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## FRP Systems in Shear Strengthening of Reinforced Concrete Structures

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### Abstract

Due to their lightweight, high tensile strength, and ease to install on irregular surfaces, the use of FRP systems for the repair and strengthening of reinforced concrete structures has become an accepted practice within civil engineering community. Extensive research has been conducted on structural members to identify the improvement in their flexural and axial capacity due to FRP strengthening. However, the analytical and experimental studies on shear strengthening with FRP systems are limited. Currently, there is no widely accepted guideline available for the design of concrete structures strengthened in shear using externally bonded FRP systems. Keeping in mind the fact that the use of these strengthening methods has been hindered mostly due to lack of comprehensive design provisions, the available guidelines/specifications are reviewed and the factors that need further investigation are identified. To improve the understanding of the general mechanisms of shear strengthening techniques with externally bonded FRP systems, suggestions for further research effort are itemized and recommendations for an improved guideline are set forth.

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### 1. Introduction

The use of Fiber Reinforced Polymer (FRP) materials in civil engineering field is increased steadily after their first noteworthy appearance in practice almost three decades ago. Although it is demonstrated by many researchers and practitioners that FRP systems have significant potential for various civil engineering applications, they mostly rally to become the prime material among the other alternatives for retrofit and rehabilitation of the reinforced concrete structures. Their well-defined material properties, high strength-to-weight and stiffness-to-weight ratios, and resistance to electrochemical corrosion as well as their easy handling make FRP material superior to other conventional materials in strengthening applications. Moreover, due to their exceptional formability, FRP systems give flexibility to the practitioners to apply the strengthening method on any flat, curved or geometrically irregular surfaces.

As it is proved by experience in many cases, the acceptance and utilization of an emerging technique using a new material (in our case, this is strengthening with FRP systems) depend on the availability of clear design guidelines, installation procedures and construction specifications. Although comprehensive standard specifications exist for all commonly used traditional construction materials, the design specifications for FRP use in strengthening, especially for shear strengthening, are still underway for full development. In general, strengthening techniques with FRP systems can be used to enhance the ductility as well as the flexural and shear capacity of all structural elements (i.e. columns, beams, slabs, structural walls), bridge components (i.e. piers, girders, decks) and in some cases of existing prestressed concrete structures. As most of the recent research efforts focus on strengthening of axial or flexural members, there are relatively less experimental and analytical data on the use of FRP systems for shear strengthening. Furthermore, the available results are scarce and sometimes controversial. Even in traditional reinforced concrete members without FRP, the shear design is a

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complex challenge and uses more empirical methods as compared to axial and flexural design methods. Adding FRP to the equation, with its specific design issues, brings another level of complication in the design.

## 2. FRP systems in shear strengthening

FRP systems used for strengthening of reinforced concrete structures mainly consist of two different methods; the externally bonded laminates and near-surface mounted bars. These systems may contain either carbon fiber (CFRP) or glass fiber (GFRP) reinforced polymers. For shear strengthening applications, generally the externally bonded CFRP systems are used. Up to date, several researchers attempted to propose analytical models for estimation of shear resistance for reinforced concrete members strengthened with externally bonded FRP laminates. Although limited, these models can be classified under four distinct groups. The first group of models relies on an empirically determined limiting value of strain/stress associated with failure of the member for which the shear contribution of the FRP is determined [1], [2]. The second group of models bases on determination of an effective FRP strain where the method of external bonding is also taken into consideration [3–9]. The third group focuses on the non-uniformity of the strain distribution in externally bonded FRP laminates [10–12]. And last group of models utilizes purely mechanics-based theoretical approaches [13–17].

Proposed analytical models that are calibrated with experimental results base on factors related not only to the material properties of FRP and concrete but also to the geometry and the scheme of strengthening applications. Needless to mention that the performance of shear strengthening of concrete structures by using externally bonded FRP laminates significantly depends on the bond behavior at interface between the FRP sheets and the concrete substrates. Shear stresses on concrete structures are transferred to FRP laminates by bond which in general is influenced by mechanical and physical properties of FRP material, concrete and adhesive. These influencing factors are summarized in Table 1. Many analytical models attempted to consider the bond characteristics at the interface in terms of bond stress-slip relationship, effective bond length and bond strength.

Table 1. Factors affecting the bond behavior at interface

Materials/Conditions		Factors
Concrete		Modulus of elasticity, strength, water content, surface conditions, drying shrinkage
FRP System	Fiber laminates	Modulus of elasticity, stiffness, geometry and density
	Resin	Modulus of elasticity, strength, spread, glass transition temperature
	Primer	
	Putty	
Loading condition		Flexure, shear, monotonic, cyclic
Environmental effects		Temperature, moisture, radiation, etc

It is demonstrated in several studies that the bond shear stress at the FRP-to-concrete interface increases rapidly with the increase in slip until it reaches to a peak stress value (bond strength). After this point, micro-cracking at interface starts and leads to a decrease in the shear stress and an increase in the slip. At this stage, debonding of FRP initiates and propagates within the effective bond length (length over which the majority of the bond stress is maintained) until the FRP system fails. Depending on the type of FRP application, (the wrapping schemes) the failure mode of the strengthened structural elements can be either failure due to debonding or rupture of the FRP material. Three typical FRP wrapping schemes are used in common for shear strengthening. The first one is the complete wrapping of structural elements. This scheme is known to be the most effective way of FRP shear strengthening. However, due to geometrical restrictions for structural elements, especially for beams, the complete wrapping may not be always possible. In this case either the FRP U-wrap scheme (wrapping around three sides) or side bonding scheme (two separate FRP sheets on opposite faces of the beam) can be utilized. The illustrations of these wrapping methods for a T-beam are presented in Fig. 1.

It is reported in majority of the experimental studies that the debonding of the FRP is the governing failure mechanism for U-wrap or side bonding methods unless a proper anchorage system is provided. To tackle with the premature FRP debonding failure, various anchorage systems including near surface mounted systems, FRP anchor spikes, additional horizontal strips as well as other mechanical anchorage systems such as steel angles, steel or FRP composite plates, and anchor bolts have been proposed [5, 18–21]. In the presence of an effective anchorage system, the premature failure mode of debonding is prevented and a more preferable FRP rupture failure is observed.

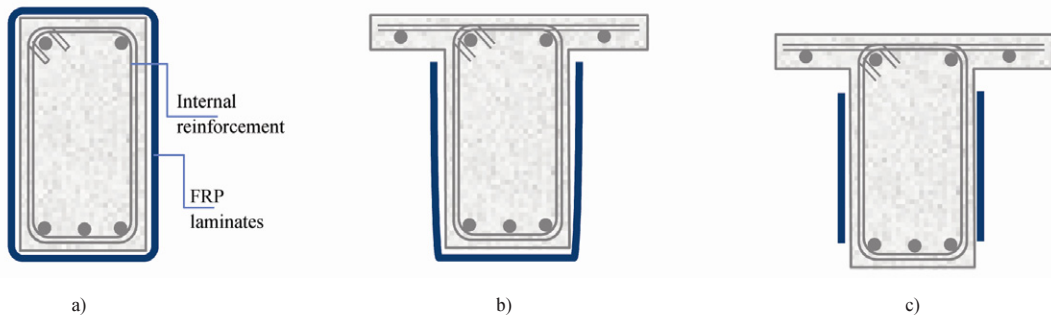


Fig. 1. Wrapping schemes for externally bonded FRP laminates: (a) complete wrapping, (b) U-Wrap and (c) side bonding

### 3. Parameters that influence the design of externally bonded FRP systems

The bond at FRP-to-concrete interface, method of application (wrapping scheme) and the provided anchorage system are the main but not the only factors to be considered in the design of FRP shear strengthening of structural elements. The other parameters that are affecting the design may be related to the mechanical and geometrical properties of FRP and concrete as well as to the available transverse reinforcement ratio and shear span-to-depth ratio. Additional to these parameters, fatigue, prestress, pre-cracking conditions and structural continuity are some of the other factors need be taken into account when designing the shear strengthening application.

### 4. Material properties of FRP and concrete

The concept of effective strain,  $\epsilon_{fe}$  can be used to evaluate the effectiveness of FRP shear strengthening methods. Effective strain is defined as the maximum strain value that can be attained in any FRP system at its nominal strength [22]. The correlation between the effective strain and a combined function ( $E_f \rho_f / f_c'^{2/3}$ ) which takes into account the amount of FRP ( $\rho_f$ ), fiber type (modulus of elasticity,  $E_f$ ) and concrete compressive strength ( $f_c'$ ) indicates that the effective strain decreases with the increase in FRP stiffness, or increase in the amount of FRP used. Concrete compressive strength, on the other hand, influences the bond performance at the interface hence a higher concrete strength will delay the premature debonding failure leading to a higher strain.

### 5. FRP configuration and layout

The configuration of the FRP system affects the failure mode of shear strengthened members. Based on an extensive review of collected experimental data [23], it was reported that the debonding is the dominant mode of failure for beams strengthened with FRP and bonded on the sides only. FRP debonding almost never occurs in beams retrofitted with complete FRP wrap and U-wraps with anchorage systems (Fig. 2).

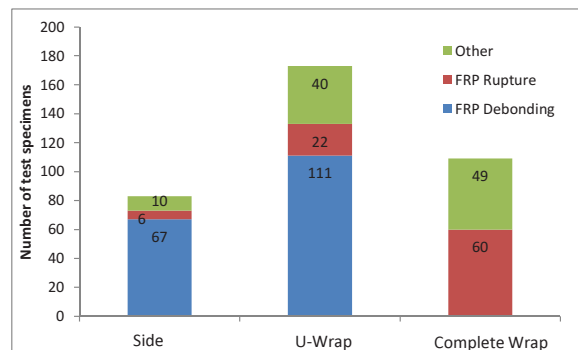


Fig. 2. Distribution of failure modes according to the FRP configuration

Contribution of FRP to shear strength when it is applied with an angle to the members' longitudinal axis (generally 45°) is also another issue that is not clearly covered within existing design codes or specifications. Using the truss analogy, similar to the calculation of contribution from steel reinforcement to shear resistance, the contribution of FRP can be calculated.

## 6. Transverse reinforcement ratio

The contribution of externally bonded FRP laminates to the shear resistance of strengthened structural members is reported to be less for members with high transverse reinforcement ratio than the ones with low transverse ratio [24–27, 8]. This fact can be explained as when the steel transverse reinforcement contributes to shear resistance effectively, the FRP laminates are subjected to less demand and contribute less to the resistance.

## 7. Shear span-to-depth ratio

Recent studies revealed the fact that externally applied FRP laminates contribute more to the shear resistance of slender beams than deep beams [8], [26]. As the shear span-to-depth ratio decreases, the arch action of deep beams become more dominant and failure of these type beams occur due to the crushing of concrete. In this case, externally provided FRP reinforcement contributes to the increase in strength but limited to the concrete strut capacity.

## 8. Current guidelines / specifications for externally bonded FRP systems

The design procedures for shear strengthening of concrete structures with externally applied FRP are available in several documents. Brief summaries of these documents are presented in this section.

### *ACI 440.2R*

One of the most comprehensive and widely used document for shear strengthening is the *Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures* [22]. This guide determines the shear contribution of externally bonded FRP based on failure modes. In complete wrapping applications, the expected failure mode is the rupture of FRP, therefore the ultimate strain of the FRP can be used for calculation of the shear contribution with a strength reduction factor of 0.75. However, regardless this fact, limiting value of ultimate strain is defined as 0.004 in ACI 440.2R. For the other two FRP configurations, namely U-wrap and side bonding applications, either FRP debonding or rupture occurs. Therefore the contribution of the FRP to shear strength should be taken into account for each individual failure mode. The model proposed by Khalifa *et al.* [28] can be utilized for estimation of the shear contribution of FRP in case of debonding failure.

### *CAN/CSA S806*

*The Canadian Design and Construction of Building Composites with Fiber Reinforced Polymers* (CAN/CSA S806 [29]) is another code that provides design rules for externally bonded FRP reinforcement for concrete. The equations in this code are based on the simplified method for shear design used in the concrete design code (CAN/CSA A23.3 [30]), which is limited to the usual cases of shear reinforcement (including FRP) perpendicular to the longitudinal axis of beams. The shear contribution of the FRP is determined based on failure modes and the ultimate strain is limited to 0.004 for failure due to FRP rupture and 0.002 for bond critical applications.

### *CAN/CSA S6-06*

*The Canadian Highway Bridge Design Code* (CAN/CSA S6-06 [31]) also provides rules for shear strengthening of concrete with externally-bonded FRPs although it mainly specifies the same expressions of ACI 440 [22]. It is stated within the code that the FRP shear strengthening system should consist of U-wraps anchored in the compression zone or complete wrapping of the cross-section only.

### *fib-TG9.3*

European fib bulletin 14, *Design and Use of Externally Bonded Fiber Polymer Reinforcements (FRP EBR) for Reinforced Concrete Structures*, (fib-TG9.3 [32]) is an informative document which utilizes an analytical model proposed by Triantafyllou and Antonopoulos [7] for calculation of the FRP contribution to shear capacity ( $V_{fd}$ ). It takes into account the FRP material properties as well as different application methods (preformed or wet lay-up FRP systems) with different level of material safety factors. Failure modes of delamination and debonding are also addressed by using a simplified

bilinear bond model and by considering the effects of the loss of composite action between the FRP and concrete substrate. Although no specific rules provided, durability is also discussed within the document conceptually.

#### *JSCE*

*Japan Society of Civil Engineering Recommendations for Upgrading of Concrete Structures with Use of Continuous Fiber Sheets* (JSCE [33]) employs a more complicated method where the rules for the design of externally bonded FRP materials are presented according to a performance-based methodology. Durability aspects such as crack width and protection from penetration of aggressive agents are also addressed.

#### *ISIS*

*The Manual for Strengthening Reinforced Concrete Structures with Externally-Bonded Fiber Reinforced Polymers*, published by the Canadian Intelligent Society of Innovative Structures (ISIS [34]) bases on the available Canadian Codes (CAN/CSA S6-06 [31] and CAN/CSA S806-02 [29]) and provides comprehensive design examples for the use of externally bonded FRP systems.

#### *The British Concrete Society*

The Technical Report 55, *Design Guidelines on Strengthening Concrete Structures Using Fiber Composite Materials* (Concrete Society [35]) follows a similar methodology with fib- Bulletin 14 (fib-TG9.3 [32]). It covers the same aspects of shear design for strengthening of concrete structures with externally applied FRP systems. However it focuses more on the practical construction issues. Although the strain in FRP is limited to 0.004 for all cases, the Technical Report 55 takes into account the mode of failure by proposing a limit strain value of one half of the ultimate design strain for FRP rupture failure and by an expression derived by Neubauer and Rostasy [36] for debonding failure.

#### *NCHRP 678*

In 2011, the NCHRP report 678, *Design of FRP Systems for Strengthening Concrete Girders in Shear* was published to address the shear strengthening of concrete members with externally applied FRP systems. The report identifies in detail the factors affecting the design of shear strengthening. Conducting an assessment to evaluate the existing design methods and after identifying their shortcomings, the report proposes a new set of design equations for calculation of the contribution of FRP to shear capacity. The proposed expressions take into account two predominant failure modes depending on the effectiveness of the provided anchorage.

## **9. Suggestions for improved design methods and standards**

Any analytical model that will be used for calculating the contribution of externally applied FRP to the shear resistance of reinforced concrete members should include, but not limited to the following parameters, i.e., stiffness of FRP reinforcement, material properties of concrete and FRP, type of FRP application (wrapping scheme), bond strength at FRP – concrete interface, effective development length, mode of failure and anchorage systems. Although the number of parameters that need to be taken into account are high, the expressions in design guidelines for estimation of FRP contribution to shear strength should be simple or simple enough to facilitate their use by practitioners. Recommended values for parameters should be available or should be appropriately assumed.

Although some of the existing guidelines take into consideration a part of the aforementioned factors with their analytical models, there is no unique one which addresses all, exhaustively. Hence an improved version of design guidelines should be developed. As for the improvement, following aspects should be further investigated and included in these guidelines:

- Interaction between internal transverse reinforcement ratio and externally bonded FRPs,
- Effectiveness of the anchorage systems and analytical expressions that represent their influence on overall behaviour or failure mode of the FRP systems,
- Practical application methods for strengthening of existing prestressed concrete structures. This shall include development of analytical models and expressions that take into account the characteristic of the prestressed concrete structures.
- Long-term fatigue performance of shear strengthening scheme with the effects of cracking on interfacial bond characteristics.

## 10. Conclusions

After its first introduction to the civil engineering field, especially for retrofit and rehabilitation purposes, significant amount of research has been conducted to develop and evaluate the concepts of flexural and axial strengthening of concrete structures with FRP materials, but limited investigations have been conducted on the use of FRP for shear strengthening. Although several analytical models have been proposed for predicting the shear contribution of externally bonded FRP, due to insufficient experimental data, these models were not calibrated accurately and hence produced diverse or in many cases contradictory estimates. As the number experimental results increase, these models can be recalibrated to produce more reliable results.

A serious concern in real practice is the lack of comprehensive design codes, guidelines and specifications. It is a fact that without design codes and standards, the real life applications of these FRP systems will remain limited. Further research efforts and investigations are essential to quantify and understand better the mechanisms associated with the use of externally bonded FRP systems for shear. Accordingly new design models and comprehensive guidelines can be developed. These new design guidelines unquestionably should lead to more economic, simpler and safer applications of FRP for shear strengthening.

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