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An Analytical and Experimental Investigation of GFRP Reinforced Concrete Deep Beams

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ABSTRACT

Today's civil construction sector faces a major challenge in the form of steel corrosion in reinforced concrete structures, which significantly reduces the structures' lifespan. Numerous approaches have been investigated to overcome this problem, and Fiber Reinforced Polymer (FRP) materials have emerged as a viable substitute because of their low weight-to-strength ratio and anti-corrosive qualities. The flexural and shear behavior of FRP reinforced thin concrete beams has been extensively studied, whereas deep reinforced concrete (RC) beams reinforced with FRP rebars have received less attention. The purpose of this study is to examine how deep beams reinforced with Glass Fiber Reinforced Polymer (GFRP) web reinforcement behave under shear. Since commercially produced FRP reinforcements that suited the necessary standards were not readily available, GFRP reinforcement bars and stirrups were made utilizing a process known as "Manual Fiber-Trusion". Tensile strength can be increased by using this technique to fabricate GFRP reinforcement in the required sizes and shapes with a certain fiber volume and resin content. In contrast to flexural failure, shear failure is more likely to occur in deep beams, which are defined by a depth equal to their span. Thirteen concrete deep beams with various GFRP web reinforcement designs were examined, with certain parameters held constant, including the "shear span to depth" ratio and the percentage of web reinforcement. The findings of two series of experiments show that deep beams reinforced with GFRP web reinforcement have a much higher ultimate shear load carrying capacity than those without. Analytical "Strut-and Tie" models were also used for comparison, and the results were marginally better than the experimental ones. Based on these findings, recommendations were made to amend the ACI 318-08 code to allow for GFRP-reinforced concrete deep beams with reduced shear span to depth ratios. In the end, a design equation that predicted the shear bearing capacity of deep beams reinforced with GFRP web produced results that were satisfactory. For such beams with small shear span to depth ratios, this equation provides a useful tool for estimating shear load capacity..

Keywords: *GFRP Reinforcement, Shear Behavior, Deep Beams, Strut-and-Tie Model, Shear Span to Depth Ratio.*

1. INTRODUCTION

Steel rust is a major issue for concrete structures in harsh environments, particularly in coastal areas, cities, and regions using de-icing salts, leading to shorter lifespans. Traditional solutions like protective coatings, special steel, and electrical methods have been largely ineffective. Fiberglass bars (FRP) offer a promising alternative, as they are rust-resistant, strong, and lightweight. However, FRP's lower elasticity and brittleness require careful management of crack size despite its high strength and corrosion resistance. Initially, limited data and high costs discouraged its widespread use, but efforts are underway to reduce FRP's price and expand its adoption in construction. While extensive research exists on FRP in concrete footers, there's a knowledge gap regarding deep beams with specific shear span ratios and web reinforcement. This study addresses that gap by testing deep beams with FRP web reinforcement. This research is divided into two parts: experimental trials and a theoretical model review to validate the findings. The GFRP reinforcements, such as bars and stirrups, were created using a simple assembly method called "Manual Fiber-Trusion" before starting the main trials. These GFRP components were tested for strength and durability prior to use. Concrete deep beam specimens, with and without GFRP web reinforcement, were then cast and tested to study their shear behavior. The goal was to examine the individual and combined effects of GFRP web reinforcement in resisting applied shear loads. The study focused on parameters such as ultimate shear strength, failure mode, crack pattern, deflection, and load-displacement behavior. Based on the experimental results, a formula for calculating ultimate shear strength was proposed.

The beams examined during the experimental phase were duplicated as STM models under comparable geometry and loading conditions as part of the theoretical review's "Strut-and-Tie Method" (STM) analysis.In order to forecast the shear strength and behavior of the reinforced beams, the outcomes of the experimental work were contrasted with those from the STM models. More research was done in SeriesII, which particularly looked at how the "a/d" ratio affected ultimate strength, in addition to the main Series-I focus on testing GFRP web-reinforced deep beams. The GFRP-reinforced thin beam testing is regarded as an add-on to the primary deep beam experiments.Composite materials made of fibers embedded in a polymer resin are known as fiber-reinforced polymers, or FRP.Glass (GFRP), carbon (CFRP), and aramid (AFRP) are the three most widely utilized fibers.Polyester, vinyl ester, and epoxy resins are common options for the resin matrix, which holds the fibers together to create a composite material.FRP materials are perfect for construction because of their high strength, low weight, nonmagnetic and nonconductive qualities, high fatigue resistance, and superior corrosion resistance.

High-strength fibers are impregnated with resin, which serves as a binder and protection, to create FRP composites.The fibers are orientated according to the anticipated applied load and provide the majority of the composite's load-bearing capability. Resin shields fibers from the elements and is essential for weight transfer between them. FRP usually uses thermoset polymers, including epoxies, because of their strength and cross-linking structure.Glass fiber reinforced polymer, or GFRP, is one of the FRP materials that is most frequently utilized in civil engineering applications, especially for reinforcing concrete structures. But because GFRP bars do not have the ribbed surface that steel bars do, they will not attach as well to concrete unless surface treatments like sand coating or wrapping with fibers soaked with resin are used.In contrast to steel, GFRP has limitations in tensile modulus, stiffness, and shear strength, despite its benefits, which include corrosion resistance and simplicity of handling. Furthermore, FRP bars do not yield like steel does, which reduces the ductility of FRP-reinforced structures, and instead show linear stress-strain behavior till failure. FRP bars may become less strong if bent on the job site, especially if hooks or stirrups are being formed.Promising findings have been found in studies on the shear reinforcing performance of FRP in concrete, especially in thin beams.But little is known about how FRPreinforced deep beams behave, particularly when their shear span-to-depth ratios are low.In order to fill the current knowledge gap, this study intends to investigate the shear strength properties of FRP-reinforced deep beams with shear span-to-depth ratios less than 1.0.

GFRP is extensively used in developed countries for various civil engineering projects, such as highway bridges, retaining walls, and walkways. More than 100 bridges worldwide have incorporated GFRP bars in their superstructures. Additionally, GFRP is commonly used in offshore platforms to address corrosion concerns.

The research focuses on the use of Glass Fiber Reinforced Polymer (GFRP) as web reinforcement in deep concrete beams, with several key objectives. First, it aims to determine the maximum load these GFRP-reinforced beams can sustain before breaking. The study also assesses the effectiveness of both vertical and horizontal GFRP components in resisting shear forces within the web of the beams. Additionally, it investigates crack patterns and failure modes, specifically analyzing how these beams fail under shear stress. A crucial part of the research is to evaluate how well GFRP web reinforcement prevents shear failure compared to traditional reinforcement methods. Furthermore, the study seeks to develop a formula that can accurately predict the shear strength of deep beams reinforced with GFRP. Finally, the research compares the actual performance of GFRP-reinforced beams with predictions made using the theoretical "Strut-and-Tie" method, offering a deeper understanding of the structural behavior of GFRP in these applications.

2. LITERATURE REVIEW

Whereas flexural failure in concrete beams is ductile, shear failure is brittle and disastrous. Since the shear strength of concrete beams is supposed to be greater than the flexural strength at every point along the beam, shear failure usually occurs before flexural failure. The degree of longitudinal reinforcement, the strength of the concrete, the existence of axial pressures, and the ratio of shear span to effective depth are the four main parameters that affect shear behavior in a beam without shear reinforcement (MacGregor, 1988).Anywhere the applied moment changes throughout a beam's length, shear forces are present.According to the ACI 318 code, a member's depth and shear capability are directly correlated.Shioya et al. (1989) tested this by studying reinforced concrete members with depths ranging from 100 to 3000 millimeters. They discovered that the shear capacity declines with increasing member depth.

Kani (1967) also investigated the "size effect" in concrete beams, revealing that the size of the beam significantly impacts its shear strength, with deeper beams exhibiting lower shear strains at failure. It is a common practice to assume that the strength of concrete directly correlates with shear capacity, with shear resistance proportional to the square root of the concrete’s compressive strength. However, Angelakos et al. (2001) found that higher cylinder strengths do not necessarily lead to higher shear strengths.

Shear transfer mechanisms in concrete beams can occur through several means: uncracked concrete shear stress, shear at the interface, dowel action, and arch action. Cracking-induced failure occurs when the shear stress exceeds the concrete’s tensile capacity, while crushing occurs when compressive shear stresses surpass the limits of the concrete’s capacity. The web of a beam transmits biaxial stress due to compressive forces in the strut between the load point and support (ASCE-ACI Committee 426, 1973). Aggregate interlock at crack interfaces enables shear transfer across a cracked concrete surface. Nilson and Winter (1991) showed that this aggregate interlock could account for up to one-third of the total shear force.

Dowel action from the longitudinal reinforcement also resists crack widening by providing tension along the crack interface. However, this dowel action is not the dominant mechanism in total shear resistance (ASCE-ACI Committee 426, 1973). The presence of longitudinal reinforcement also reduces crack width, which limits further crack propagation. Thus, increasing the amount of longitudinal reinforcement can extend the beam's shear capacity. When shear resistance is greater, arch action occurs, where shear is transferred through compressive struts. This arch action is more common in deep beams, where diagonal cracks develop between the load and support.

When concrete footings lack shear reinforcement, their capacity is primarily determined by the load at which cracking occurs. However, due to the presence of tensile stresses, beams with shear reinforcement can provide some degree of resistance to shear even after cracking, as demonstrated by Collins et al. (1996), who found that reinforced beams exhibit increased load-bearing capacity. Beams without stirrups, with longitudinal reinforcement ratios between 0.75% to 2.5%, often fail due to shear. Beams with lower reinforcement ratios tend to fail under lower shear stresses, while those with higher ratios often fail in flexure.

In reinforced concrete beams, axial compression from applied loads enhances shear capacity, while MacGregor and Wight observed that axial strain reduces this limit. Since 1973, model evaluations of shear behavior in concrete beams with and without reinforcement have been extensively studied. The ASCE-ACI Joint Committee 445 (1998) reviewed numerous models developed between 1973 and 1998, including notable ones such as Collins' "Compression Field Theory" (1978), Vecchio and Collins' "Modified Compression Field Theory" (1986), and Hsu’s “Fixed Angle Softened Truss Model” (1992).

The initial shear model, developed by Ritter (1899) and Morsch (1902), proposed that compressive forces in concrete between diagonal cracks absorb the shear. However, Nielsen (1984) later demonstrated that diagonal cracks do not always form at 45°, refuting this assumption. Collins’ Compression Field Theory (CFT) developed in 1972 was a breakthrough in explaining shear behavior. Collins suggested that principal strain and principal stress directions were aligned, and this idea was further refined in Vecchio and Collins' Modified Compression Field Theory (MCFT), which considered the reduction in concrete compressive strength in cracked regions.

Hsu’s later work (1992) proposed the "Pivoted Softened Truss Model," refining the approach to account for varying angles in the diagonal struts with applied shear. Other contributions, like Loov's shear friction models (1998), predicted significant shear cracks at slip interfaces, although these models were only accurate under specific conditions. Several internal mechanisms, such as uncracked concrete, aggregate interlock, dowel action, and tensile forces opposing shear, resist shear failure in concrete beams.

Shear reinforcement, typically provided as vertical stirrups, is essential for preventing sudden, brittle shear failure, improving shear capacity, and ensuring ductile flexural failure. Stirrups are most effective when diagonal cracks cross or approach them, providing additional resistance. In FRP-reinforced concrete beams, stirrups help maintain aggregate interlock, thus preserving shear transfer through cracked sections. Proper spacing of stirrups helps confine the concrete, reducing crack widths and enhancing compressive strength, which increases the beam’s overall shear capacity.

De Paiva and Siess (1965) conducted tests on small reinforced concrete beams with a shear length-to-depth ratio of 0.7 to 1.3 and a depth range of 150 mm to 300 mm. They examined various reinforcement levels and found that adding vertical or inclined stirrups did not alter the progression of diagonal cracks, although it increased strength. Increasing the vertical stirrups reduced deflection at critical loads. They also observed that beams with small shear length-to-depth ratios showed a higher load-bearing capacity beyond diagonal cracking without shear reinforcement.

Leonhardt and Walther (1966) tested larger beams with a length-to-depth ratio of 0.9 to 1.0, concluding that tie-arch action plays a significant role in deep beam behavior. They suggested web reinforcement was unnecessary for deep beams, though others later contradicted this view.

Ramakrishnan and Ananthanarayana (1968) tested beams with length-to-depth ratios of 0.9 to 1.8, finding that shear failure was predominant. They proposed a shear strength formula based on concrete splitting strength.

Kong et al. (1970) conducted tests on beams with length-to-depth ratios of 1 to 3, highlighting the effectiveness of horizontal web reinforcement in controlling crack width and deflection.

Smith and Vantsiotis (1982) tested 52 deep beams and observed that both vertical and horizontal web reinforcements increased shear strength, with vertical reinforcement being more effective for a/d ratios below 1.0.

Lehwalter (1988) tested deep beams with varying shear span-to-depth ratios and found that both horizontal and vertical web reinforcement had positive effects on shear strength, though vertical reinforcement became less effective as the a/h ratio increased.

Tan et al. (1995) tested beams with shear length-to-depth ratios ranging from 0.27 to 5.38, observing that failure modes shifted from shear to flexure-shear with increasing a/d ratios.

3. MATERIALS AND METHODS

3.1 Concrete

A concrete mixing machine was used at a testing lab to prepare the concrete for casting. The concrete used had a compressive strength of 40 N/mm² (M40 grade) and complied with IS 8112 (1989) requirements. With a water-to-cement ratio of 0.38, the mix ratio that was chosen was 1:1.02:1.93. The following were important material quantities per cubic meter:

- 1059 kg of coarse aggregate (20mm maximum size)
- 560 kg of natural river sand
- 548.5 kg of Portland cement (43 grade)
- 208 liters of water

The coarse aggregate was 20mm crushed granite stones, and river sand was used as fine aggregate after sieving. The concrete was tested for properties such as initial and final setting times, specific gravity, fineness, and compressive strength, adhering to IS 8112 standards. Cubes were cast alongside each batch of concrete for strength verification and tested at 7 and 28 days.

3.2 GFRP Constituent Materials

Glass Fiber

E-Glass fiber from Saint Gobain Vetrotex was utilized; it is compatible with vinyl, polyester, epoxy, and phenolic resins. The fiber has outstanding surface quality, exceptional wettability, and great mechanical qualities. Its tensile modulus was 65-75 GPa, and its tensile strength was 1700-1800 MPa.

Epoxy Resin

Because of its superior electrical qualities, dimensional stability, and strong bonding strength with fibers, epoxy resin was chosen as the matrix material. The epoxy resin's density was between 1.2 and 1.4 kg/m³, and its typical tensile strength was 95 MPa. The "Manual Fiber-Trusion" production method benefited from its delayed curing period.

Resin-Fiber Mix Proportion

Based on the technical specifications supplied by the glass fiber manufacturer, the required fiber amounts were determined in order to achieve a 75% fiber volume fraction in the GFRP bars and stirrups. The fibers were impregnated using a resin mixture that contained 25% resin and hardener by volume. To find the best fiber-resin mixture for creating bars with different diameters (8mm, 10mm, and 22mm), several experiments were carried out.

3.3 Properties of GFRP

The GFRP bars' tensile strength and modulus of elasticity were determined through compression tests, showing higher values than FRP bars made by the conventional pultrusion method. A sand coating was applied to the bars to enhance the bond strength with concrete.

3.4 Manual Fiber-Trusion Method

Arrangement of Parallel Fibers

Fibers were arranged parallel by looping them between two fixed points. This alignment ensured proper bonding during the pulling process, which was critical to maintaining the structural integrity of the GFRP bars during production.

Manual Fiber-Trusion Process

The process involved looping the fibers and passing them through a die after impregnating them with resin. Excess resin was removed, and the fibers were shaped to the desired size by the die. The wet fibers were then placed into molds to form bars of the required shape and size.

Molding of Bent Bars and GFRP Stirrups

The process for creating GFRP stirrups was similar to that of straight bars, with an additional step where the flexible wet fibers were inserted into molds to create stirrups of the desired shape. This allowed for the production of both straight and bent GFRP reinforcement.

Post-Curing Process

After the bars and stirrups were molded, they were allowed to cure for 12-15 hours in a dry environment. They were then post-cured in an electric oven at 120°C for two hours to ensure the complete curing of any remaining resin. After post-curing, finishing work was done on the bars and stirrups, such as trimming excess material and resin.

4. RESULTS AND DISCUSSIONS

4.1 Results of GFRP Reinforced Deep Beams Tested in Series-I

In Series-I, nine GFRP-reinforced deep beams were tested to evaluate the effectiveness of web reinforcement in improving shear capacity. One of these beams served as the "control beam" and was reinforced without web support. The remaining beams were reinforced with various web support configurations, including horizontal and vertical reinforcements with different spacing.

The experimental setup involved applying two-point loads at the top of the beams with a constant shear span of 350 mm on either side. A total span of 1050 mm was maintained to assess the shear performance of the GFRP-reinforced beams. The tested parameters included concrete strain, GFRP reinforcement strain, deflection, and crack width on the surface of the beams. The experimental results were compared to determine the role of web reinforcement in enhancing shear resistance. A proposed equation to predict the ultimate shear capacity of deep beams with GFRP reinforcement was developed and compared with the experimental results.

4.1.1 Key Observations from Series-I

- The control beam (GFRDB-1) failed due to flexure-shear with dowel splitting, while beams with web reinforcement exhibited higher shear capacity.
- Beams reinforced with both horizontal and vertical web reinforcement (e.g., GFRDB-9) showed significant improvement in shear resistance, exhibiting shear failure rather than flexure-shear failure.
- Variations in the spacing of web reinforcement influenced the beams' failure modes and ultimate shear capacities. Beams with tighter web reinforcement spacing performed better in terms of load-carrying capacity.

4.1.2 Results of GFRP Reinforced Deep Beams Tested in Series-II

In Series-II, four GFRP-reinforced beams with an increased shear span-to-depth ratio of 1.08 were tested. One beam was designated as the "control beam" (GFRDB-1(a)) and was constructed without web reinforcement. Other beams in this series included configurations with only vertical or only horizontal web reinforcement, as well as combined reinforcement. Unlike Series-I, three-point bending tests were conducted with a single-point load at mid-span, maintaining a shear span of 525 mm. The results showed significant differences in behavior compared to Series-I, where the increase in the shear span-to-depth ratio altered the internal shear resistance mechanism.

4.2 Behavior of GFRP Reinforced Deep Beams

4.2.1 FRP Deep Beams without Web Reinforcement

The control beams from both Series-I (GFRDB-1) and Series-II (GFRDB-1(a)) were cast without web reinforcement to assess the contribution of web reinforcement to shear resistance. In Series-I, the control beam showed flexural cracks that initiated at the mid-span and propagated upwards as the applied load increased. These cracks extended to approximately 90% of the beam's depth before the beam ultimately failed due to a combination of flexure-shear and dowel splitting. In contrast, the control beam in Series-II failed due to shear, indicating that the increased shear span-to-depth ratio changed the failure mechanism from flexure-shear to pure shear.

4.3 Strains in GFRP Reinforcements

4.3.1 Analysis of Strain in GFRP Main Bar Reinforcement

In this study, the strain in the GFRP main bar reinforcements was carefully analyzed. All deep beams tested were intentionally over-reinforced to prevent flexural failure, ensuring that shear failure would dominate. This over-reinforcement led to the expectation that the tensile stress in the GFRP main bars would remain below their ultimate capacity due to the excessive structural reinforcement. The strain observed in the GFRP main bars was significantly lower than the ultimate strain, with values not exceeding 50% of the ultimate tensile strain. For instance, strain values ranged from 4000 to 6000 microstrains across different beams, which is considerably lower than the maximum limit of 20,000 microstrains, as suggested by the ISIS Canada Design Manual 3 for GFRP reinforcement and M40-grade concrete. The maximum observed strain in the GFRP bars (for GFRDB-5) was about 37% of the ultimate tensile strain, which occurred after the formation of the first shear crack. Strain values continued to increase progressively until beam failure, showing a near-linear relationship between the applied load and strain development.

4.3.2 Impact of Web Reinforcement

Beams reinforced with either vertical, horizontal, or combined web reinforcement exhibited improved performance compared to the control beams. The presence of web reinforcement delayed the onset of diagonal shear cracks and improved the ultimate load-carrying capacity. The combination of vertical and horizontal web reinforcement provided the best results, significantly increasing the beams' shear resistance and preventing dowel splitting, which was common in beams without web reinforcement. The experimental results demonstrate the critical role of web reinforcement in deep beams reinforced with GFRP, especially in controlling crack propagation and enhancing shear capacity.

5. CONCLUSIONS

This section provides a summary of the study's findings and suggestions for additional research.The following points have been established in light of the earlier discussions and important observations:

- GFRP web reinforcements, both horizontal and vertical, greatly increase the deep beams' shear-carrying capacity.Comparing the shear performance of GFRDB-9 and GFRDB-1 made this clear.However, the amount and positioning of GFRP web reinforcement determine how much improvement is achieved.
- The ultimate load-carrying capability of deep beams reinforced with GFRP webs can rise by up to three times when compared to those without web reinforcements.This increase demonstrates the advantageous effect of enclosure reinforcement and is particularly noticeable in beams with a combination of vertical and horizontal web reinforcements. The potential issue of failure in the bent portion of FRP stirrups, which is a known concern in FRP shear reinforcement, does not need to be a critical design criterion for deep beams with combined web reinforcement. In such cases, the contribution of the bent portion can be considered negligible.
- It is advised that the permissible strain limit for FRP shear reinforcement, which is set at 2000 microstrains in the ISIS Canada Design Manual 3, be raised for deep beams that use combined GFRP web reinforcement in light of the strain values found in this investigation.
- GFRP-reinforced deep beams having an a/d ratio less than 1.0 failed mainly due to diagonal shear cracks and other forms of cracking.Similar to steel-reinforced deep beams, these deep beams also displayed the "tie-arch" behavior.

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