FRPRCS-14, Belfast - June 2019

CFRP Contribution in Reinforced Concrete Beams Strengthened in Shear with Anchored CFRP Strips

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Abstract

Premature failure of CFRP due to debonding has been a major concern in shear strengthening of RC beams. Therefore, adequate anchorage needs to be provided for CFRP materials to prevent premature failure. Existing guidelines encourage the use of anchorage to increase the effectiveness of the strengthening system; yet, they do not provide any guidance on the effect anchorage has on the CFRP contribution. A CFRP anchorage system that consist of CFRP strips and CFRP anchors has proven to significantly enhance the shear capacity. Design equations to compute CFRP contribution to the shear capacity of beams strengthened with anchored CFRP materials are presented. The proposed guidelines adopt the variable angle truss model for evaluating CFRP shear contribution. A simple model to calculate the effective strain in anchored CFRP strips was developed. A database that consists of 42 tests conducted on beams strengthened with anchored CFRP was collected. The comparison between predicted contributions and experimental results showed that the proposed equations provided reasonable estimates.

Keywords: CFRP design guidelines; Shear strengthening; CFRP anchors; Reinforced Concrete

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Introduction

U-wrap configuration is the most common application for shear strengthening of reinforced concrete beams with CFRP materials [1,2]. Yet members with the U-wrap strengthening scheme are still highly vulnerable to premature failures due to debonding. Debonding of the CFRP material from the concrete surface typically occurs at much lower strains than the fracture strain of the CFRP fibers, thus preventing the utilization of the material strength and reducing the effectiveness of the strengthening system. When adequate anchorage is provided, the ultimate capacity of the member will be controlled by the fracture of the CFRP material. CFRP rupture occurs when the fibers reach their ultimate strain.
Recent studies have shown that adequately designed CFRP spike anchors can provide sufficient anchorage for CFRP strips in shear strengthening applications [1-3]. The efficiency of the anchors and their performance in shear strengthening applications was clearly demonstrated in these studies. Test results have demonstrated the ability of CFRP anchors to develop the full strength of CFRP strips. Testing of full-scale T-beams that contain transverse steel reinforcement strengthened in shear with U-wrap bonded CFRP strips showed a negligible shear strength increase (less than 5%). However, when CFRP anchors were used to provide anchorage for the U-wrap strips, shear strength increases of up to 50% were achieved [1]. The CFRP spike anchor installation procedure for providing end anchorage for CFRP strips in shear strengthening can be found in [1-3].
Although shear strengthening using anchored CFRP material is the most practical, efficient, and feasible strengthening configuration, the shear capacity of members strengthened with anchored CFRP systems cannot be accurately predicted by current design guidelines, as most existing guidelines ignore the effect of anchorage in their design provisions. Current guidelines do not consider the use of anchored CFRP materials in shear strengthening.
Therefore, accurate shear strength predictions of members strengthened in shear with anchored CFRP material cannot be obtained using existing design procedures for U-wrap without anchorage. This paper aims to develop simple design equations to predict the CFRP shear contribution for beams strengthened with anchored CFRP U-strips using CFRP spike anchors.

Database for Shear Strengthening with Anchored CFRP Strips

A considerable amount of research has been conducted to evaluate the use of CFRP for the shear strengthening of reinforced concrete members. However, the majority of these studies were carried out on tests that utilized bond-critical CFRP configurations and were mainly focused on small-scale specimens that had rectangular cross-sections with little to no transverse reinforcement [4]. Such specimens are not representative of actual in-situ members. Test data on the use of anchored CFRP configurations for shear strengthening of reinforced concrete beams is limited [4].
A database comprised of tests from Kim et al. [1] and Jirsa et al. [2] was collected. The tests included in this database are summarized in Ghannoum et al. [5]. The collection of test data provided a range of reinforced concrete member geometries, web widths, member heights, transverse steel reinforcement spacing, CFRP reinforcement ratios, CFRP strip widths, concrete strengths, and various CFRP strip configurations. The cross-sectional dimensions of the specimens included in the database are shown in Fig.1. A high-resolution optical measurement system was utilized to measure the strains on the surface of the concrete and CFRP strips. A detailed discussion of the optical measurement system can be found in Shekarchi [3].

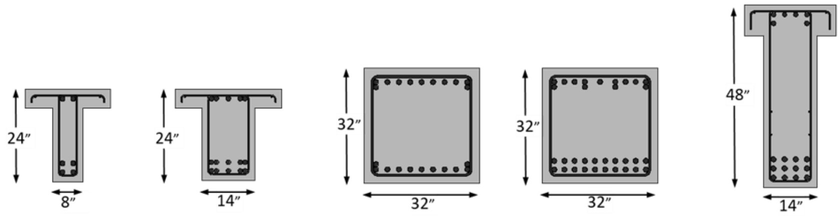

Figure 1: Cross-sectional dimensions of test specimens in the database

Contribution of Anchored CFRP Strips to Shear Strength

Most available guidelines on shear strengthening with CFRP materials do not consider the effect of anchorage in their design procedures. The effectiveness of shear strengthening systems using CFRP materials is heavily reliant on their failure modes, which in turn govern the ultimate capacity of the strengthened member. If debonding is the controlled failure mechanism, the contribution of the CFRP will rely on bond strength between the CFRP material and the concrete surface. The bond strength depends on several parameters, which makes reasonable estimates of the CFRP contribution difficult.
The inclination of the critical shear crack has a significant influence on the shear resistance of strengthened members. Adopting the variable-angle truss model can significantly impact CFRP contribution. Therefore, a variable-angle truss model would be more suitable in determining the CFRP shear contribution for members strengthened with anchored CFRP systems. CFRP shear contribution, V_f, can be computed using Eq. (1). The simplified version of the Modified Compression Field Theory provides a simple relationship that relates the angle of inclination to the longitudinal strain, ε_s, as given in Eq. (2). The strain in the longitudinal reinforcement in Eq. (2) can be evaluated via sectional analysis or through Eq. (3), an adaptation from AASHTO LRFD.

Effective Strain Model

Surface strain data obtained by the optical measurement showed that after full debonding of the CFRP strips, uniformly distributed strain was observed along the length of the strips. It was found that the use of CFRP spike anchors led to uniform strain distribution across and along each strip, and resulted in CFRP strip fracture. It was noted that CFRP strips crossing the critical crack did not rupture simultaneously. The failure was consistently initiated by the fracture of one of the strips, followed by instantaneous fracture of adjacent strips crossing the critical crack. Thus, strains in the strips crossing the shear crack are not equal at ultimate. Based on the optical measurement system data, CFRP strains at ultimate can vary by up to 50% [2]. A relationship between CFRP strains at the shear failure, defined as effective strain, ε_{fe}, and CFRP axial rigidity, $\rho_f E_f$, was obtained by curve-fitting of test data. The effective strain was determined by averaging the vertical strains in all the CFRP strips that cross the critical shear crack at the ultimate shear capacity of the member.
The ratio of effective strains to ultimate strain, R, is termed the reduction factor. A simple relationship between the reduction factor and axial rigidity is shown in Fig.2 and given in Eq. (4). Eq. (4) conservatively estimates the reduction factor for most tests. At low axial rigidity values, the measured reduction factors ranged from approximately 0.8 to 1.1. Therefore, a reasonable upper limit for the reduction factor can be taken as 0.8, or 80%, of the fracture strain, which was found to correspond to the average effective strain for all tests in the database.

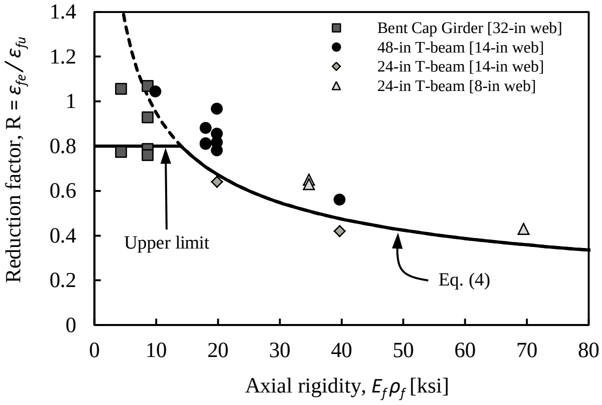

Figure 2: Reduction factor for effective strains in anchored CFRP strips

Evaluation of Proposed Equations

To evaluate the reliability of the proposed design equations, experimental test results were compared to the predicted shear contributions based on the proposed equations. Fig.3 provides a comparison between the experimental and predicted CFRP shear contributions using ACI440.2R-17 with an effective strain of 0.004, and Eq. (1) with effective strains calculated based on Eq. (4) and (5). Overestimated predictions obtained by proposed equations correspond to tests that were stopped just prior to fracturing the CFRP strips in order to preserve the specimens for testing in other spans.
The average ratio of the experimental-to-predicted CFRP shear contribution using the proposed equations is 1.12 with a coefficient of variation of 18%, whereas using ACI440.2R-17 yielded an average ratio of 2.78 with a coefficient of variation of 26.3%. The predictions of ACI440.2R-17 for CFRP shear contributions are therefore found to be very conservative, where the level of conservatism increased as the amount of CFRP contribution increased.

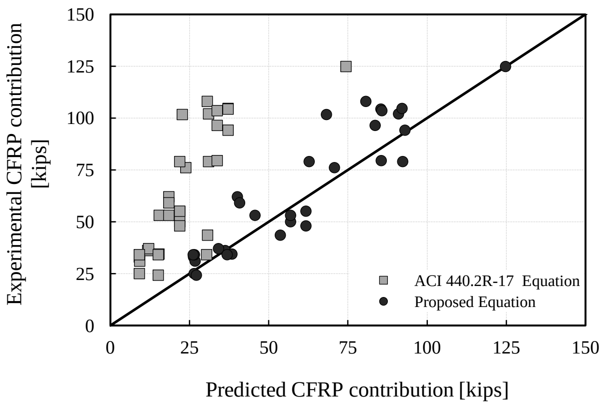

Figure 3: Experimental and predicted CFRP shear contributions

Conclusions

A simple model was presented to calculate the CFRP contribution to the shear resistance in beams strengthened with anchored CFRP strips. The proposed model introduces a CFRP reduction factor that determines the effective strain in the CFRP strips at the ultimate shear capacity of the member. The proposed model yielded reasonable estimates of the measured CFRP shear contribution when compared to test results.

Table 1: Proposed design equations for anchored CFRP

CFRP Contribution to Shear Strength	
$V_f = \frac{A_{vf} f_{fe} d_{fv} (\sin \alpha_f + \cos \alpha_f)}{s_f} \cot\theta$ $V_f = \frac{A_{vf} f_{fe} d_{fv}}{s_f} \cot\theta$ for α_f=90° where $A_{vf} = 2nt_f w_f$ and $f_{fe} = E_f \varepsilon_{fe}$	(1)
Determination of Critical Shear Crack Angle	
$\theta = 29^o + 3500\varepsilon_s$ for 29° ≤ θ ≤ 50° or use the observed crack angle	(2)
$\varepsilon_s = \frac{(\frac{\lvert M \rvert}{0.9d} + \lvert V_{u@M} \rvert)}{E_s A_s}$	(3)
Reduction Factor on Effective CFRP Strain	
$R = \frac{3}{\sqrt{E_f \rho_f}} \leq 0.8$	(4)
$\varepsilon_{fe} = R\,\varepsilon_{fu}$	(5)

References

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