NONLINEAR CYCLIC BEHAVIOR OF
CONCRETE MRF BEAMS WITH
INNOVATIVE FRP STRENGTHENING
TECHNIQUE

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ABSTRACT

The effectiveness of externally bonded fiber-reinforced polymer (EB-FRP) laminates for the strengthening of shear deficient reinforced concrete (RC) moment-resisting frame (MRF) beams is studied through large-scale testing under cyclic loading on a series of flanged specimens. This paper presents the experimental performance of specimen S5, a 4/5-scale MRF T-beam designed to have a 25% shear over-stress at the end-yielding region and externally retrofitted with EB-FRP using an innovative strengthening detail consisting in anchored U-wrap carbon FRP (CFRP) strips in conjunction with crack control joints. In addition to overcome the large shear deficiency of S5, the proposed EB-FRP shear strengthening scheme enabled the specimen to work well beyond the ASCE 41-13 prescriptive end rotations, with a total rotation at the onset of strength loss of 0.038 rad, 30% higher than the corresponding prescriptive value.

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The effectiveness of externally bonded fiber-reinforced polymer (EB-FRP) laminates for the strengthening of shear deficient reinforced concrete (RC) moment-resisting frame (MRF) beams is studied through large-scale testing under cyclic loading on a series of flanged specimens. This paper presents the experimental performance of specimen S5, a 4/5-scale MRF T-beam designed to have a 25% shear over-stress at the end-yielding region and externally retrofitted with EB-FRP using an innovative strengthening detail consisting in anchored U-wrap carbon FRP (CFRP) strips in conjunction with crack control joints. In addition to overcome the large shear deficiency of S5, the proposed EB-FRP shear strengthening scheme enabled the specimen to work well beyond the ASCE 41-13 prescriptive end rotations, with a total rotation at the onset of strength loss of 0.038 rad, 30% higher than the corresponding prescriptive value.

Introduction

For the past twenty years, numerous studies, such as [1]–[3], have reported the benefit of externally-bonded fiber-reinforced polymer (EB-FRP) laminates as shear strengthening mechanism for reinforced concrete (RC) beams. Several analytical models to assess the shear contribution of the EB-FRP have been proposed, some of which are currently adopted in design guidelines [4]–[6]. However, very limited research has been conducted on the seismic response of FRP-shear-strengthened RC beams under cyclic loading [7]–[10]. In order to increase the effectiveness of EB-FRP as an external shear reinforcement technique, adhesive bonding may be supplemented by mechanical anchorage. However, none of the cited design guidelines provide the necessary detail and guidance on mechanical fastening techniques for the FRP laminates. The lack of anchorage-related design provisions and the limited amount of available experimental data demonstrate the need for further research and provide an opportunity for innovation.

This paper presents the experimental results of a large-scale shear deficient RC moment-resisting frame (RC-MRF) T-beam, labeled S5 hereafter, externally strengthened with an innovative EB-FRP detail. Specimen S5 was part of a larger investigation on the seismic performance of flanged RC-MRF beams with various design and detailing deficiencies. The
An experimental program was used to evaluate the need of retrofit for the beam members of the lateral resisting system of an existing building in California. Further details on this project and the performance of other specimens can be found in [10], [11].

**Experimental Program**

The specimens in this study were 4/5-scale equivalent tip-loaded horizontal cantilevers that reproduced the characteristics of a series of existing shear-deficient MRF beams. With a maximum shear demand of 1,054 kN and a nominal shear capacity of 843 kN provided by the transverse reinforcement (no shear contribution from concrete was considered), specimen S5 presented a 25% shear over-stress at the end-yielding region. Figure 1 depicts the geometry and internal reinforcement for specimen S5, and Figure 2 shows the EB-FRP strengthening solution, which consisted of two-layer strips of uniaxial CFRP with over-the-top CFRP rope anchors (Fyfe Co. LLC patent) combined with intermediate shallow sawcut joints.

The novelty of the proposed EB-FRP strengthening detail is twofold: first, the US patented anchors (Fyfe Co. LLC patent) passing through the flanges create a desirable fully closed stirrup-like external reinforcement; secondly, the shallow sawcut grooves in between the CFRP strips are highly effective at keeping flexural cracks away from the FRP reinforcement and promoting the distribution of plastic rotations among multiple parallel small cracks, resulting in a more ductile failure compared to hinging regions with one dominant crack only.

![Figure 1. Geometry and internal reinforcement.](image1)

![Figure 2. FRP shear reinforcement for specimen S5.](image2)

All specimens were framed into a reaction block and quasi-statically loaded at their free-end under stepwise increasing vertical displacement reversals, in accordance with the ASCE 41 testing methodology. Three cycles were applied at each displacement level until the peak capacity was reached; thereafter, two cycles were applied. The load protocol for S5 is shown in Figure 3. The following variables were continuously monitored via external and internal instrumentation: flexural and shear deformations; deformed shape; reaction block’s displacement and rotation; steel reinforcement strains.
The sawcut grooves were successful in forcing the development of flexural cracks at the desired locations between the FRP strips. Peak capacity was reached at 3.4% drift (0.034 rad), with no discernable debonding of the CFRP strips. Hinge formation started during the first cycle at 3.8% drift (0.038 rad), characterized by excessive crack opening and concrete crushing at the end-yielding region. Sudden fracture of the second-next CFRP strip adjacent to the reaction block during the second cycle at 3.8% drift (0.038 rad) resulted in structural failure of the specimen with an immediate loss of strength.

Table 2 summarizes the experimental load-deformation results for specimen S5, including: shear, displacement, moment, total and plastic rotation values at yield ($V_y, \Delta_y, M_y, \theta_y$), peak strength ($V_p, \Delta_p, M_p, \theta_p, \theta_{pp}$), and onset of strength loss ($V_L, \Delta_L, M_L, \theta_L, \theta_{Lp}$). Considerably high rotation values were achieved - 0.034 rad at peak and 0.038 rad at strength loss- thanks to the EB-FRP scheme by a beam that, otherwise, would have prematurely failed in shear.

Figure 4 provides the cyclic performance of the specimen S5 in terms of moment-rotation and shear-displacement. The experimental results are compared against analytically determined flexural and shear capacities for as-tested material properties (with $M_y$ and $M_u$ the yield and ultimate moments determined from moment-curvature analysis under monotonic loading, and $V_s$ and $V_f$ the transverse steel and FRP shear contributions, respectively), as well as the ASCE 41 generalized backbone curve, which accounts for cyclic degradation. The proposed EB-FRP was capable of accommodating the ASCE 41 prescriptive flexural end-rotations, with $\theta_L$ being about 30% larger than the deformation at peak of the prescriptive envelope.
Conclusions

An innovative EB-FRP shear strengthening detailing, consisting of two-layer anchored CFRP strips in full-wrap configuration combined with intermediate sawcut joints, was implemented on specimen S5. The EB-FRP reinforcement was successful at overcoming the 25% shear deficiency of the beam and enabled the development of an appreciable total rotation at failure of approximately 0.04 rad, 30% larger than the ASCE 41 prescriptive value.

References