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Shear strengthening of steel plates using small-diameter CFRP strands

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ABSTRACT

This paper presents the results of a comprehensive research program, including experimental and analytical studies, to examine the use of small-diameter CFRP strands for shear strengthening of steel structures and bridges. The experimental program examined the effectiveness of the proposed strengthening system to increase the shear capacity of steel plates subjected to pure shear stresses using a unique test set up. A nonlinear finite element analysis (FEA), calibrated the experimental results, was used to study parameters which were not included in the experiments. Research findings indicated that the proposed system is effective for shear strengthening of steel structures and eliminated the typical debonding failure commonly observed by CFRP laminates.

1. Introduction

Due to the known benefits of Fiber Reinforced Polymer (FRP) materials, their use for retrofitting (strengthening and repair) of concrete structures became a common practice. The use of FRP material for steel structures is also required due to the increasing demand for traffic loads, problems due corrosion and deterioration due to fatigue loadings. The new bridge design codes require designing for higher vehicular loads in comparison to that used in the initial design of the bridges. The production of high modulus Carbon FRP (CFRP) with elastic modulus higher than that of steel, offers a promising alternative for flexural and shear strengthening of steel structures and bridges [1].

Due to the uncertainties and the reported debonding failure experienced by using FRP sheets/plates for strengthening steel members, numerous studies were conducted experimentally and analytically to investigate the bond behavior [2–4]. Understanding the bond mechanism of the CFRP to steel initiated by testing of flexural steel members strengthened with CFRP. Based on understanding of the bond behavior, researches introduce several schemes for the use of externally bonded, high-modulus CFRP materials for flexural strengthening of steel members which have shown significant increase in flexural capacity and stiffness [5–11]. However, to increase the total load-carrying capacity of the strengthened member, the shear capacity should also be increased along with its increase of the flexural capacity.

Shear capacity of the web plate of steel girder is typically controlled by the compressive component of the applied shear. Therefore, the ultimate shear strength of the steel web plate is typically controlled by elastic buckling of slender webs or yielding of the steel material of compact or non-compact webs. Therefore shear capacity of the web plate can be increased by reducing the state of stress in the web plate. Strengthening of web plates by using Carbon Fiber-Reinforced Polymer (CFRP) materials could help reducing the stress level and consequently increase the shear capacity.

Very limited numbers of research have been reported on the use of FRP for shear strengthening of existing steel girders. Patnaik et al. (2008) [12] published results of experimental and analytical program focused on shear strengthening of steel built-up I-beams. Test results confirmed the effectiveness of the proposed CFRP shear strengthening to increase the shear capacity of steel beams up to 26%. The reported failure mode of the strengthened specimen was due to debonding of CFRP sheet from the steel substrate. Okeil et al. [13–15] increased the lateral stiffness of steel plate by bonding pultruded GFRP sections to the surface. The strengthened system increased the shear strength by 56 percent. The reported failure mode of the strengthened specimens was debonding of the GFRP stiffener followed by immediate web buckling. The study on using T-shaped GFRP stiffeners as shear strengthening was investigated analytically by Babaizadeh (2012) [16]. Results of FE analysis showed that strengthening steel beams with different flange width can result in increase of shear capacity up to 66% for square shear zones and up to 36% for rectangular shear zone. An application of CFRP strips as shear reinforcement was also investigated by Narmashiri et al. (2010) [17]. Strengthening system consist of applying CFRP on one or both faces of the steel web, and the research included also different reinforcement CFRP ratio. Results of the experimental research showed clearly that externally bonded CFRP could increase the shear capacity of steel I-beam up to 51 percent. The reported failure modes

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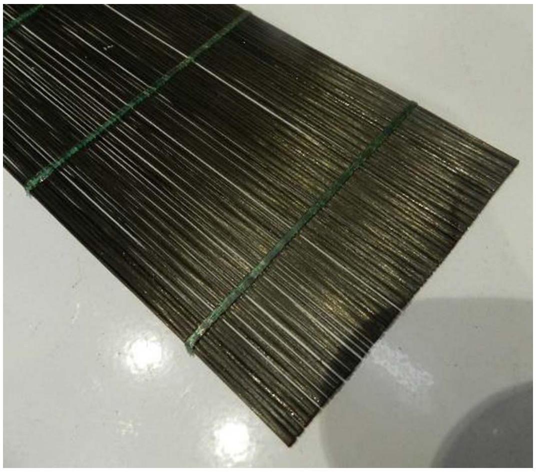

Fig. 1. Small-diameter CFRP strand sheet.

were longitudinal delamination and debonding of the CFRP strips.

The proposed small-diameter CFRP strands shown in Fig. 1, is a promising alternative strengthening system for steel structures. The CFRP strands are provided in sheets and the strands are stitched together leaving a gap between the strands to allow the adhesives to penetrate and totally cover the strands.

Performance of small-diameter CFRP strand sheets subjected to flexure and axial compression are documented in previous publications [8,18]. This paper evaluates the efficiency of the proposed small-diameter CFRP as shear strengthening system for steel girders subjected to direct shear loading.

2. Experimental program

2.1. Test setup

To simulate an applied pure shear stresses acting on a steel plate of typical web of steel plate girder, a square plate specimen is used. The plate is clamped to a heavy steel frame, rotated 45° and subjected to tensile load on diagonally opposite corners as schematically shown in Fig. 2(a). The applied tensile load to the rigid steel frame induces equivalent shear forces along the edges of the steel test plate through uniformly distributed pre-stressed bolts as shown in Fig. 2(b). The shear forces along the edges of the specimen induced compressive stresses perpendicular to the direction of the applied tensile load and tensile stresses parallel to direction of the applied tensile load.

The steel plate specimen was pre-stressed to the articulated built-up steel frames through series of 40 mm (1–1/2 in.) diameter high-strength

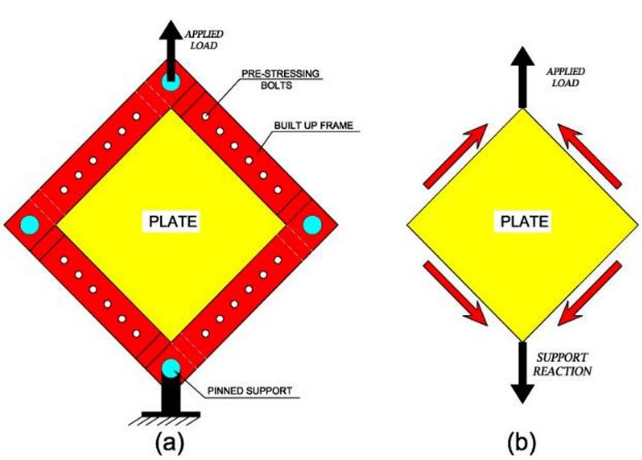

Fig. 2. State of forces acting on the test plate subjected to the applied tensile load.

(HS) bolts. Twenty-four HS bolts were torqued using 1500 kN·mm (1100 lb·ft) impact wrench. Induced stresses were transferred to the test plate through the friction of the connection induced by the bolts. The exposed area of test plate had a dimensions of 910 × 910 × 5 mm (36 × 36 × 3/16 in.) resulting in slenderness ratio (h/t) of 192. The frame was made up by four very stiff steel plate legs, each consist of stiff short and long plates having dimensions of 760 × 200 × 25 mm (30 × 8 × 1 in.) and 1320 × 200 × 25 mm (52 × 8 × 1 in.), respectively. Each two legs were connected at the corners using high-strength steel pins with a diameter of 100 mm (4 in.) to allow rotation. To avoid bearing of the test plate on the pins at the corners, holes of the steel plate were machined with diameter of 127 mm (5 in.) which are slightly larger than the pin diameter. Two 2000 kN (440 kip) capacity hydraulic actuators were used to apply the tensile load to the steel frame. The two hydraulic actuators were connected to the same controller to ensure that the loads are equal from each actuator. Two highly stiffened spreader beams were especially designed to transfer the tensile load to the shear frame. The bottom spreader beam was pre-stressed to the strong floor using high strength bars. Schematic sketch and view of the test setup are shown in Fig. 3.

2.2. Instrumentation

Vertical and horizontal strains of the plate at mid-point were measured using electrical resistance strain gauges with a gage length of 5 mm (3/16 in.). Four Strain gauges were attached to both faces of the control plate, with two strain gauges on each face. Two vertical strain gauges were attached in the direction of the applied tensile load and two horizontal strain gauges were attached in direction of the compressive component. Total of eight strain gauges were attached to the strengthened specimens at mid-point. Four strain gauges were attached to the base steel and the remaining four strain gauges were attached on the outer surface of the CFRP strand sheets. The overall out-of-plane lateral deformation of the steel plates was measured using five linear string potentiometers. OptotrakCertus® motion capturing system was also used. The motion capturing system measures a three-dimensional (3-D) coordinate system using Infrared Emitting Diodes (IRED) attached to the specimen at points of interest. The IREDs were attached to the front face of the test specimens along with the vertical and horizontal centerlines and were spaced at 75 mm (3 in.). All instrumentations were connected to an electronic data acquisition system. The instrumentations used to measure behavior of the specimens are shown in Fig. 4.

2.3. Test matrix

A total of nine square steel plates were included in this research as given in Table 1. The CFRP strands were externally bonded at an angle of 45°, 90°, and ± 45° relative to the applied tensile load using one and two layers of the High-Modulus (HM) CFRP strands on each side of the plate. The HM small-diameter CFRP strands was selected as the result of the research undertaken for plates subjected to compression proven to be the best effective strengthening system in comparison to Intermediate-Modulus (IM) and Low-Modulus (LM) small-diameter CFRP strands [18]. The following nomenclature was adopted to distinguish the various cases. All specimens were 915 × 915 mm (36 × 36 in.) and 5 mm (3/16 in.) thick, consequently the slenderness ratio was 192. The first number is the set number. The second number represents angle of the orientation relative to the applied tensile load. Last letters show the number of layers and the elastic modulus of the CFRP material used. Fig. 5 shows configuration of each specimen including orientation of HM CFRP strands. A layer of the low-modulus polyurea putty was used between the steel plate and the CFRP strands for all strengthened specimens. The control specimen in each set was used for the strengthened specimen with one layer and subsequently two layers of HM CFRP strands to eliminate the effect of plate initial imperfections.