Shear Strengthening of Reinforced Concrete Beams Using Fibre Reinforced Polymer: A Critical Review

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Abstract: The primary purpose of reinforcing bar stirrups in a reinforced concrete beam is to improve shear strength. The FRP system may significantly improve a concrete beam's ultimate shear strength, serviceability, and ductility. The application of FRP for the repair and reinforcement of the structures has become very popular due to its low weight, high tensile strength, and simplicity of installation on uneven surfaces. FRP material outperforms other traditional materials in strengthening applications due to its high strength-to-weight and stiffness-to-weight ratios, resistance to corrosion, and ease of handling. The overall objective of this research is to investigate and improve the understanding of the recent research in the area of shear FRP strengthening of reinforced concrete beams. In this paper, recent publications were reviewed to see how different anchoring procedures, different factors that affect FRP performance and different failure scenarios affect the shear strengthening of concrete beams. The benefits and limits of FRP systems, as well as some current research trends are discussed in this project. From the research, it can be stated that type of anchorage technique and different parameter give a different impact to failure mode of the beam.

1. Introduction

Failure in structures often leads to damage and can be defined as a weakening of the structure which may cause undesirable displacements, stresses or vibrations to the structure that negatively affects the functionality of the structure [1][2][3]. Concrete is one of the most well-known materials to be reinforced in terms of strength since it is unable to sustain a considerable amount of weight alone. Using internal steel reinforcing bars in concrete buildings is a common technique of improving structural strength. Reinforcement bars, on the other hand, will lose their strength as time goes on due to their construction. As a consequence, an external fiber-reinforced polymer must be used to aid reinforced concrete in performance. FRP is a composite material consisting of a polymer reinforced with carbon, glass and aramid fibres.

Because of its excellent strength-to-weight ratio, FRP is applied in many different sectors, including construction, marine, aerospace and automotive. FRP may be used to enhance material with high corrosion resistance and can also be utilized to maintain damaged structures. Carbon was the most commonly used composite material in construction, exceeding all other composite materials in terms of strength and weight. This is because carbon is stronger and lighter than other materials.
Comparing carbon fibre to glass fibre, carbon has a fibre content and density that is appropriate for materials with normal weight percentages. Moreover, compared to the other composite materials, carbon has the largest longitudinal tensile modulus and tensile strength. Consequently, carbon is a very suitable and extensively utilized material for increasing structural strength.

Concrete is a key building material in the construction industry. To make the concrete strong, the presence of steel reinforcement is needed, however this is not enough to support a greater weight. As a consequence, the presence of internal steel reinforcement coupled with external FRP was needed to create concrete that could resist a higher weight. Reinforcing steel bars have been utilized to construct most existing structures. This gives the concrete structure strength, but the problem is that the internal reinforcement state will decrease based on the time. There are numerous historically important structures should be conserved for future generations. However, if preventive maintenance is overemphasized, it may adversely affect the uniqueness of the component structure as well as increase the component cost owing to the use of new materials.

Additionally, another way to cope with this problem is to demolish the old structure and replace it with a new one. This action will be costly owing to the new design, the huge quantity of materials needed, the high construction cost, and the time required to create the new structure. Another solution to this question is the usage of FRP. The correct technique for applying this external reinforcement as well as the kind of anchoring strategy to employ is important. According to the literature, different studies have been done to improve the flexural and axial strengthening of RC structures using FRP. But still little research has been done on utilizing FRP for shear strengthening. Moreover, the findings are restricted and sometimes disputed even with typical reinforced concrete components without FRP. Due to the lack of experimental data, several analytical models were developed to estimate the shear contribution of externally bonded FRP. However, a research was needed based on various anchoring methods and several variables affecting FRP’s shear strengthening. The aim of this research is to review the effect of different anchorage techniques, different parameters on the shear strength of RC beams using FRP and the effect of RC beams strengthened with FRP in failure modes.

2. Effect of different anchorage techniques on shear strengthening
Kim and Smith [4] recognized the need for anchoring the ends of FRP strips or sheets in their experimental to prevent premature debonding failure and to efficiently manage shear stress without debonding. Uji [5] stated that sufficient fibre sheet anchoring is required, comparable to steel stirrups. However, this was observed in all situations at the time, except for columns. When adequate anchoring is utilized, failure is avoided since the strength development in the FRP depends completely on the anchor’s strength and not on the strength of the connection between that FRP and the concrete layer. Using a practical anchoring technique, the debonding failure mode is successfully prevented, resulting in a more desired FRP rupture mode than elsewhere [6][7].

This is worth to mentioning that installing an anchoring system does not avoid debonding completely. Along the length of the FRP strips or sheets, a certain degree of debonding must occur in order to be successful. In the absence of an anchoring mechanism, the strength of the whole reinforcing system depends solely on the connection between the FRP material and the concrete substrate. This section discusses the various anchoring methods and split into three categories: (a) FRP anchors using FRP products for anchoring, (b) metal anchors using steel or aluminium for anchoring, and (c) mixed anchors using anchoring metals and FRP. Anchorage systems for externally bonded FRP methods are extremely beneficial in preventing or delaying interfacial crack opening, increasing the total possible transmission of interfacial shear stress and providing a stress transfer mechanism where there is no bond length beyond the critical section. Different methods of anchoring FRP utilized in the literature, together with their advantages and disadvantages, have been studied. The details of different anchorage techniques are described in the following sections.

2.1. Near surface mounted anchorage technique
Lorenzis and Teng [8] indicated that the enhanced effectiveness of the near surface mounted (NSM) anchorage method is significantly influenced by the bond behaviour of NSM FRP reinforcement and the components to be reinforced. Khalifa and Nanni [9] initially proposed NSM anchoring method.
Figure 1 details a typical aspect of the NSM anchoring technique. A groove is formed across the whole length of the shear span as illustrated in Figure 1, situated either at the web-flange or on the flange's soffit face. FRP sheets are then connected to the concrete surface and groove walls applying glass FRP (GFRP) bars [6], carbon fibre (CFRP) strips, CFRP coat [10], or hardwood strips [11]. The FRP bar diameter utilized in these experiments varied from 10 mm to 13 mm. Micelli et al. [12] used NSM method to connect two CFRP sheets. Researchers utilized the NSM anchoring technique to connect continuous fiber-reinforced polymer sheets and FRP sheet strips.

2.2. FRP extension anchorage technique
According to figure 2, this method consists of extending U-wrap legs under the flange. Application of FRP U-wraps is very attractive since it is a simple technique that substantially delays the debonding of longitudinal FRP layers, thereby improving flexural capacity. Owing to load concentration, FRP U-wraps may fracture at the beam soffit corners. The proposed method aims to improve effectiveness by preventing premature debonding and reducing stress concentration. The use of this technique was shown in the anchoring of CFRP sheet strips [13], GFRP sheets [13], CFRP sheets with 45 degree fibre direction [13], GFRP continuous sheets [13], CFRP continuous sheets [14], and triaxial GFRP continuous sheets and a total of GFRP continuous sheets. Despite the fact that this anchoring technique is easy and cheap.

2.3. Horizontal anchorage system
As shown in Figure 3, this method includes attaching horizontal laminate sheets of FRP to U-wrap scheme's free ends. It was chosen to use a horizontal strip constructed of CFRP sheet with an internal cross-section for the horizontal strip [15]. Although the FRP horizontal anchoring method considerably increased the FRP shear involvement, the methodology did not completely prevent debonding failure.
3. Effect of different parameters on shear strength using FRP

The findings of the published experimental research were provided to recognize the roles performed by the various factors affecting the performance of FRP shear-strengthened anchored RC beams. The following parameters must be considered when designing a FRP shear reinforced beam. Moreover, curves are used to connect the dots showing the apparent outcomes for the various anchoring techniques to provide a more accurate representation of the data set. Specimens with 200 mm or less beam height were utilized to avoid interference with the results. Shear span to effective depth ratios below 2.5 are regarded excellent results. Finally, the research eliminated specimens with a flexure failure mechanism.

3.1. Beam depth

According to Collins and Kuchma [16], RC beams lose their shear strength as the beam expands. Other than those reported by some researchers [17][18][19][20][21], most specimens for anchored FRP shear reinforced beams were below 350 mm. Godat et al. [22] analyzed the average of the FRP shear strength as a percentage of the overall FRP shear strength. The FRP rope anchoring which was followed by FRP extension and sandwich plates methods offered the greatest shear strength. The lowest shear strength for FRP was attained by combining the extension anchoring and horizontal FRP techniques. This is essential to highlight that the number of research examining the efficacy of these methods is low, requiring further investigation. Shear contribution of FRP varies with the depth of beam is shown in figure 4.
FRP. The higher the FRP shear contribution, the higher the beam and the greater the bond surface must be in the beam. FRP debonding was the failure mode for all anchored specimens, save those reported by Kim et al. [23], where the beam depth surpassed 450 mm.

3.2. Ratio of shear span (a) to the effective depth (d)
The gap between load and closest support is called shear span. To differentiate between shallow and deep beams, two a/d ratios were computed. If shallow beams reveal shear or flexural cracks, the ratio of shear span to the effective depth (a/d) is required. In the research by [24], the effect on FRP shear influence is removed by omitting a/d 2.5 values. The shear strength of FRP seems to drop as the ratio of shear span to the effective depth rises for the different methods evaluated in this study. Both NSM and spike anchoring methods demonstrated this trend. This implies utilizing FRP for shear enhancement becomes less attractive as this ratio rises. Conversely, with the FRP spike anchoring method, the FRP strain decreased as the a/d ratio rose. When the a/d ratio exceeded 3.5, no FRP debonding failures occurred. The importance of the ratio of shear span to the effective depth in calculating FRP shear strength influence is not addressed in the current FRP enhancing design guidelines, despite many research acknowledging the usefulness of this ratio in design of RC beams.

3.3. Compressive Strength of Concrete
The compressive strength of concrete (fc) is one of the main factors to influence the FRP shear contribution and affects the FRP/concrete interface behaviour and failure mechanism. FRP shear strength rises with the value of compressive strength of concrete. For spike anchoring method, the strain has a tendency to drop. Except for a sample in Baggio et al. [25], there was FRP debonding with f<sub>c</sub> greater than 35 MPa in the database. There is no scientific explanation for this phenomenon since it is intended to prevent FRP debonding failure and avoid concrete crushing in the compression zone.

4. Failure modes of FRP
Failure processes in reinforced concrete beams include flexural failure and shear failure, the two most common kinds of failure. These failure modes are further split into many kinds of failure, including tension, compression, debonding, crushing, rupture, flexure, and compression shear failure for the former. In design, some are favored above others. However, others must be avoided if one is to prevent catastrophic structural failures. For example, in concrete, crushing and shear failure modes are unwanted since they occur failure quickly and without notice. Due to its brittleness and complexity of processes, a typical RC beam's shear behavior is difficult to predict [26][27].

Because of the impact of different bonded FRP failure modes such as debonding failure and tensile rupture failure, calculating the shear capacity of a reinforced concrete structure externally reinforced with fibre-reinforced polymer (FRP) sheets is even more challenging [28][29]. Therefore, the methods for estimating shear capacity and identifying the failure mode recommended in design codes are based on empirical or semi-empirical equations derived from design equations for typical RC structures rather than analytical solutions [30]. This section will discuss the failure modes identified via a review of research on shear strengthening of RC beams employing FRP to provide a comprehensive overview of the failure modes observed in experimental testing.

4.1. Externally applied FRP debonding failure modes
When CFRP materials are placed in a "U"-wrap or side-bonded fashion, debonding failures are a significant issue because if the CFRP starts to separate from the concrete substrate, the beam may collapse extremely rapidly, reducing member ductility. Recent design guidelines for externally applied FRP materials restrict the effective tensile strain of the material to 0.004 in/in, or 40% of its ultimate value to avoid this kind of failure [31]. This implies that 60% of the potential of the CFRP system is never utilized in practice. When tested in debonding mode, nearly all side-bonded beams and the overwhelming majority of "U"-wrapped beams failed. Although debonding is regarded as a failure mechanism in CFRP systems, the carbon fibre sheets must operate correctly. Large stresses in CFRP near cracks are produced by strain incompatibility with concrete substrate. Concrete fracture results in localized CFRP material debonding at the crack location is illustrated in figure 5.
Figure 5. The concrete surface is covered with CFRP after cracking [32].

To ensure debonding does not result in a structural collapse, many measures are required. The quality of the surface preparation performed before the CFRP is installed, as well as the effective bond length established between the CFRP and the concrete surface, as well as the compressive strength of the concrete substructure and the axial rigidity of the applied system, all have an impact on CFRP debonding. In relationship applications, a strong connection between the CFRP and the concrete surface is needed since the CFRP material cannot be fully wrapped around a concrete component. Any laitance, dust, oil, existing coatings or other elements that may interfere with the CFRP system should be removed from the surface as well as any other components that may interfere with the CFRP system. A sufficient bond length is required for CFRP sheets to withstand shear pressures. However, the amount of shear stress the CFRP can take does not grow linearly with the bonding length. After shear crack development, only the bonded part of CFRP material that extends beyond the fracture can resist shear forces.

When it comes to bond strength between concrete and CFRP, one of the most important variables affected by this issue is the concrete’s compressive strength. Debonding occurs most frequently in concrete a short distance from the concrete CFRP contact, and is usually always evident in concrete. A piece of concrete remains attached to the CFRP even after debonding occurs. It is evident from the fact that the concrete failure plays an essential part in determining the total structural strength of the entire system [33]. The debonded strip pushed a piece of the concrete substrate away from the beam, causing the concrete substrate to fracture. Last but not least, the system's axial stiffness affects its surface debond propensity. Triantafillou [34] stated the effective bond length required to achieve the ultimate tensile force carried by the CFRP strips depends nearly proportionately on the axial rigidity of the CFRP utilized in the application.

4.2. Failure modes of anchor

The FRP debonding, FRP rupture, flexural failure and concrete crushing have been considered as failure modes in this study. Godat et al. [36] tried with a variety of anchoring techniques, however none were successful in decreasing the FRP debonding failure mechanism as shown in figure 6. Graph illustrating the ratio of failure modes produced by each anchoring method FRP debonding is a characteristic of fiber-reinforced polymer extension, horizontal and patch anchoring techniques.

The CSA/S606 [35] standard recommends using the horizontal FRP anchoring technique to secure shear-reinforced polymer beams. During concrete crushing, FRP debonding failure occurred in all specimens connected to FRP rope, showing the FRP was debonded. Data indicated that debonding failure is the most common failure mechanism for NSM and FRP spike anchoring techniques, the second most common being debonding failure. The FRP rupture failure mechanism characterizes horizontal and insertion anchoring techniques. This anchoring technique can only be used for FRP sheets and needs prior slab reinforcement locations information.
Figure 6. Failure mechanisms of shear-strengthened FRP beams [36].

Longitudinal reinforcement succumbed before failure when the anchoring method was employed to secure the structure. Debonding was found to cause failure in 56 percent of the 11 specimens secured utilizing the metallic anchoring technique. The average shear strength for each of the various anchoring methods investigated in this research is approximately 80%. The total shear strength of the anchored and unanchored beams is deducted from the overall shear strength \( V_{\text{total}} \) computed as \( V_f = V_{\text{total}} - V_{\text{control}} \) to determine the shear strength \( V_f \) owing to anchoring. It is important to highlight that in certain instances; some experiments did not utilize a reinforced specimen or anchorage. In this situation, \( V_{\text{control}} \) was the weakest. This assumption is unlikely to have any major influence on findings.

The FRP shear strength of anchored specimens utilizing FRP extension and extension-and-metallic methods was lower than the shear strength of the control specimen. In certain instances, FRP sheet expansion beneath the flange has been found to reduce FRP sheet shear strength and increase the probability of FRP debonding failure. It is produced by the existence of residual stresses at the web-flange corner, resulting in high stress concentrations and reduced anchoring technique performance. In this study, the relationship between failure mode and FRP shear strength can be shown. In certain instances, while the FRP is brittle, the FRP rupture and flexure failure modes do not result in significant FRP shear strength.

For example, FRP extension anchoring method, failure to bind together is characterized as FRP debonding. However, after compared to other anchoring techniques, average shear strength showed the greatest. In addition, all horizontal specimens failed according to FRP break, while their shear strength showed half that of the FRP rope anchoring technique. Anchoring methods may prevent or postpone debonding, which improves the shear strength of FRP. When proposing an anchoring technique for inclusion in existing design standards, these two problems should be considered.

5. Conclusions

In this research, different anchoring methods for FRP shear strengthening were emphasized and analyzed the efficiency of each approach in strengthening shear involvement and preventing FRP debonding failure. The influence of variables that significantly affect the shear contribution of FRP may negate the benefits of anchoring techniques. This will also result in failure modes in anchoring technique. The NSM technique may improve bonding efficiency while minimizing exposure to unfavorable conditions. This technique has the potential to increase the shear contribution, but due to the requirement of specialized equipment, this strategy is extremely difficult to implement. From the literature, sandwich plate systems have a good strength-to-weight ratio, making them increasingly desirable for building form use. With increasing beam depth for NSM and metallic anchoring methods,
shear strength begins to drop. There was a connection between shear contribution and beam depth and the size of the bonded area in FRP.

Using FRP rope anchoring method, the maximum shear strength was obtained, followed by FRP sandwich plate and FRP extension anchorage methods. Only a few anchoring methods were effective in producing FRP rupture and flexural failure modes. The FRP extension anchorage approach exhibited yielding in longitudinal reinforcement. The finding of this paper showed that, more research is needed to enhance the contribution between the parameters and the shear strength and FRP strain, as well as the failure mode utilizing anchoring method.

6. References

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