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Shear behavior of full-scale reinforced concrete T-beams strengthened with CFRP strips and anchors

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HIGHLIGHTS

- Nine 1220 mm deep T-beams were strengthened in shear using anchored CFRP.
- With CFRP anchors, CFRP strips ruptured in all tests.
- The effective strain in the CFRP strips was about 1/2 of the fracture strain.
- CFRP shear-strength contribution was greater in beams with less transverse steel.

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ABSTRACT

Nine tests were conducted on 1220 mm deep T-beams strengthened in shear using Carbon Fiber-Reinforced Polymer (CFRP) strips and CFRP anchors. The use of anchors resulted in most CFRP strips reaching fracture, but not simultaneously. The shear contribution of FRP was larger in beams with less transverse steel reinforcement. Because CFRP and steel reinforcement have different material and bond properties, interactions between the two materials need to be taken into account when determining the shear capacity of a strengthened member.

1. Introduction

Carbon Fiber-Reinforced Polymers (CFRPs) can be quickly applied in retrofit or repair applications, with a minimum of functional disruption and with virtually no change in the geometry of structural elements. Many studies have been conducted on the application of externally bonded FRP in strengthening reinforced concrete bridge members (NCHRP report 655 [1]). A large number of studies have also been performed to investigate the shear strengthening of structural members using CFRP materials (e.g., [2–7]). NCHRP report 678 [8] provides a comprehensive summary of shear strengthening studies using FRP. The report identifies key parameters affecting the behavior of systems strengthened with FRP based on a database of reported test results. The report highlights the need for mechanical anchorage of FRP materials to concrete members so that the full strength of the FRP materials can be utilized. The report also recommends further investigations of the interactions between the internal transverse steel reinforcement and externally bonded FRP shear reinforcement on shear strength of concrete members.

Although there have been numerous experimental studies on shear strengthening using FRP materials, relatively few included mechanical anchorage of external FRP to concrete members, and even fewer used CFRP anchors (e.g., [8–23]). Moreover, many previous experimental studies were conducted on specimens that might not represent typical construction practices, such as small-scale specimens, specimens without transverse steel reinforcement, or specimens completely wrapped with FRP [24].

Anchorage of FRP materials is needed in cases where complete wrapping is not practical, such as in members that include flanges, floor slabs, or bridge decks. CFRP anchors have been proven to develop the full strength of externally applied CFRP strips in shear strengthening applications [18]. In a previous experimental program conducted by Kim et al. [23], 610 mm deep reinforced concrete T-beams were strengthened in shear using U-wrapped CFRP

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strips and CFRP anchors. In most cases, CFRP anchors prevented detachment of U-wrapped CFRP strips from the beams and anchored CFRP strips were able to increase the shear strength by up to 40%; but only for beams with a shear-span (a) to effective depth (d) ratio exceeding two (a/d = 2.1 and 3.0).

Nine tests were conducted on 1220 mm deep T-beams strengthened in shear using externally applied CFRP strips and CFRP anchors. Beam depth and overall dimensions were selected to represent full-scale bridge sections. The specimens tested constitute the largest reinforced concrete beams strengthened in shear using CFRP strips anchored with CFRP anchors tested to date. The tests were further designed to investigate the effects of the following key variables on the efficiency of CFRP shear strengthening: (1) the amount and spacing of steel stirrups; (2) the amount, layout, and inclinations of CFRP strips; and (3) the layout of CFRP anchors.

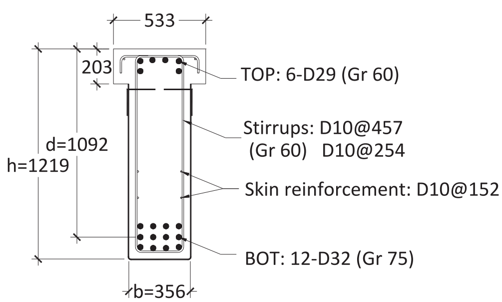

Fig. 1. Cross-section of the 1220 mm T-beams.

2. Experimental program

2.1. Specimen details

T-beams with an overall depth of 1220 mm were tested with a shear-span to depth (a/d) ratio of 3.0. The a/d ratio was selected based on findings of a previous study [23], which demonstrated limited benefits from CFRP strengthening at a/d ratios below 2.0. Test specimens were strengthened in shear by externally applying CFRP fibers in strips that were wrapped around the web and anchored using CFRP anchors just below the flange of the T-beams.

In Fig. 1, the cross-section of the 1220 mm beams used in this study is shown. Two stirrup spacings were considered to evaluate the effects of the transverse reinforcement ratio. Stirrups were 10 mm diameter bars spaced at either 457 or 254 mm on center. The flexural strength of test specimens was designed to exceed the expected shear strength. Skin reinforcement was also provided on the side of the beams in the flexural–tension region.

2.2. Material properties

Measured concrete compressive strength at time of testing was approximately 27 MPa. Transverse steel was ASTM A615 Grade 60 with a measured yield stress of 476 MPa. The manufacturer specified thickness of CFRP laminates was 0.28 mm. Ultimate stress and strain of the CFRP laminate used in this study were 1062 MPa and 0.0105 respectively based on manufacturer's specifications. The specified modulus of elasticity of CFRP laminates (E_f) was 102,000 MPa. Although the rupture stress of the CFRP laminates is much higher than the yield stress of the steel, the elastic stiffness of CFRP was roughly half that of steel, which implies that large strains must be developed in order to effectively utilize the full capacity of the CFRP materials when anchors are provided. In addition, CFRP is a brittle material

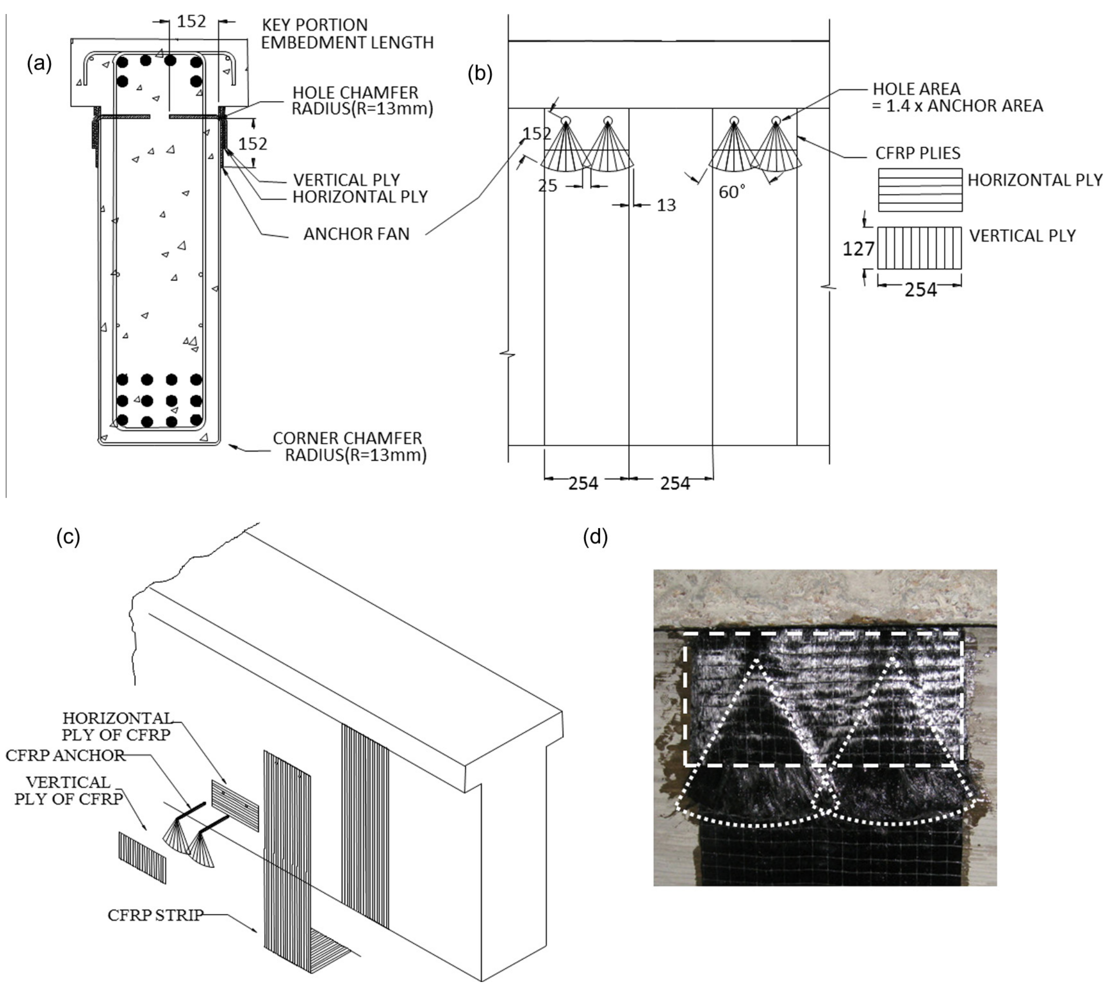

Fig. 2. CFRP strip and anchor details (all units are in mm) – (a) cross-section, (b) side, (c) isometric view, (d) photo of CFRP anchors.