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SMALL-DIAMETER CFRP SHEAR STRENGTHENING SYSTEM FOR STEEL BRIDGE GIRDERS

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ABSTRACT:

This paper summarizes the findings of a comprehensive research program, including experimental and analytical studies undertaken to examine the use of small-diameter Carbon Fiber Reinforced Polymer (CFRP) strands for shear strengthening of steel structures and bridges. The small-diameter CFRP strands are stitched together with a gap between the strands to allow each strand to be completely covered by the adhesive material. Most of the current research findings on the use of CFRP laminate revealed failure due to debonding. However, the small-diameter CFRP strands have showed high bonding characteristics. The experimental program first examined the proposed strengthening system to increase the buckling capacity of steel plates. The research then continued to examine the same strengthening system for increasing the shear capacity of steel plate by subjecting a steel plate to pure shear loading conditions. The research extended to testing a large-scale beam using the same strengthening system to verify the performance. The effectiveness of the strengthening system was investigated by varying various parameters believed to affect the behaviour including different CFRP orientation and reinforcement ratio. Research findings indicated that the proposed system is effective for shear strengthening of steel structures and the proposed material used eliminated the typical debonding failure mode, commonly observed for strengthening systems using CFRP laminates.

INTRODUCTION

The shear strength of steel bridge girders is controlled by the capacity of the web plate. Strengthening of web plates using FRP materials could help reduce the stress level in the web, and potentially increase the shear capacity controlled by elastic bucking or material yielding [1]. The performance of CFRP materials in tension is well documented. However, their behaviour in compression is relatively unknown. To evaluate the efficiency of CFRP materials for enhancing the shear capacity of steel girders, the effectiveness of the proposed material in increasing the compression resistance has to be assessed. The proposed small-diameter CFRP strands, provided in sheet configuration as shown in Figure 1, is a promising alternative strengthening system for steel structures. The CFRP strands are stitched together leaving a gap between the strands allowing each strand to be totally covered by the epoxy adhesive, resulting in an excellent bond mechanism [1].

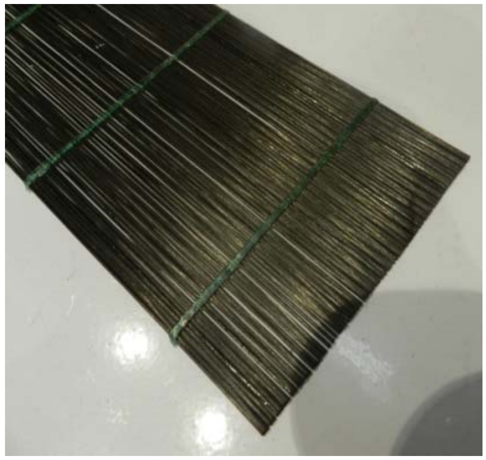


Figure 1: Proposed small-diameter CFRP strands

MATERIAL PROPERTIES

The tensile and compressive characteristics of the three types of CFRP strands including High-Modulus (HM), Intermediate-Modulus (IM), and Low-Modulus (LM) were determined. The measured properties of CFRP strands and the strength of witness panels are given in Table 1 and Table 2, respectively.

Table 1: Tensile properties of small-diameter CFRP strands

CFRP Strand	Rupture Strain mm/mm (in./in.)	Rupture Stress MPa (ksi)	Elastic Modulus MPa (ksi)
Low-Modulus(LM)	0.0168	2,353 (341)	140,253 (20,342)
Intermediate-Modulus (IM)	0.0104	2,220 (322)	212,752 (30,857)
High-Modulus (HM)	0.0032	806 (117)	255,430 (37,047)

Table 2: Compressive Properties of Small-Diameter CFRP witness panel

CFRP Witness Panel	Compressive Strength MPa (ksi)	Elastic Modulus MPa (ksi)
Low-Modulus (LM)	95.29 (13.82)	24,766 (3,592)
Intermediate-Modulus (IM)	121.44 (17.61)	40,987 (5,945)
High-Modulus (HM)	69.89 (10.14)	47,358 (6,869)

UNIAXIAL COMPRESSIVE STRENGTHENING

The experimental program undertaken to study the effectiveness of the proposed CFRP strands in increasing the buckling capacity consisted of two phases. The first phase included testing of 14 steel plates with different slenderness ratio (height-to-thickness) ranging from 48 to 154 under uniaxial compressive load. Eight steel plates were strengthened with HM CFRP strands. The remaining six specimens were un-strengthened and used as control specimens. The second phase identified the most effective type of CFRP strands among the three types of LM, IM and HM. Eighteen steel plates were tested using two selected slenderness ratios of 77 and 154. The effectiveness of using different reinforcement ratio of CFRP materials was also investigated by applying one and two layers of CFRP strands. The test setup, shown in Figure 2, was designed to be a self-reacting A-frame. The test plates were welded at both ends to high-strength steel tubes (sleeves). Two high-strength chrome-painted steel pins were greased and inserted inside the sleeves. The pins were loaded by two high-strength steel prestressing bars and two hydraulic jacks. Detailed explanation and discussions of the test setup, instrumentation and test results are described in the recently published documents [1-3]. Results of the experimental program showed that the bond characteristics between the steel and the small-diameter CFRP strands was excellent and there were no signs of debonding observed during testing up to buckling.

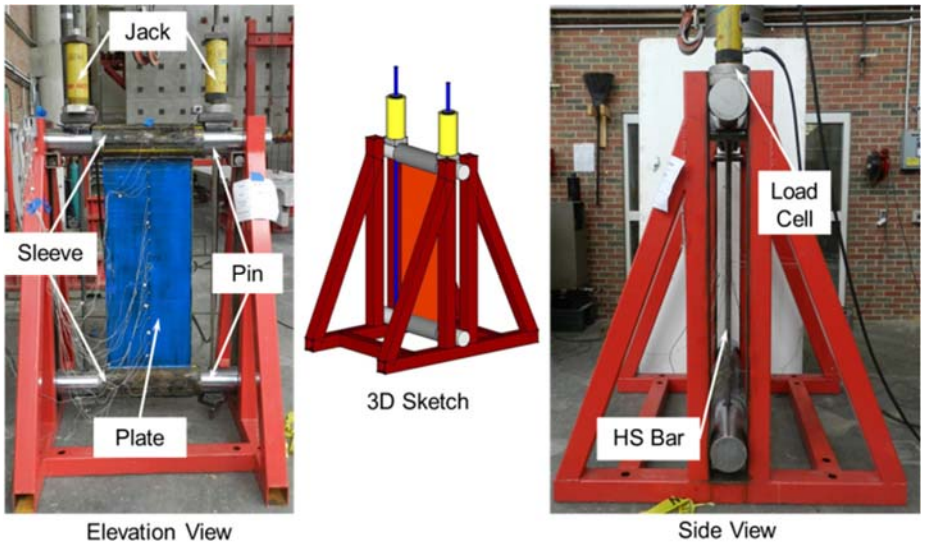


Figure 2: Test setup for uniaxial compression testing of plates

The research also included development of FE analysis calibrated by the experimental results and used to study other parameters including the effects of two end boundary conditions as pin-pin and fix-fix, six slenderness ratios ranging from 48 to 144 and three reinforcement ratios. Results of the FE analysis were used to develop design charts to predict the buckling load vs slenderness ratio of steel plate strengthened by small diameter CFRP strands [4].

SHEAR STRENGTHENING OF STEEL PLATE

The research was extended to examine the proposed small-diameter CFRP strands for shear strengthening of steel web girders. The considered parameters are the fiber orientation and number of layers of the CFRP strands. To simulate pure shear stress acting on a steel plate, the square plate specimen is rotated 45 degrees and clamped to a heavy steel frame, which is subjected to tensile load. The applied tensile load to the steel frame induces equivalent shear forces along the edges of the steel test plate. Two 2000 kN (440 kip) capacity hydraulic actuators were used to apply the tensile load to the steel frame. Two stiffened spreader beams were specially designed to transfer the tensile load to the shear frame. The bottom spreader beam is prestressed to the strong floor to provide reaction equal to the applied load. A schematic sketch and view of the test setup is shown in Figure 3. The steel plate is prestressed to the articulated built-up steel frames through series of high-strength bolts. The forces induced in the steel frame are transferred to the test plate through a friction-type connection provided by the bolts. The frame is made up of four very stiff steel plate legs, each consist of stiff short and long steel plates [4, 5].

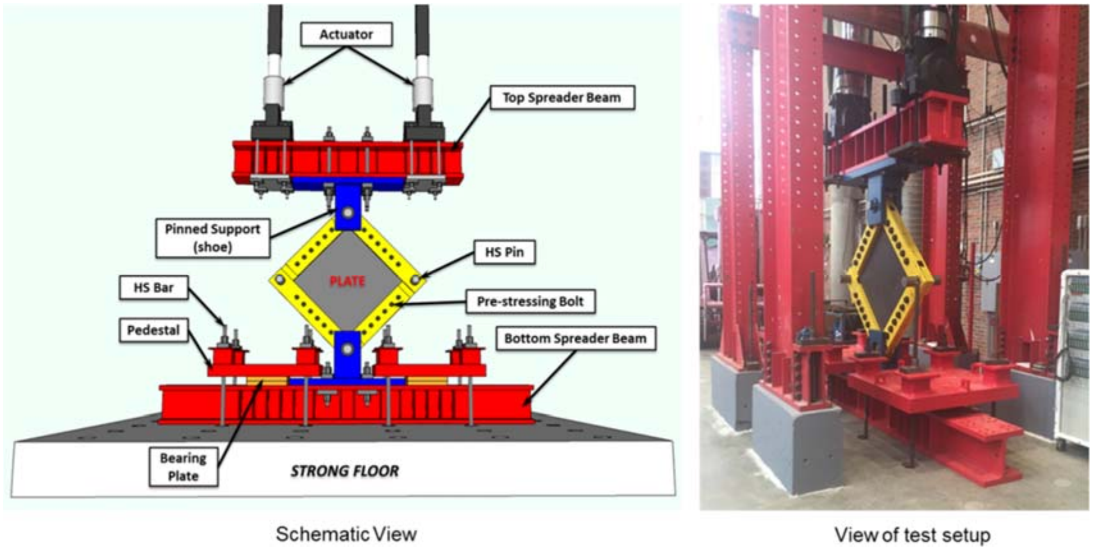
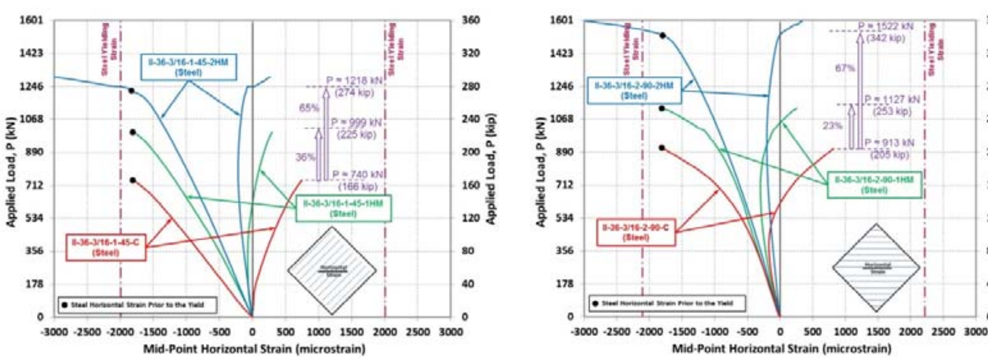


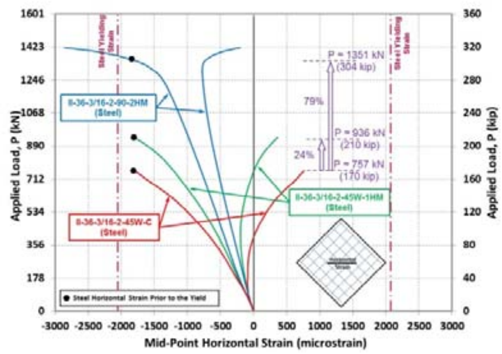
Figure 3: Pure shear test setup

The nine square steel plates included in this phase were used to study the effectiveness of the externally bonded CFRP strands externally bonded in three orthogonal directions at an angle of 45°, 90°, and ±45° relative to applied tensile load using one and two layers of the HM CFRP strands on each face of the plate. The control specimen was later used as a strengthened specimen with one layer and subsequently two layers of HM CFRP strands.

The total applied load versus measured horizontal strains at mid-point of the control and strengthened specimen with CFRP strands at an angle of 45°, 90°, and ±45° are shown in Figure 4(a), (b) and (c), respectively. The shear capacities of the strengthened plates were compared to the control plates prior to the steel yielding. The measured horizontal strains of the steel plate confirm the effectiveness of the CFRP in increasing the shear capacity of the plate. The trend indicates that increasing the reinforcement ratio of the CFRP strands contributes to higher shear capacity. Percentage increase in shear capacity reveals similar effect of the CFRP strengthening system for plates strengthened with different configurations.



(a) (b)



(c)

Figure 4: Applied load vs. horizontal steel strain with CFRP strands at an angle of:
a) 45°, b) 90°, c) ±45°

The increase in the shear capacity and lateral stiffness with an increase of reinforcement ratio for different CFRP strands orientations is shown in Figure 5. Results show that one layer and two layers of externally bonded HM CFRP strands can increase shear capacity of the strengthened plates up to 36 and 79 percent, respectively. The trend indicates that increasing the reinforcement ratio of the CFRP strands contributes to higher shear capacity. The load-deformation behaviour of the plates reveal that the strengthening system increased their lateral stiffness for each additional layer of CFRP strengthening. The increase in the lateral stiffness of strengthened plate with two layers of CFRP strand is highly dependent on the fiber orientation of additional layers.

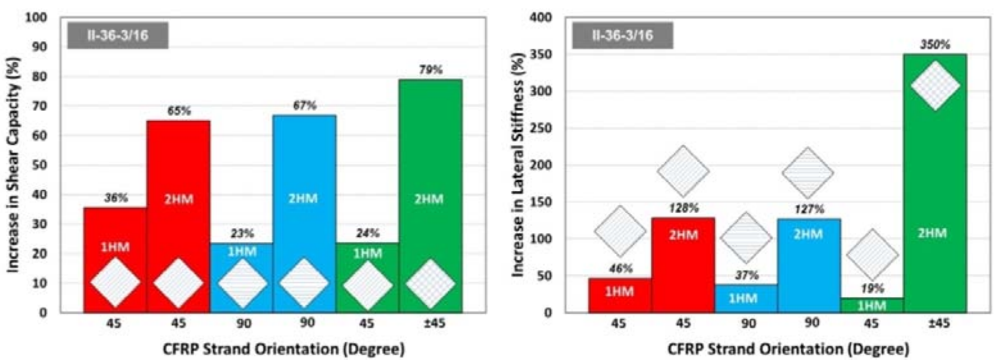


Figure 5: Shear capacity and lateral stiffness percentage increase of plates strengthened with one and two layers of HM CFRP strands

The analytical phase of the research program was based on a nonlinear FE analysis to model the behaviour of the steel plates strengthened with CFRP strands subjected to shear forces. The FE models were calibrated with the experimental results. The calibration process resulted in building confidence to use the developed FE models as a tool to study several parameters and for the development of the design guideline.

To examine the effects of the slenderness ratio, plate thicknesses were varied from 5 mm (3/16 in.) to 19 mm (3/4 in.) covering a wide range of plate slenderness ratio ranging from 48 to 192. The FE model considered the steel plates subjected to diagonal vertical tensile load and CFRP strands with an angle of 45° relative to the vertical tensile loads. Figure 6 shows the percentage increase in shear capacity vs slenderness ratio of steel plates strengthened by HM, IM, and LM CFRP strands. Results of two reinforcement ratios including one and two layers of the CFRP strands are compared. Results confirm that the CFRP strengthening system is more effective for the plates with higher slenderness ratio. Reinforcement ratio also has noticeable effects on increase of shear capacity. Percentage increase in shear capacity is almost in direct correlation with increase in reinforcement ratio. The most effective material is confirmed as HM CFRP followed by IM CFRP for the shear strengthening of steel plates regardless of slenderness ratio and reinforcement ratio. The shown percentage increase of the shear capacity is realistic to the typical values required in practice.

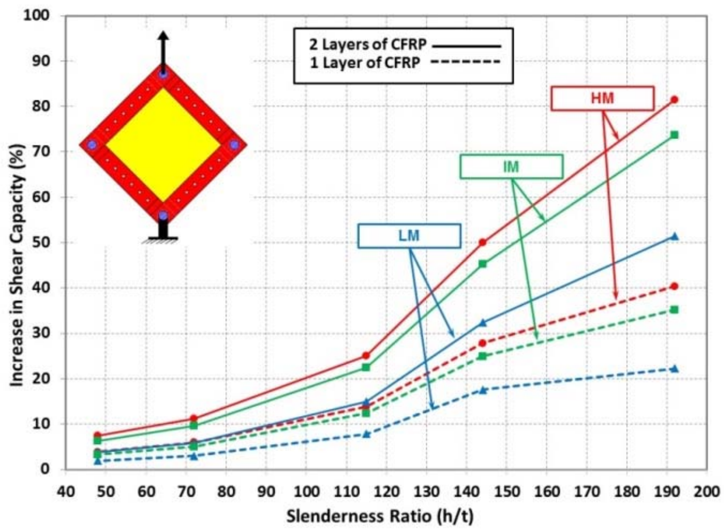


Figure 6: Percentage increase in shear capacity vs slenderness ratio of plates strengthened with one and two layers of HM, IM, and LM CFRP strands oriented 45° relative to the vertical tensile load

SHEAR STRENGTHENING OF STEEL BRIDGE GIRDERS

The research concluded by testing the proposed strengthening system in increasing the shear capacity of a steel bridge girder. The parameters considered were CFRP orientations and the number of CFRP strand layers. The 3.7 m (12 ft) span steel girder is a built-up section consisting of 380 x13 mm (15x1/2 in.) flange sections, and a 914 x 13 mm (36x3/16 in.) web section. The web of the steel bridge girder was stiffened and consisted of six 914 x 914 mm (36x36 in.) shear panel zones. The two panels at both ends of the beam were selected to be tested as controls and strengthened sections. The simply supported steel girder was laterally braced using A-framed supports at both ends. The applied load was induced by several 445 kN (100 kip) capacity loading jacks on a loading beam. The loading beam was placed on top of the steel bridge girder 0.9 m (3 ft) from one support and 2.1 m (9 ft) from another support. The steel girder test setup is shown in Figure 7.

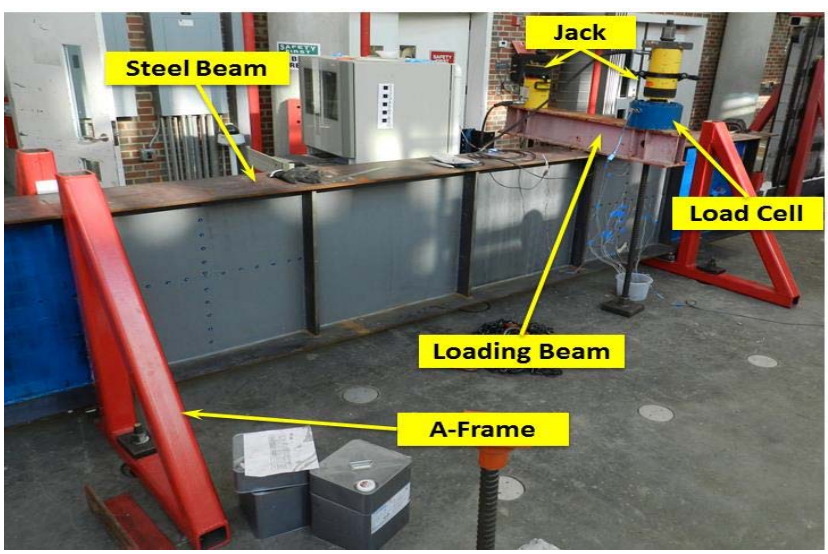


Figure 7: Steel girder test setup

A total of 12 tests were carried out in this research using the remaining four steel web panels as given in Table 3. Only high modulus CFRP strand was used. The studied factors affecting the strengthening results were fiber orientation and the number of CFRP layers. Each panel was tested three times. The first test was used as a control test, the second test when the panel was strengthened with one layer of CFRP strands, and the third test when the panel was strengthened with two layers of CFRP strands. The loading was stopped for each test when the maximum strain of the steel panel reached 1600 $\mu\varepsilon$ to reuse the same panel for the three tests.

Table 3 Shear Strengthening Test Matrix

Test Name	Set No.	No. of CFRP Layers	Fiber orientation	Shear Resistance Prior to yielding kN (kips)
Set I Control		0	-	460 (104)
Set I 1HM	I	1	0 (Horizontal)	568 (128)
Set I 2HM		2	90 (Vertical)	760 (171)
Set II Control		0	-	520 (117)
Set II 1HM	II	1	90 (Vertical)	663 (149)
Set II 2HM		2	90 (Vertical)	791 (178)
Set III Control		0	-	421 (95)
Set III 1HM	III	1	45 (Compressive)	615 (138)
Set III 2HM		2	45 (Compressive)	804 (180)
Set IV Control		0	-	454 (102)
Set IV 1HM	IV	1	45 (Compressive)	618 (139)
Set IV 2HM		2	± 45 (Tension)	752 (169)

Test results are compared to the control tests in Figure 8. Results show that one layer and two layer strengthening system increases the shear capacity up to 46% and 91%, respectively. The difference in shear capacity percentage increase was due to the different CFRP fiber orientation. Results confirm that regardless of the reinforcement ratio, applying strands in the direction of compressive stresses improve shear capacity more than other orientations. Installing strands parallel to the compressive stresses might reduce out of plane deformation and delay elastic/inelastic buckling.

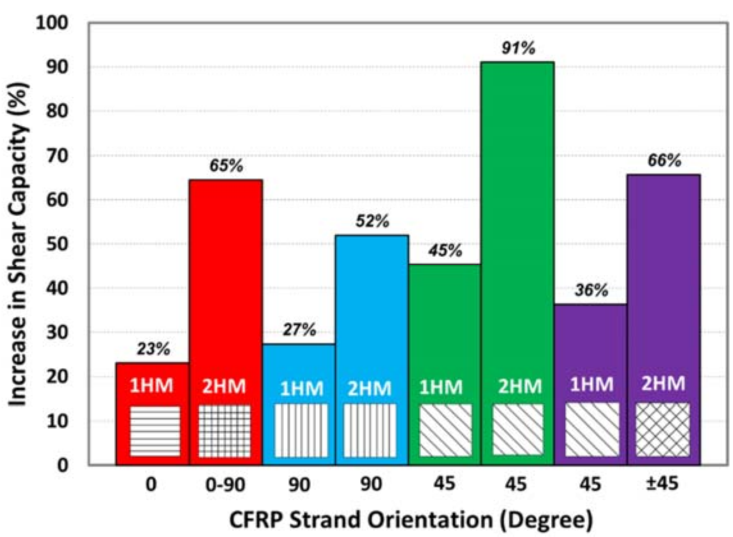


Figure 8: Shear capacity percentage increase of steel web panel strengthened with one and two layers of HM CFRP

CONCLUSIONS

The research findings of the experimental and analytical program may be summarized as follows:

- Use of small-diameter CFRP strands for uniaxial compressive and shear strengthening of steel plates is very effective in increasing the shear capacity.
- The proposed system did not debond.
- The effectiveness of the small-diameter CFRP strengthening system increased by increasing the slenderness ratio of the plates subjected to shear loads.
- High-Modulus (HM) small-diameter CFRP strands provide a more effective strengthening system in comparison to Intermediate-Modulus (IM) and Low-Modulus (LM) CFRP strands for shear strengthening of steel plates.
- Increasing the reinforcement ratio increases the shear strength.
- The optimum orientation is to install the strands in the direction of principal compression stress.

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