exhibit significantly higher deflections and strains post-cracking compared to their steel-reinforced counterparts. This behavior is primarily attributed to the lower modulus of elasticity of GFRP bars and their distinct bond characteristics with concrete. Furthermore, the shear strength of GFRP-reinforced beams was found to be lower than that of steel-reinforced beams, highlighting the need for adjusted design methodologies. The study underscores the necessity for over-reinforcement in GFRP-reinforced beams to achieve adequate flexural stiffness and suggests the potential benefits of hybrid reinforcement, combining GFRP and steel, to improve overall structural performance and ductility.

1. Introduction

Conventional concrete structures, such as beams, are typically composed of steel rebars and concrete. The primary role of the concrete in these structures is to withstand compressive forces. Tensile and shear forces, on the other hand, are primarily resisted by the steel rebars that are embedded within the concrete. This combination of materials is effective because the concrete provides inherent resistance to compressive forces, while the steel enhances the structure's tensile and, to some extent, shear strength. However, the longevity of the steel rebars can be compromised due to corrosion. a problem that has long troubled the industry. The inevitable long-term ingress of harmful agents such as chlorides and alkalis, due to inherent defects in heterogeneous materials like concrete, coupled with the combination of moisture and oxygen, leads to the corrosion of steel reinforcing bars. This rapidly results in deterioration and necessitates repair or decommissioning of the structural concrete member, and solutions like rebar coating can be expensive. Recent advancements in composite material technology have paved the way for a novel design and construction strategy. This new strategy involves designing structural members not with steel reinforcing bars, but with Fiber Reinforced Polymer (FRP) reinforcing bars. Besides offering significant benefits in corrosive environments, FRP is electromagnetically neutral and lightweight,

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making it suitable for situations where these properties are crucial [1].

FRP materials were originally developed for the use in the aerospace and automotive industries due to their high strength and light weight. While it is challenging to pinpoint the exact date of the first use of FRP bars, the technology gained momentum in the 1980s and 1990s [2], [3], [4], [5], [6], [7]. The desire for non-corrosive reinforcement in structures exposed to harsh conditions, for example coastal environments or chemical processing plants, drove the development and adoption of GFRP reinforcement. Although there is a growing body of research on the behavior of concrete beams reinforced with GFRP bars, there is still a need for in-depth investigations into specific aspects of their performance [8], [9], [10], [11].

2. Fiber reinforced polymer (FRP) types

In the context of reinforcement and new construction, the fibers typically utilized are glass, carbon, and aramid. These are all synthetic fibers, fabricated through human processes. However, recent research trends have pivoted towards sustainable composites that incorporate natural fibers, such as basalt fibers. These fibers are derived from natural sources and offer an eco-friendlier alternative. Table 1 outlines the standard mechanical properties of these various fibers. It's important to note that the strength and modulus values in this table are for the raw fibers. When these fibers are processed into FRP composites, like pultruded profiles, bars, and sheets, the resulting strength and modulus are significantly reduced compared to the raw fibers. This is due to the manufacturing process and the addition of other materials. All these fibers exhibit a linear elastic stress-strain relationship, meaning they deform proportionally with the applied stress and do not undergo plastic deformation or yielding. This characteristic is crucial in many applications where predictable, elastic deformation is required.

In structural composites, glass fibers are the most frequently utilized. They're employed in structural profiles, reinforcing bars, and strengthening applications. There are four grades of glass fibers available: Electrical glass (E-glass), window glass (A-glass), Corrosion resistant glass (C-glass, also known as AR-glass or Alkali-Resistant glass), and Structural glass (S-glass, also known as high-strength glass). E-glass is the most popular due to its relatively low cost and electrical insulation properties. S-glass, which has a higher tensile strength and modulus than E-glass, is typically used in the aerospace industry due to its high strength. S-glass is nearly four times as expensive as E-glass. All types of glass, except AR-glass, are susceptible to alkaline attack. Glass fibers do not conduct electricity and can be easily used near electrified railway lines, communication facilities, power lines, and constructing medical centers that contains MRI machines. [12].

Table 1: Comparison between different FRP rebar types and steel rebar [12]

Bar type	Density (kg/m^3)	Longitudinal modulus (GPa)	Longitudinal tensile strength (MPa)	Ultimate tensile strain (%)
Steel	7850	210	450-700	5–20
GFRP	1750-2180	35-60	450-1600	1.2–3.7
CFRP	1430-1670	100-580	600-3500	0.5–1.7
AFRP	1330-1450	40-125	100-2500	1.9–4.4

3. Manufacture of FRP reinforcing bars

There are many methods used to manufacture FRP materials used for structural engineering applications including, but not limited to, pultrusion, wet lay-up, filament winding, pull-winding, and injection molding [13]. Pultrusion is the typical process used to manufacture straight internal reinforcement products such as bars, rods, and tendons, and will therefore be the focus of this discussion. The pultrusion process is an automated system which requires very little labor and is thus highly economical. It is an ideal process for products with a constant cross-

section. Figure 1. depicts the typical steps involved in the process. The process begins with the raw fibers stored in small spools called rovings, which are kept on metal racks called creels. As the fiber rovings pass through a bath of polymeric resins, guide plates are used to spread them, ensuring maximum impregnation of the fibers into the resin. After leaving the resin bath, the fibers go through a preforming system that aligns the individual fibers and removes excess resin. The wet fibers are then pulled through a heated die with a specific shape, which molds the section and cures the resin. Due to the high temperatures, the composite shrinks and detaches from the internal walls of the die, exiting as the finished product. The cured composite is typically pulled using urethane pads on a caterpillar belt.

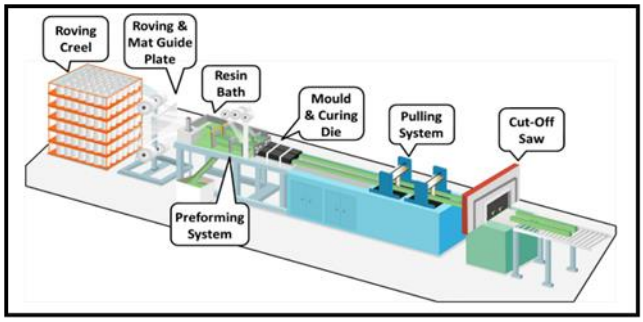

Figure 1. Pultrusion process [13]

A cut-off saw is positioned at the end of the assembly to create products of set lengths. Since the fibers and pultrusion system are continuous, any length of section is possible, but it will be limited by transportation and handling constraints. The composite reinforcement produced in the pultrusion process will have a smooth surface [13]. To enhance the bond mechanisms between the reinforcing bar and concrete, manufacturers apply various surface treatments to the smooth bars. A common treatment is sand blasting the surface of the bars. Another treatment involves creating ribbed bars by cutting grooves into the smooth bar or using compression molding. Some manufacturers produce bars that are helically wrapped with fibers and then sand coated [14], as shown in Figure 2.

Figure 2. Various FRP surface treatments [15]

4. Advantages and disadvantages of using GFRP reinforcing bars

FRP reinforcing bars have emerged as a favored substitute for traditional steel reinforcement in new concrete structures, thanks to the superior durability properties of FRP composites. Concrete structures reinforced with steel are prone to reinforcement corrosion. This corrosion induces tensile stresses in the concrete, often resulting in spalling or delamination of the concrete. Corrosion also diminishes the reinforcement area available for providing strength, thereby weakening the structure. Consequently, corrosion can lead to deterioration that may be confined to aesthetic issues only, or it may advance to structural failure. GFRP reinforcing bars are immune to electrochemical corrosion, making this technology a compelling solution for structures in corrosive environments, and have been successfully utilized in various applications such as bridge decks, bridge piers, underground concrete storage tanks, and concrete barrier walls [13], [16], [17], [18].

FRP materials are electromagnetically neutral, a property that is beneficial for structures housing equipment sensitive to magnetic fields that can be affected by the presence of steel [13]. Additional advantage of GFRP reinforcing bars is their extremely high strength-to-weight ratio. With tensile strengths significantly higher than the yield strength of steel, GFRP bars weigh approximately one fourth of steel bars [19]. While the weight of the reinforcement is minimal compared to the weight of the concrete, this reduced reinforcement weight doesn't significantly decrease the overall weight of the structure. However, this lighter weight is beneficial as it enhances ease of installation, handling, and shipping.

Other benefits include lightweight and ease in transportation, FRP composites are generally less energy-intensive to produce. FRPs also have minimal ecological and carbon footprint compared to the traditional materials [12].

However, there are disadvantages to using GFRP reinforcing bars instead of conventional steel bars.

Although the cost of GFRP bars continues to decrease as manufacturing processes are refined, the initial material cost of FRP reinforcement remains more expensive than steel. However, it has been shown that if a life-cycle analysis is performed to compare FRP reinforcement with other reinforcement alternatives (unprotected steel, cathodic protection, and epoxy-coated steel), the cost of the FRP design is significantly less. This is a result of the superior durability of FRP reinforced structures that do not require the extensive rehabilitation work that is typical of steel reinforced structures [7].

Another drawback of FRP reinforcing bars, particularly GFRP, is their relatively low tensile modulus of elasticity compared to steel. As a result of this lower axial stiffness, concrete structures reinforced with GFRP will experience larger reinforcement strains, leading to the formation of wider cracks and consequently larger member deflections. Therefore, the design of GFRP reinforced concrete structures is typically governed by serviceability limits rather than ultimate strength limits. Concrete members reinforced with FRP may require more bars to meet serviceability requirements, potentially leading to highly congested formwork for cast-in-place concrete [20].

When designing concrete structures reinforced with FRP materials, the potential for creep rupture must also be considered. Polymeric resins are viscoelastic and their behavior is characterized by time-dependent factors including creep, stress relaxation, and load rate effects. Creep is the gradual deformation of a material over time under sustained loading. When FRP materials are subjected to constant high stress levels, sudden failure may occur - a failure mode known as creep rupture. To prevent failure of an FRP reinforced member due to creep rupture of the FRP reinforcement, design standards have specified limits on the maximum allowable stress to be carried by the reinforcement under service loading. These stress limits are typically expressed as a percentage of the ultimate tensile strength of the FRP [13]. Other considerations when using FRP products include exposure to ultraviolet radiation, highly, and moisture exposure. The impact of these factors on the performance of internal GFRP reinforcing bars is significantly harmful.

Almusallam and Al-Salloum [21] investigated the durability of GFRP rebars in concrete beams under sustained loads in harsh environments. The laboratory tests revealed significant losses in the tensile strength of GFRP bars when they were subjected to a sustained stress of about 20-25% of their ultimate strength in the three environments considered in this study. The losses were 27-29% after 4 months, 37-47% after 8 months, and 47-55% after 16 months. For the unstressed specimens exposed to the same environments, the loss in tensile strength ranged between 2 and 10% after 4 months, 13 and 17% after 8 months, and 16 and 22% after 16 months. The results clearly indicate that the GFRP bars undergo significant degradation when subjected to sustained stress over a period of time. Similar losses were observed in the flexural strength of these beams.

Masmoudi et al. [22] conducted an experimental modal analysis on GFRP to determine its damping properties through vibration tests. The damping ratio (ξ) of GFRP bars was found to range between 1.1% and 1.5% for all tested diameters, sweeping across the first three modes. It was observed that as the diameter increased, the damping also increased, particularly noticeable in the first mode. These properties were quantitatively confirmed to be acceptable, especially for critical excitations such as earthquakes.

The bonding behavior between two different types of GFRP bars and concrete was examined and compared with standard steel bars in a study by Fava et al. [23]. GFRP bars that were sanded and spirally wrapped exhibited brittle bond behavior, characterized by the sudden debonding of the entire sand coating layer. Interestingly, these bars were also capable of undergoing a continuous debonding process, even when used

with high-strength concrete. On the other hand, ribbed GFRP bars displayed a bond behavior that was similar to their steel counterparts, albeit with a different debonding mechanism. These GFRP bars necessitated nearly 30% more fracture energy during the debonding process. When compared under the same experimental conditions, both types of GFRP bars demonstrated bond strength that was, on average, lower than that of steel bars, although the strengths were comparable.

Bazli et al. [24] conducted an experimental study to assess the short-term degradation of materials when submerged in harsh solutions, as well as the long-term mechanical performance of GFRP. The study found that the flexural and compressive strengths of the GFRP profiles diminished in comparison to their un-aged strength values. Specimens that were immersed in an alkaline solution with a pH of 13.6 exhibited the most significant reduction in flexural and compressive strength during bending and compression tests. Similarly, submersion in an acidic solution also led to a substantial decrease in both the flexural and compressive strength of GFRP.

Mechanical characteristics of three different types of GFRP reinforcing bars at elevated temperatures were studied experimentally by Hajiloo et al. [25] and conducted both steady-state and transient temperature tests on GFRP bars. All types of bars lost strength and stiffness when exposed to high temperatures. Three different types of GFRP bars were tested: Type A (sand coated), Type B (with external braided fibers), and Type C (ribbed bar). In the steady-state tests, Type A bars demonstrated a linear decrease in tensile strength, but they retained 40% of their original strength at room temperature after being exposed to 375°C. Type B bars, on the other hand, maintained most of their strength (80%) at temperatures below 250°C, but their strength sharply dropped to 35% around 400°C. Type C bars exhibited a linear decrease in strength up to 250°C, after which the retained strength remained constant up to 350°C. When heated to 438°C and 486°C, the retained strength for Type C bars was 51% and 36%, respectively. Transient temperature tests, which are more representative of fire conditions than steady-state tests, were also conducted. The results from both types of tests were relatively similar, but the transient temperature method is recommended for its applicability. In these tests, Type A bars failed at 518°C under a sustained load of 75 kN (22% of room temperature strength). Type B bars, subjected to 25% (64 kN) of the original strength, did not fail at 420°C. Type C bars failed at 508°C under a load of 70 kN (25% of ultimate strength). Based on the results of both the steady-state and transient temperature tests, the critical temperature for all tested bars would be above 400°C. However, since matrix decomposition occurs at 400°C, it is recommended to consider 400°C as the critical temperature.

D'Antino and Pisani [26] conducted a study on the long-term behavior of Glass Fiber Reinforced Polymer (GFRP) reinforcing bars. The study involved 9 short-term tests and 17 long-term tests on these bars. The bars were subjected to various tests including short-term tests (9 bars), relaxation tests (10 bars), and creep tests (7 bars). Long-term tests were carried out over periods of 1000 and 2000 hours, with five different initial applied stresses considered: 0.1*ff*, 0.2*ff*, 0.4*ff*, 0.6*ff*, and 0.8*ff*, where '*ff*' represents the short-term tensile strength of the bar. The results from the relaxation and creep tests were scattered, which is attributed to the random distribution of the rebar properties. As a result, it is recommended to conduct a large number of tests to obtain reliable results on the long-term behavior. The long-term tests did not impact the strength and elastic modulus of the GFRP bars when the initial applied stress was less than or equal to 0.6ff. However, an initial applied stress of 0.8*ff*, used in two tests, resulted in the complete failure of the bar in less than 8 hours. The study concluded that a linear viscoelastic behavior can be assumed under service loads for the bars tested in this study.

AlAjarmeh et al. [27] investigated the compressive characteristics of GFRP bars. The study systematically examined the impact of the bar diameter and the ratio of unbraced Length to bar diameter (Lu/db) on the compressive behavior of GFRP bars, using a novel method. The study found that the diameter of the bar does not affect the failure mode of GFRP bars with

the same Lu/db ratio. Bars with a Lu/db ratio of up to 4 failed due to crushing, those with a ratio greater than 8 failed due to buckling, and those with a ratio between 4 and 8 failed due to a combination of crushing and buckling. Bars with smaller diameters were found to be more effective in resisting compressive loads compared to bars with larger diameters. Smaller diameter bars also demonstrated similar tensile strength, while larger diameter bars failed at a compressive stress of only 75% and 65% of their tensile strength, respectively. The study concluded that the slenderness ratio significantly influences the failure behavior and load capacity of GFRP bars under compression, but it does not significantly affect the compressive modulus of elasticity.

Jia et al. [28] conducted a study on the behavior of GFRP bars that were embedded in concrete and subjected to tap and salt water at high temperatures. This was done to speed up the effects of both tap water and simulated seawater environments. The GFRP samples, which had varying depths of concrete cover, were tested under four levels of relative humidity. Additionally, GFRP bars were embedded in concrete with different water-to-cement (w/c) ratios. The study also found that the tensile strength of the GFRP samples decreased over time when immersed in both tap and salt water, with the decrease being more significant in salt water. However, the degradation mechanisms of the GFRP samples differed when immersed in tap and salt water. The normal pore solution from the tap-water immersion had a greater impact on the GFRP bar in terms of moisture absorption and alkaline ion concentration than the salt-water immersion. On the other hand, the pore solution from the salt-water immersion had a greater effect on the depth of moisture penetration in the bars than the tap water immersion. The difference in tensile strength of GFRP samples immersed in tap and salt water was determined by the depth of the concrete cover of the test samples. Samples with a thicker cover showed a larger decrease in tensile strength when immersed in salt water compared to tap water. In this study, the change in tensile strength of GFRP samples in salt water was slightly larger than those immersed in tap water when the concrete cover was 47 mm. The depth of the concrete cover had a negative impact on GFRP bars exposed to humid conditions due to the moisture gradient created along the cover zone. More moisture was retained in the concrete cover that was deeply embedded. The w/c ratio of the concrete cover negatively affected the durability of the GFRP bars.

5. Shear failure in reinforced concrete beams

Shear in concrete beams refers to the internal force that causes adjacent sections of the beam to slide past each other horizontally. It is an important structural consideration because failure due to shear can lead to the formation of diagonal cracks, and in severe cases shear failure. When a load is applied to the beam, it induces shear forces that act perpendicular to the longitudinal axis of the beam. These share forces can cause the concrete beam to crack along inclined planes, resulting in diagonal cracks that radiate from the point of maximum shear. If the applied shear forces exceed the shear capacity of the beam, shear failure occurs, which can lead to catastrophic structural damage [29]. Shear failure can lead to the formation of diagonal cracks, which can propagate rapidly, compromising the structural integrity of the beam and the entire structure. Understanding shear behavior is essential to prevent shear failures, which can have severe consequences.

By looking at a section along a shear crack, Figure 3 four different mechanisms can be seen providing to the overall shear resistance of a slender Reinforced Concrete (RC) beam. The contribution from stirrups, the contribution from the uncracked concrete portion, the contribution from the aggregate interlock along the cracks and the contribution from the dowel action of the reinforcement. The contribution from stirrups is the resistance to crack opening provided by the transverse reinforcement in the beam. Since crack surfaces are not smooth, and aggregate interlock is present, a crack must widen sufficiently for differential movement along the crack surface. The addition of transverse reinforcement restricts this crack opening. As such, the contribution from stirrups is related to the stiffness, strength and amount of transverse

reinforcement used. Additionally, the stirrup contribution tends to increase as the stirrup crosses the crack closer to perpendicular.

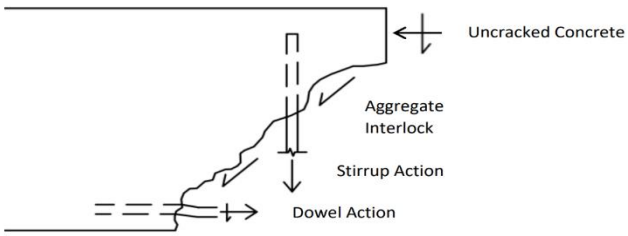

Figure 3. Concrete shear mechanisms [30]

Two additional factors have been recognized that can impact the shear resistance of concrete reinforced beams. They are the residual tensile stresses across cracks and arch action. The residual tensile stresses transpire due to the retention of small portions of concrete crossing small cracks. This causes some of the tensile strength to remain until the crack widens [31].

Aggregate interlock is the resistance to crack differential translation caused by the non-smooth crack surface of the concrete. Due to the heterogeneous nature of concrete and the relative strength of the aggregate compared to the cement matrix for low and mid strength concrete, shear cracks propagate largely around aggregate. This causes resistance to crack sliding and a tendency for increased shear forces to widen the cracks. Aggregate interlock is a complex mechanism that is affected by the concrete mix design, concrete compressive strength, and the flexural stiffness of the beam. Beams reinforced with longitudinal GFRP exhibit lower aggregate interlock due to increased crack widths [32].

Dowel action is the result of induced tensile forces in the longitudinal reinforcement due to the crack opening and the shear resistance of the longitudinal reinforcement itself. The addition of tensile stress to longitudinal reinforcement necessitates extra care in detailing the longitudinal reinforcement. This is especially true in areas that have lower flexural loads combined with high shear loads. It has been theorized that dowel action in GFRP RC beams will be less than in steel RC beams due to the lower transverse stiffness and strength of GFRP deformed bars [32]. The exact influence of using GFRP reinforcement on dowel action has not been investigated.

The uncracked concrete contribution is the shear carrying capacity of the concrete compressive zone. This concrete can carry significant shear stress as the flexural compression stress keeps the principal tensile stress below the tensile capacity of the concrete. The uncracked concrete contribution is impacted by the depth of the neutral axis and the concrete stress-strain behavior. In beams with GFRP longitudinal reinforcement, the lower stiffness of the reinforcement causes a reduced uncracked compression zone and reduces its ability to resist shear [33].

There are also other factors that contribute a significantly on shear capacity of concrete beams , as found by the researchers Christianto et al. [34]. They are longitudinal reinforcement ratio (ρ) and shear span to depth ratio (a/d). A lower steel ratio can lead to a greater extension of the flexural crack that appears on beams. Additionally, the opening of the crack is likely to be broader in comparison to beams that have a higher steel ratio. The a/d ratio affects the type of shear failure. For a/d = 2.5 is the critical value. If a/d < 2.5 the mechanism shear resistance is arch action and a/d > 2.5 the mechanism shear resistance is beam action.

6. Shear failure modes of RC beams

When the beam's ability to resist shear is less than its ability to resist bending, and the shear force is greater than what the beam's materials can handle, shear failure happens. A shear load is a force that causes a material to break along a plane parallel to the force direction. This type of failure is abrupt and does not give any warning signs i.e. brittle failure. The ratio of the effective span to the depth of the beams and their size are key factors in deciding the type of shear failure. Shear failure is a type of failure that should be avoided and usually stirrups are used in the beam to stop the shear failure. The shear failure mechanism is marked by shear sliding along a fracture in beam without shear reinforcement and yielding of stirrups in a beam with shear reinforcement. There are four main shear failure modes, and they consist of the following:

6.1. Shear compression failure:

Watanabe et al. [35] found that this type of failure occurs when the concrete crushes along a diagonal plane that is perpendicular to the direction of the shear force. This type of failure is also sudden and brittle, but it is less common than diagonal tension failure. It usually happens when the beam is heavily reinforced and has a large shear span to depth ratio.

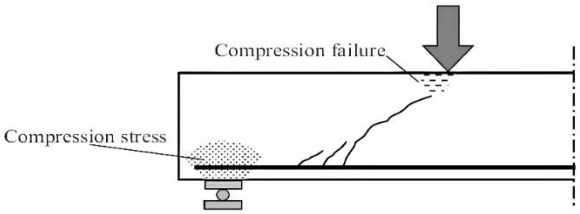

Figure 4. Shear compression failure [36]

6.2. Anchorage failure:

El-Mihilmy and Tedescois. [37] defined it as the breaking of concrete along the longitudinal reinforcement (before the concrete fails in compression) because of tiny diagonal cracks. It happens when the main reinforcement does not have enough anchorage length past the crack.

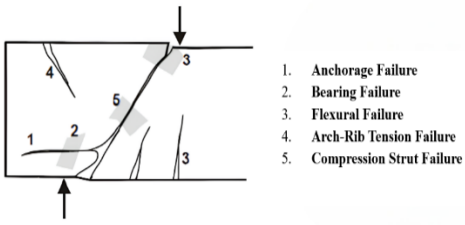

Figure 5. Anchorage failure [38]

6.3. Splitting or compression or true shear failure:

Mohamed and Kalpana, 2016 [39] found that this type of failure occurs in deep beams when the shear span to effective depth (a/d) of beams is less than 1. In this type, shear is transferred by a strut and tie mechanism in which tension reinforcement acts as tie and concrete acts as strut. After the formation of inclined cracking, shear is carried as an inclined thrust between the load and the reaction point and it behaves as a tied arch. The final failure becomes a splitting failure or it may fail in compression at the reaction. The analysis of such an end section is closely related to the analysis of a deep beam.

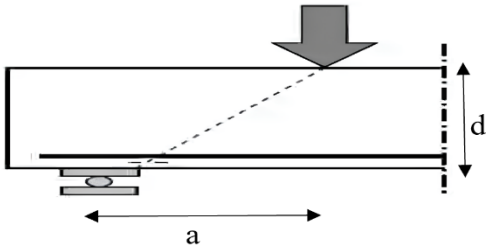

Figure 6. Splitting failure [36]

6.4. Diagonal tension failure:

Słowik and Marta. [40] found that this type of failure happens when the concrete cracks along a diagonal plane that is parallel to the direction of the shear force. This sort of failure is sudden and does not give any warning signs i.e. brittle failure. It is an undesired kind of failure and should be prevented by providing adequate shear reinforcement in the beam.

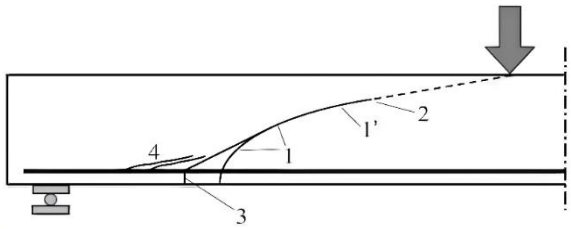

Figure 7. Diagonal tension shear failure [36]

7. Shear strength design provisions

Shear capacity in RC beams is the maximum shear force that the beam can resist before failure. It is achieved through a set of mechanisms that involve the contribution of concrete, ratio of the longitudinal reinforcement (ρs), shear reinforcement, shear span/effective depth ratio (a/d), compressive strength of concrete (f_c'), density of concrete, maximum size of coarse aggregate, beam size, the tensile strength of the longitudinal and transverse reinforcement (f_y), clear length to depth ratio (L/d), the number of layers of longitudinal reinforcement, and other factors all influence the beam's shear strength [41], [42].

Based on simple beam tests, [43] introduced an expression for predicting the shear capacity of

concrete beams reinforced with steel in SI units and includes the effect of the shear span and the reinforcement ratio.

$$V_C = 2(\, f_c' . \rho \, . \frac{d}{a} \,)^{1/3} . b_w . d \quad \ldots\ldots (1)$$

Where:

f_c': the compressive strength of concrete mixture (MPa).

a: the effective shear span(mm).

b_w: the width of the section (mm).

ρ: the longitudinal reinforcement ratio.

d: the effective depth (mm).

In account of a set of experiments conducted Collins and Kuchma. [44] proposed a modification to the simplified AC1 shear design equation to account for the size effect. The suggested formula S_e is a function of S_x which is a function of the member, the layout of the reinforcing and, the maximum aggregate size in the concrete. It should be noted that the proposed equation has been derived from tests performed on normal strength steel reinforced concrete member.

$$V_C = \frac{245}{(1275+Se)} \sqrt{f_c'}\ bd \quad \ldots\ldots (2)$$

Where:

$S_x = 0.9d$

$S_e = \frac{35Sx}{a+16}$

b: the width of the section (mm).

The nominal shear strength provided by the concrete V_c is computed per ACI 318-02 [45] can be calculated as follows:

$$V_c = \frac{1}{6}\sqrt{f_c'} b_w d \quad \ldots\ldots (3)$$

The shear strength may also be computed by the more detailed calculation for members subject to shear and flexure only:

$$V_c = \left(0.16\lambda\sqrt{f_c'} + 17\rho_w \frac{V_u d}{M_u}\right) b_w d \quad \ldots\ldots (4)$$

Where:

$$\rho_w = \frac{A_s}{b_w d}$$

$V_u d$: the factored shear force at a distance from the support equals to the depth of the beam.

Mu: the factored moment acting on the beam.

And the quantity computed by equation (4) should be not greater than:

$$V_c = 0.29\lambda\sqrt{f_c'} b_w d \quad \ldots\ldots (5)$$

Where shear reinforcement is required, the minimum area of shear reinforcement required is computed by:

$$A_v = 0.062\sqrt{f_c'}\frac{b_w s}{f_y} \geq \frac{0.35 b_w s}{f_y} \quad \ldots\ldots (6)$$

Where:

s: the space between shear reinforcement.

f_y: the yield strength of the reinforcement.

The shear strength to be provided by the shear reinforcement is obtained from:

$$V_s = \frac{A_v f_y d}{s} \quad \ldots\ldots (7)$$

The shear strength Vs computed by equation (7) must not exceed:

$$V_s \leq \frac{2}{3}\sqrt{f_c'} b_w d \quad \ldots\ldots (8)$$

And the nominal shear strength V_n computed as:

$$V_n = V_c + V_s \quad \ldots\ldots (9)$$

According to Eurocode 2, 2004 [46], the shear capacity of a reinforced concrete member can be calculated as follows:

$$V_{Rd} = V_{Rd,s} + V_{Rd,c} \quad \ldots\ldots (10)$$

Where:

$V_{Rd,c}$: the design shear resistance of the member without shear reinforcement.

$V_{Rd,s}$: the contribution of web reinforcement.

$$V_{Rd,c} = [C_{Rd,c} k \left(100\rho_I f_{ck}\right)^{\frac{1}{3}} + k\sigma_{cp}\Big] b_w d \ldots (11)$$

$$C_{Rd,c} = \frac{0.18}{\gamma_c} \quad \ldots\ldots (12)$$

$$k = 1 + \sqrt{\frac{200}{d}} \leq 2 \quad \ldots\ldots (13)$$

$$\rho_I = \frac{A_s}{b_w d} \leq 0.02 \quad \text{……. (14)}$$

$$\sigma_{cp} = \frac{N_{Ed}}{A_c} \quad \text{……. (15)}$$

Where:
γc: the partial factor of concrete, its value depends on the design condition, where γc =1.5 if the design condition is persistent & transient and γc =1.2 if the design condition is accidental. As for the cases not mentioned in the code, it is recommended to consider the value of γc equal to 1.
f_{ck}: the characteristic compressive strength of concrete in (MPa).
ρ_I: the longitudinal reinforcement ratio.
σ_{cp}: the mean axial stress in the cross-section.
N_{Ed}: the axial force in the cross section of beam (N).
Ac: the cross-sectional area of the member in (mm^2).

Additionally, the web reinforcement contribution can be calculated as follows:

$$V_{Rd,s} = A_{sw} \frac{1}{s} f_{yd} \ cot\alpha \quad \text{……. (16)}$$

Where:
A_{sw}: the area of shear reinforcement within length.
f_{yd}: the design yield strength of shear reinforcement.
α: the angle between the shear reinforcement and the beam axis.

The total design shear resistance is the sum of the contributions from concrete and shear reinforcement, but it cannot exceed the maximum value given by:

$$V_{Rd,max} = 0.5 v_{max} b_w d \quad \text{……. (17)}$$

The shear strength of concrete estimated according to the proposed equation is in good agreement with the experimental results of the research done by Wegian and Abdalla. [47].

$$V_{cf} = 2\left(f_c \frac{\rho E_f}{E_s} \frac{d}{a}\right)^{1/3} bd \quad \text{……. (18)}$$

Where:
E_f: elasticity modules of the FRP reinforcement.
E_s: elasticity modules of steel reinforcement.

CSA S806-12 [48] follows similar provisions for the design of FRP reinforced concrete as for steel reinforced concrete. The factored shear resistance (V_r) of a transversely FRP reinforced concrete beam is defined as the sum of two components as shown in Equation (19).

$$V_r = Vc + Vs \quad \text{……. (19)}$$

$$V_{r,max} = 0.22\phi_c f_c' b_w d_v + 0.5V_p + \left[\frac{M_{dc} V_f}{M_f}\right] \quad (20)$$

Where:
ϕ_c: the material resistance factor for concrete.
b_w: the concrete web width.
d_v: the effective shear depth.
V_p: the component in the direction of the applied shear of the effective prestressing force.
M_{dc}: the decompression moment.
V_f: the factored applied shear.
M_f: the factored applied moment.

The concrete contribution, for normal sized members, is determined in accordance with Equation (21).

$$V_C = 0.05\lambda\phi_c k_m k_r (f_c')^{\frac{1}{3}} b_w d_v \quad \text{……. (21)}$$

Where:
λ: the modification factor for the density of concrete.
k_m: the modification for moment interaction defined by Equation (22).
k_r: the modification factor for the stiffness of longitudinal reinforcement defined by Equation (23).

$$k_m = \sqrt{\frac{V_f d}{M_f}} \leq 1.0 \quad \text{……. (22)}$$

$$k_r = 1 + (E_F \rho_{Fw})^{\frac{1}{3}} \quad \text{……. (23)}$$

This calculation for the concrete contribution to shear is an empirical modification of the provision in CSA A23.3 for steel reinforced concrete members, which for members containing the minimum transverse reinforcement is defined by Equation (24).

$$V_c = 0.18\phi_c\lambda\sqrt{f_c'}b_w d_v \quad \text{……. (24)}$$

The modifications to the steel reinforced concrete contribution calibrate the equation in line with existing beam tests. This accounts for the reduced aggregate interlock and reduced compressive zone resistance from using a lower stiffness FRP reinforcement material. The stirrup contribution is unchanged from CSA A23.3 if using steel stirrups and follows Equation (25).

$$V_{ss} = \frac{\phi_s A_v f_y d_v}{s}\cot\theta \quad \text{…….. (25)}$$

Where:
ϕ_s: the steel resistance factor.
A_v: the area of transverse steel reinforcement.
f_y: the steel yield strength.
s: the spacing of transverse reinforcement.
θ: the angel of the principle compressive stress at the mid height of the section.

According to ACI 440.1R-15 [49] The design of FRP shear reinforcement is based on the strength design method and the strength reduction factor of 0.75 given by ACI 318 for reducing nominal shear capacity of steel-reinforced concrete members should also be used for FRP reinforcement. The design shear strength (ϕV_n) must be larger than the factored shear force (V_u) at the section considered. Computation of the maximum shear force (V_u) at beam supports can be attained following ACI 318-19 [50] equations for non-prestressed members provisions**:**

If $A_v \geq A_{vmin}$

Then use either of:

$$Vc = \left[0.17\lambda\sqrt{f_c'} + \frac{N_u}{6A_g}\right]b_w d \quad \text{……. (26)}$$

$$Vc = \left[0.66\lambda(\rho_w)^{1/3}\sqrt{f_c'} + \frac{N_u}{6A_g}\right]b_w d \quad \text{……. (27)}$$

If $A_v \leq A_{vmin,}$ then use:

$$Vc = \left[0.66\lambda_s\lambda(\rho_w)^{1/3}\sqrt{f_c'} + \frac{N_u}{6A_g}\right]b_w d \quad \text{…. (28)}$$

Where:

λ: the modification factor to reflect the reduced mechanical properties of lightweight concrete relative to normal weight concrete of the same compressive strength.
λs: the factor used to modify shear strength based on the effects of member depth, commonly referred to as the size effect factor.
N_u: the Axial load and is taken Positive for compression and negative for tension.
A_g: the gross area of concrete section (mm^2).

And the nominal and factored total contribution of both of the concrete and the web reinforcement can be calculated as follows:

$$V_n = Vs + Vc \quad \text{……. (29)}$$

$$\phi V_n = \phi Vs + \phi Vc \quad \text{……. (30)}$$

Where Vs can be calculated from equation (7).

GFRP reinforced concrete beams are not necessarily expected to behave in a similar manner to the steel reinforced beams. However, a comparison of their sensitivities may prove interesting. Size effect is now recognized as an important consideration in the design of steel reinforced concrete members, and it would be unwise to ignore the problem when developing new codes for GFRP reinforced members.

8. FRP as longitudinal reinforcement

This section concentrates on the experimental investigation the characteristics and performance of FRP composites utilized as internal reinforcing bars especially GFRP.

Wegian and Abdalla [47] conducted an assessment of the shear capacity of eleven simply supported concrete beams. These beams, reinforced with various types of FRP bars, had a cross-section of 500x250mm and a clear span of 2300mm. The concrete compressive strength (f_c') for the beams varied between 30 MPa and 35 Mpa. Steel stirrups were used at 400mm, and utilizing reinforcement ratios of 0.4%, 0.6%, and 1.5%. The specimens were tested under four-point loading to examine their deflection, cracking, and shear capacity. The study concluded that concrete beams reinforced with

fiber-reinforced polymers (FRP) exhibit linear behavior up to the point of cracking, and after cracking, they continue to behave linearly but with reduced stiffness. Generally, strains and deflections are higher in concrete beams reinforced with FRP bars compared to those reinforced with steel. Due to the reduced compression stress block and the nature of cracking in beams reinforced with FRP bars, their shear strength is significantly lower than that of beams reinforced with steel. The code equations developed for concrete members reinforced with steel tend to overestimate the shear capacity of the beams reinforced with FRP bars. Lastly, the study found that the ACI-440 equations tends to be overly conservative when estimating the shear capacity of beams reinforced with FRP bars.

Ashour A. [51] conducted a study examining the flexural and shear capacities of 12 concrete beams reinforced with GFRP bars. Every beam shared identical dimensions of 2100mm in length and 150mm in width. The study investigated three different depths for these beams: 200mm, 250mm, and 300mm, as seen in Figure 8. For each of these depths, two different ratios of GFRP reinforcement were applied, under and over-reinforced. Two different concrete compressive strengths (f_c') were experienced with 34 and 59 MPa. Beams that were under-reinforced experienced flexural failure due to the rupture of GFRP bars, while over-reinforced beams encountered shear failure. Beams that failed in flexure displayed significant deflection compared to beams of the same depth that failed in shear.

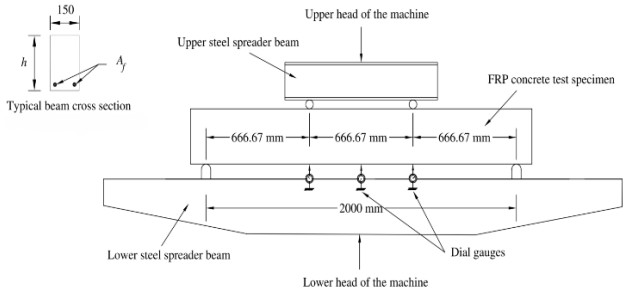

Figure 8. Test specimen details and test setup [51]

Shin et al. [52] carried out a study on the performance of twelve concrete beams reinforced with GFRP bars. These beams, each measuring 300x400mm and 4000mm in length. The acquired compressive strengths of the concrete (f_c') were 34 and 45 MPa. Five GFRP reinforcement ratios were used for the study, ranging from 0.24% to 1.27%. Minimum shear reinforcement was used. A shear span to depth ratio (a/d) of 3.4 was provided, as seen in Figure 9. The beams were monitored for crack widths, crack spacing, mid-span deflections, and strains. The study concluded that the behavior of beams reinforced with GFRP bars is bilinearly elastic until failure. After the initiation of cracks, the stiffness of these beams is further reduced compared to beams reinforced with steel bars. Additionally, the deflections and strains in beams reinforced with GFRP bars are generally larger than those in beams reinforced with steel bars. This is attributed to the low modulus of elasticity and the unique bond characteristics of the GFRP rebars. To ensure sufficient flexural stiffness for deflection, over-reinforcement is required in the flexural design of FRP reinforced concrete beams. The deflection in concrete beams reinforced with GFRP bars can be accurately predicted using the ACI 440.1R-06 equations. The crack width is independent of the concrete strength and decreases as the reinforcement ratio increases.

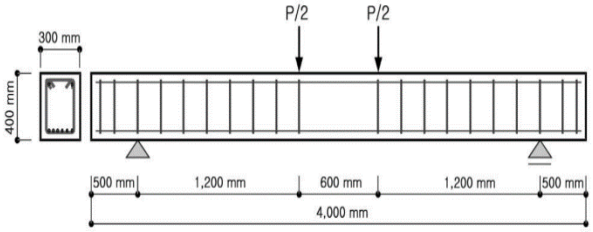

Figure 9. Details of specimens [52]

Bentz et al. [53] conducted a study on the shear strength of eleven concrete beams with varying geometry, each reinforced with FRP. Reinforcement ratio of approximately 0.5% and 2.0%, with or without GFRP stirrups. each beam had a different shear span to depth ratio, ranging from 3.33 to 3.92. All beams were formed using ready-mix concrete with a desired strength of approximately 35 MPa. The conclusion drawn was that concrete members reinforced with FRP exhibit the same size-effect on shear strength as those reinforced with steel. Furthermore, it was found that the strain effect on the shear strength

of FRP reinforced concrete members is identical to that of steel-reinforced members.

Yoon et al. [54] conducted an experimental program to examine the flexural strength and deflection characteristics of concrete Beams reinforced with multiple layers and combinations of different reinforcement types (steel, GFRP, and CFRP bars), with minimum shear reinforcement, and design compressive strength (f_c') of the concrete of 90 Mpa, with different longitudinal reinforcement ratios (0.6%, 1.83%, and 2.33%). The shear span to depth ratio (a/d) was approximately 5. The study involved a total of six beams, each with dimensions of 230x250mm and a length of 2300mm. The findings revealed that due to the lower elastic modulus of FRP bars and the low reinforcement ratio, the post-cracking stiffness of FRP bar-reinforced beams was significantly lower, and deflection was higher than that of steel-reinforced beams. However, the lower stiffness and higher deflection of FRP bar-reinforced beams could be managed and improved by hybrid reinforcing with steel bars. The ductility of beams reinforced with a hybrid of steel was considerably higher than that of FRP-bar reinforced beams. Hybrid reinforcing with steel bars emerged as a potential solution to overcome the low ductility of FRP bar-reinforced beams. In the case of FRP bar-reinforced beams, crack propagation was quicker and deeper, and the maximum crack width was larger than in steel-reinforced beams. However, the introduction of hybrid reinforcing with steel bars helped control the propagation and width of cracks in FRP-bar reinforced beams.

Nguyen-Minh and Rovňák [55] during their experimental program examined the behavior and shear capacity of concrete beams reinforced with GFRP. The tests involved 12 large-scale concrete beams, some reinforced with GFRP and others with steel with varied tensile reinforcement ratio (1.01% to 2.02%). Steel stirrups were placed with a 60 mm spacing at the ends and 200 mm spacing elsewhere, with a/d of approximately of 2.5, details of the specimens are depicted in Figure 10. The results showed that the shear capacity of GFRP-reinforced concrete beams was less than that of traditional reinforced concrete beams. Two design compressive strength (f_c') for concrete were used 34.6 and 46.3 Mpa. The impact of the quantity of GFRP and steel reinforcing bars on the shear capacity of the beams was almost identical. Increasing the GFRP reinforcement ratio from 1.01% to 2.02% led to a 27.6% increase in the beams' shear resistance, while the equivalent increase for steel reinforcement was 31.8%. Additionally, using high-strength concrete could significantly reduce beam deflection. The formulas of ACI 440.1R-03 and ACI 440.1R-06 provided more conservative results for a tensile reinforcement ratio of less than 1.5%. This could be due to an underestimation of the dowel action contribution of FRP rebars.

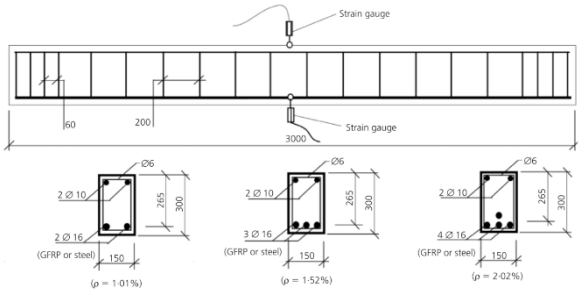

Figure 10. Details of the specimens and setup [55]

Miàs et al. [56] carried out an experimental study on the immediate and time-dependent deflections of eight simply supported GFRP RC beams with steel stirrups. and concrete compressive strength (f_c') of 30 MPa. The beams were reinforced with sufficient amount of steel stirrups as shear reinforcement within the shear region, and no stirrups were provided in the pure bending region. Every beam had a width of 140 mm, a depth of 190 mm, and 2450 mm long. The specimens were tested under sustained loading for a duration of 250 days. Initially, the beams were subjected to a short-term loading that represented the service load, followed by the application of a lower sustained load. The application of the sustained load, which was less than the maximum, after a cycle of unloading and reloading, resulted in an "immediate" deflection after cycling that was larger than the deflection corresponding to the same load in the initial monotonic loading. The immediate deflection after cycling was between 1.2 and 2 times larger than those of the initial monotonic loading, depending on the reinforcement ratio

and the level of sustained load. The difference between both deflections was more pronounced when the load was closer to the cracking load. The time-dependent deflection saw a significant increase with time in the initial period. Ten days after loading, the total deflections increased by around 60% for beams reinforced with 2Ø12 GFRP bars and about 50% for beams reinforced with 2Ø16 GFRP bars, while 90% of the total increase was achieved around 90 days after loading. Beams reinforced with 2Ø12 GFRP bars exhibited a total immediate deflection ratio that was around 11% higher than beams reinforced with 2Ø16 GFRP bars, indicating the influence of the reinforcement ratio on the total deflections.

Hamid et al. [10] conducted a study on simply supported concrete beams, with minimum amount of steel stirrups. Eight beams longitudinally reinforced with GFRP and another eight with steel, and were subjected to four-point monotonic loading until it failed. All specimens have the same concrete compressive strength (f_c') of 24 MPa, and two types of shear to span ratio (a/d) of 1.5, 3 to the study effect of a/d, two distinct reinforcement ratios, namely 0.6% and 0.8%, were taken into account. They discovered that all GFRP RC beams exhibited linear behavior until failure, attributed to the low plasticity in the reinforcement bars. Additionally, these failures occurred at larger displacements compared to steel RC beams. In both types of beams, two failure modes were observed: shear failure (as seen in Figure 11) in beams with low stirrup ratios and shorter shear span length, and flexural failure (as seen in Figure 12) in beams with higher stirrup ratios and longer shear span length. However, the shear capacity of beams reinforced with GFRP bars was found to be lower than that of beams reinforced with steel bars, as also indicated by the calculated flexural capacities using ACI 440.1R-06. Lastly, the strain distribution along the longitudinal reinforcement of beams reinforced with GFRP bars differed significantly from that of beams with steel bars. Specifically, the strain on stirrups in beams reinforced with GFRP bars was higher than the strain on stirrups in beams reinforced with steel, particularly in beams with a shorter shear span length.

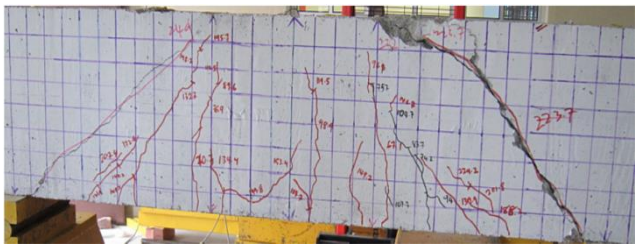

Figure 11. Shear failure mode [10]

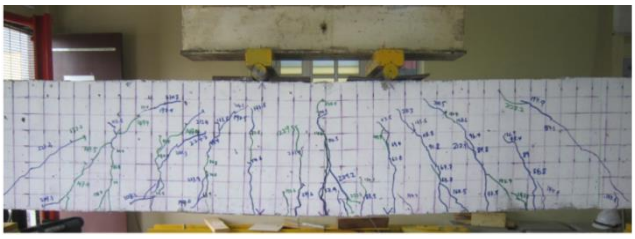

Figure 12. Flexure failure mode [10]

Hamid et al. [57] assessed the shear capacity of six concrete beams, each measuring 200mm in width, 400mm in height, and 2000mm in length with a/d less than 2.5. Two different concrete compressive strengths (f_c') were tested 20MPa and 30 MPa. All beams were provided with sufficient amount of steel stirrups as shear reinforcement within the shear region. The glass fiber-reinforced polymer (GFRP) reinforced concrete (RC) beams were strengthened using various reinforcement ratios, including 0.6%, 0.8%, 1.2%, and 1.5%. In contrast, the control beams had reinforcement ratios of 0.6% and 0.8%. These beams had varying reinforcement ratios and were longitudinally reinforced with glass fiber-reinforced polymer (GFRP) bars for both compression and tension bars, and with minimum shear reinforcement. Steel stirrups were used as shear reinforcement within the shear region. The study concluded that beams reinforced with GFRP bars, especially those with a higher reinforcement ratio, exhibited higher deflection. Consequently, all GFRP RC beams displayed lower flexural stiffness compared to steel RC beams, which can be attributed to the low axial stiffness due to the low modulus elasticity of GFRP bars. The shear strength of beams reinforced with GFRP bars was significantly lower than that of equivalent beams reinforced with steel bars. Beams with a lower reinforcement ratio tended to fail in flexure failure, while those with a higher reinforcement ratio tended to fail in shear with critical diagonal cracks, as shown in Figure 13. In beams with

multiple layers of longitudinal reinforcement bars, the steel stirrup detached from the bend location, which improved the beam's ability to resist high shear stresses in the stirrup. A high reinforcement ratio of longitudinal GFRP bars influenced the shear capacity of GFRP RC beams, but resulted in low flexural stiffness. The ACI 440.1R-06 equations provided a conservative prediction of the shear strength of GFRP RC beams.

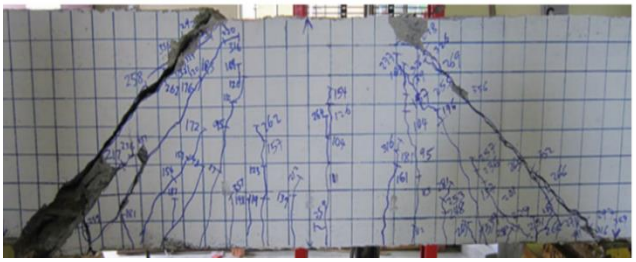

Figure 13. Diagonal shear failure of GFRP RC beam [57]

Goldston et al. [58] investigated the performance of twelve concrete beams reinforced with GFRP bars under both static and impact loading with shear reinforcement spaced to guarantee flexural failure. Concretes of two different compressive strengths (f_c') were used in the experimental program of approximately 40 MPa and 80 MPa, with shear span to depth ratio (a/d) of 7.9, test setup is shown in Figure 14. The failure mode of GFRP RC beams can be accurately forecasted using sectional analysis typically employed for conventional RC beams. The ratio of the beam's reinforcement to the computed balanced reinforcement can serve as an indicator for the GFRP RC beams failure mode. Concrete crushing on the top surface was observed for GFRP RC beams reinforced beyond the balanced reinforcement. Conversely, for GFRP RC beams reinforced less than the balanced reinforcement, the governing factor was the rupture of the GFRP reinforcement bars. The load-deflection behavior of both normal strength and high strength concrete GFRP RC beams under static loading exhibited a bi-linear response. The initial segment of the response indicated an uncracked behavior of the beam, while the latter part indicated the cracked behavior of the GFRP RC beam. Moreover, GFRP RC beams designed as over-reinforced with 1.0% and 2.0% reinforcement ratio demonstrated signs of reserve capacity or "ductility" prior to complete failure. Under impact loading, irrespective of the shear capacity of the GFRP RC beams, the over-reinforced beams were observed to experience minor inclined shear cracking and crushing of the concrete cover around the impact zone at approximately 45^{o} angles, resulting in a "shear plug" type of failure, as shown in Figure 15. However, the GFRP RC beams under static loading were found to be flexure-critical. Therefore, the shear behavior of flexure-critical GFRP RC beams must be taken into account in dynamic modeling or when designing beams for impact loads. Steel reinforcement was found to be more effective in controlling midspan deflection, showing a decrease of 32% compared to a GFRP RC beam.

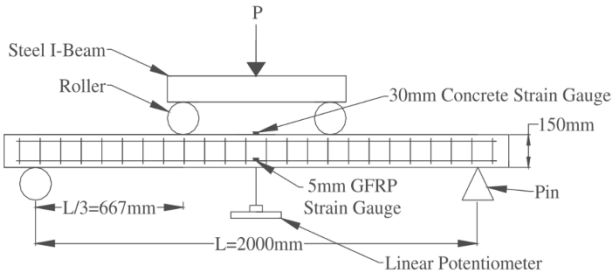

Figure 14. Test setup [58]

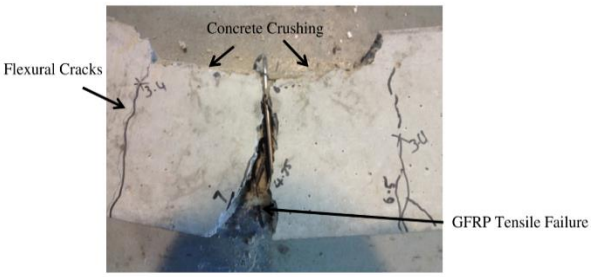

Figure 15. Failure of GFRP RC beam [58]

Kaszubska et al. [59] conducted a study to examine the impact of the longitudinal GFRP reinforcement ratio on the shear capacity of seven concrete beams without stirrups, measuring 150x400mm and 1800 clear span, and without transverse reinforcement. The flexural reinforcement ratio, which primarily influenced the variation in the beams, corresponded to approximately 1%, 1.4%, and 1.80%. The beams were cast of concrete class C25/30. The findings suggest that GFRP reinforced beams are not affected by changes in the reinforcement ratio if the ratio is less than 1.40%. The use of GFRP

longitudinal reinforcement in two layers delayed diagonal shear failure and increased the shear strength by approximately 28%. Beams reinforced with two layers of GFRP reinforcement exhibited a more extensive crack pattern than beams with a similar reinforcement ratio but reinforced in one layer. However, the application of two reinforcement layers proved to be more effective than one reinforcement layer in terms of shear strength, primarily due to the higher tension stiffening effect provided by the flexural reinforcement (one or two layers). Nevertheless, a larger number of cracks appeared in beams with a larger number of bars and a similar reinforcement ratio. The critical shear crack inclination varied between 35º and 51º. The crack pattern for each reinforcement ratio is shown in Figure 16.

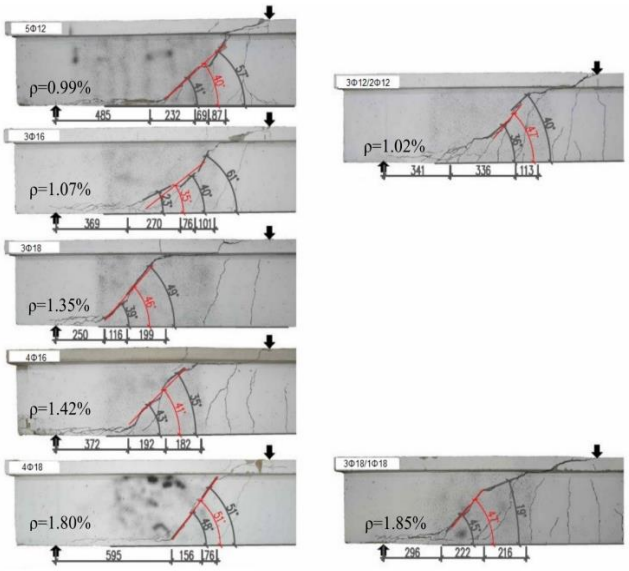

Figure 16. Crack pattern in GFRP reinforced beams [59]

The performance of concrete beams, either partially or fully reinforced with glass fiber polymer (GFRP) bars, was examined in a study done by Moawad and Fawzi [9]. Six beams were tested, each measuring 150mm in width, 200mm in depth, and 1700mm in length, with a clear span of 1500mm under four-point loading with two different concrete compressive strengths (f_c') of 30MPa and 60 MPa, and Stirrups were designed to guarantee flexural failure of the beams. The study concluded that an increase in the GFRP reinforcement ratio could potentially alter the failure mode from flexural shear failure. Furthermore, an increase in the GFRP reinforcement ratio resulted in a decrease in the number of cracks but an increase in the crack width. The use of GFRP bar reinforcement in concrete beams affected the stiffness of the beam specimens. As a result, beams with a low GFRP reinforcement ratio exhibited significant deformation and an enhancement in post-cracking stiffness.

9. Influence of longitudinal reinforcement on the shear capacity of RC beams

Gale and Ibell [60] studied the effects of compression reinforcement on the shear strength of four reinforced concrete beams measuring 200mm in depth, 100mm in width, and a clear span of 2000mm. The average concrete compressive strength (f_c') for all four specimens was 49.6 MPa, and a shear span to depth ratio (a/d) of 3. Two beams were without stirrups, and the other two had shear reinforcement spaced at 75 mm. The researchers concluded that the presence of top compression steel plays a crucial role in increasing shear capacity provided that stirrup reinforcement is also present. In fact, beams containing top steel along with stirrups have demonstrated strength gains of up to 22% beyond what is predicted by code standards. However, a different scenario emerges when a beam relies solely on bottom (tension) reinforcement. Such beams tend to fail close to the load levels predicted by the code. Interestingly, beams containing top steel without stirrups also exhibit failure patterns near the code predictions. Beams, typically heavily reinforced or prestressed in the bottom region, exhibit a contrasting reinforcement pattern: lighter reinforcement near the top. The top steel often serves the purpose of creating a reinforcing cage during construction. Remarkably, experimental research suggests that this configuration is ideal for effectively increasing shear capacity using the top steel. It's worth noting that existing bridges are unlikely to feature beams with both top and bottom steel but lacking shear reinforcement. Considering this, typical concrete beams including those with minimal shear reinforcement may experience up to a 15% enhancement in shear capacity.

Zakaria et al. [61] experimentally studied 10 simply supported beam specimens with varying

sizes, reinforcement ratios, and shear span ratios, with stirrups and concrete compressive strength (f_c') of 40 MPa. and the results revealed that augmenting the quantity of longitudinal reinforcement enhances control over the opening of shear cracks near the longitudinal reinforcement. This implies that the shear cracking mechanism is significantly influenced by the ratio of longitudinal reinforcement. An increase in the amount of longitudinal reinforcement results in reduced spacings between shear cracks, leading to smaller shear crack openings. This phenomenon can be attributed to the enhanced bond effect between the longitudinal reinforcement and the adjacent concrete, which improves crack control characteristics and diminishes crack spacing. Furthermore, a larger quantity of longitudinal reinforcement effectively curbs the growth of flexural cracks and prevents their transformation into flexure-shear cracks.

Alam and Hussein [62] in their experimental study, the shear strength of concrete beams reinforced with various amounts and types of materials was examined. The design strength of the concrete was 40 MPa, the shear span to depth ratio (a/d) of 2.5, and with different reinforcement ratios (0.5%,1%, and 2%). The beams were only longitudinally reinforced with steel, GFRP, and CFRP bars, and without stirrups. They tested a total of 16 beams, divided into two groups with effective depths of approximately 300mm and 450mm for each group. Their findings indicated that the load-deflection behavior of the beams post-cracking is governed by the axial stiffness of the reinforcing bars. Moreover, for all types of reinforcements used in their study, the shear strength of the beams with an effective depth exceeding 300mm increased with the reinforcement ratio. The normalized shear strength exhibited a linear increase with the cubic root of the axial stiffness of the reinforcing bars.

Chidananda and Khadiranaikar [63] reported the test results of 12 concrete beams, each measuring 150mm in width, 180mm in depth, and 1200mm in length with minimum shear reinforcement, and reinforced with glass fiber-reinforced polymer (GFRP) bars. The core variation for each beam in three groups was a percentage of reinforcement (0.5%, 1%, 1.5% and 2%), and of different concrete compressive strength (M50, M60, and M70). With a/d of approximately 2.5. These beams were subjected to a four-point loading system. It was observed that as the reinforcement ratio increased from 0.5% to 2%, there was a corresponding decrease in crack widths by 72.72%, and a decrease in deflection by 39%. Furthermore, it was found that both an increase in the grade of concrete and the percentage of reinforcement led to an increase in the moment resistance of the beams reinforced with GFRP bars.

Christianto et al. [34] conducted an experimental study to investigate the impact of longitudinal reinforcement on the shear capacity of six concrete beams with the size of 1100 × 70 × 125 mm, a/d ratio 4.28, compressive strength (f_c') for concrete varying from 50 to 110 MPa, and without stirrups. The findings revealed a significant correlation between the ratio of longitudinal reinforcement and the shear strength capacity ratio (Vu/Vc) of concrete beams, specifically those without coarse aggregate and transverse steel. As the longitudinal reinforcement ratio increases, so does the shear strength capacity of the concrete beam. Notably, the shear strength capacity of a beam with the highest longitudinal reinforcement ratio is approximately 82.82% greater than that of a beam with the lowest ratio.

10. Analytical investigations on the use of FRP as main reinforcement

Kalpana and Subramanian [64] conducted both an analytical and experimental investigation into the behavior of concrete beams reinforced with GFRP bars. The findings revealed that a decrease in the stiffness of the GFRP bars leads to an increase in crack width. However, as the strength of the concrete increases, the changes in the ultimate crack widths are relatively minor. GFRP bars embedded in high-strength concrete perform better than those in normal-strength concrete in terms of deflection and load-carrying capacity, thanks to their high tensile strength. The general behavior of the Finite Element (FE) models, as depicted by the load-deflection plots at midspan, aligns well with the experimental data.

Masmoudi et al. [65] conducted an analytical study, supported by experimental data, to examine GFRP RC beams. The findings revealed that when the reinforcement of GFRP exceeds 2%, the stress does not significantly increase. Therefore, it is not beneficial to increase the section of reinforcements in GFRP beyond 2% as it does not result in a substantial increase in stress. GFRP bars, having a lower elasticity modulus, produce more deflection for equivalent loads and spans. Unlike steel, which develops a maximum strength of 25% (in the plastic phase) and a deformation limited to 10%, GFRP bars only develop 75% of their strength at 15% deformation (in the elastic phase).

Adam et al. [66] carried out an analytical investigation into the flexural behavior of concrete beams reinforced with glass fiber reinforced polymers (GFRP) bars using a finite analysis program, ANSYS. Their findings were corroborated by an experimental program. A strong correlation was observed between experimental results and numerical analysis regarding predicted ultimate loads of test specimens. GFRP RC beams reinforced beyond the balanced reinforcement typically failed due to concrete crushing, which is a form of compression failure. On the other hand, beams reinforced with a GFRP ratio lower than or nearly equal to the balanced reinforcement ratio exhibited signs of GFRP reinforcement rupture. The recorded tensile reinforcement strain for GFRP bars fell within the range of 0.012–0.0177. These strains correspond to approximately 60–90% of the estimated ultimate strains of the GFRP bars, as determined from the tensile test.

Yang et al. [67] conducted a study examining the damage behavior of concrete beams reinforced with GFRP bars, using a finite element (FE) model based on previous experimental data. In three-point tests of GFRP-reinforced concrete beams, the cracking loads were relatively small, and the maximum crack widths, fractal dimension, and deflections corresponding to the ultimate loads were relatively large compared to typical results for steel-reinforced concrete beams. The research presented an analysis of the effects of different GFRP reinforcement ratios for tensile reinforcement, compression reinforcement, and stirrup-type shear reinforcement on the energy dissipation behavior of concrete beams. The strength and corrosion resistance of GFRP bars can be fully utilized by applying such bars for tensile and stirrup-type reinforcement without causing additional damage to the beam. However, when GFRP bars are used for compression reinforcement, the values and corresponding ratios of the strain energy consistently increase with the GFRP reinforcement ratio. Therefore, it is suggested that the use of GFRP bars for compression reinforcement should be as controlled as possible to prevent further damage when the compression reinforcements are under significant stress.

Mohammed and Said [68], utilized a finite element analysis program, ABAQUS, to analyze concrete beams reinforced with GFRP bars under varying parameters. The findings revealed that the ultimate load capacity of a GFRP beam is higher than that of a steel-reinforced beam. However, GFRP beams exhibit a higher amount of deflection compared to steel beams. Consequently, the load capacity of a steel-reinforced beam is 30% less than that of a GFRP-reinforced beam. Moreover, the deflection percentage in the steel model is 83.8% less than in the GFRP model. The number and width of cracks are more pronounced in the GFRP-reinforced beam than in the steel-reinforced beam. Generally, the serviceability, as represented by cracks and deflection, is lower in the GFRP-reinforced beam than in the steel-reinforced beam, which exhibits higher serviceability. The results also demonstrated the expected linear elastic behavior of GFRP up to the failure stage, with no yielding point. Increasing the number of reinforcing layers does not enhance the ultimate load capacity of the beams nor affect the percentage of deflection at equal reinforcement values. However, the strain decreases by 33.34% in a beam with two layers of reinforcement compared to a single-layer model.

11. Sustainability of FRP

Sustainability is about fulfilling the requirements of the present without jeopardizing

the ability of future generations to meet their own needs. In the past, the primary objectives of structural design were to optimize material and resource usage and to achieve high performance at a low cost. However, the approach to sustainable design considers not just performance, but also the environmental, economic, and social impacts of the choice of material and the energy and resource consumption throughout its life cycle.

The sustainability of materials is evaluated by examining their entire life cycle, from extraction to disposal, which includes stages such as fabrication, processing, construction, maintenance, recycling, and waste management. An ideally sustainable material would have a circular life cycle that depends on renewable resources and energy and generates no waste, while minimizing adverse effects on the environment, people, and society, as discussed by Lee et al. [5].

A sustainable approach to disposing of FRP waste has been proposed by Bank and Yazdanbakhsh [69], which involves repurposing FRP composites for different uses. Ideally, FRP waste should be recycled as components in other applications. However, the unique production and application processes of FRPs make it challenging to reuse FRP components as extensively as traditional materials like steel and timber. There are three primary methods for discarding FRP composites: landfill dumping, incineration, and reuse or recycling. The most cost-effective method is landfill dumping. However, waste composites need to be sorted and separated, which can be difficult due to the challenge of separating valuable fibers from hardened resins in FRP products, especially when steel and other components are attached to the FRP products.

Qureshi J. [12] discussed that Fiber Reinforced Polymers (FRPs) do not corrode and exhibit superior performance in chemically aggressive environments. FRP composites have better resistance to creep and fatigue loads compared to other materials. This results in lower maintenance requirements for structures that utilize FRP materials. Therefore, the anticipated durability of such structures is improved by using FRPs. The sustainability of FRPs can be more comprehensively understood by evaluating various stages of their lifespan and their environmental impact. This approach provides deeper insights into the life cycle assessment of FRPs.

12. Conclusions

In recent times, A major challenge confronting the construction industry has been to design and construct durable and eco-friendly concrete structures, and the use of GFRP bars as a substitute for traditional steel reinforcement in concrete structures has gained significant attention in recent years. This interest stems from the numerous advantages that GFRP bars offer, including their corrosion resistance, making them an attractive choice for reinforcing concrete elements in aggressive environments. Studies have consistently demonstrated the superior corrosion resistance of GFRP bars compared to traditional steel reinforcement, particularly in aggressive environments such as marine or chloride-rich conditions as well as Long-term durability assessments have shown promising results, indicating minimal degradation of GFRP bars over extended service life. The study suggests that combining GFRP with traditional steel reinforcement can mitigate some of the drawbacks associated with GFRP, such as lower stiffness and increased deflections. Hybrid reinforcement can enhance the ductility and overall structural performance, offering a balanced approach to leveraging the strengths of both materials. However, despite extensive investigations into the use of GFRP bars for flexural reinforcement, there remains a notable gap in research concerning their performance in shear-critical regions, and very few studies investigated contribution have explored the implications of incorporating both GFRP and steel as longitudinal reinforcement within the same concrete element (hybrid reinforcement) and understanding the compatibility, flexural behavior, and most importantly its effect on the shear capacity. Moreover, no study has taken into account the effect that the compression reinforcement has on the shear behaviour of concrete beams reinforced with hybrid flexural reinforcement.

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