Rehabilitations and Retrofitting of Structural Steel Channel Sections Under Flexure

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***Abstract*: An experimental study to investigate the stiffness and strength enhancement in a structural steel channel section strengthened by six different carbon fiber–reinforced polymer (CFRP) wrapping configurations is described in this paper. An approach of transforming the singly symmetric open section such as a channel section to a closed section by CFRP wrapping as a means to increase the stiffness and strength is demonstrated. A total of 21 specimens, both CFRP reinforced and bare steel specimens, were tested in four-point bending. Two different CFRPs, unidirectional and bidirectional fabrics, were used in wrapping the specimen. While the unidirectional layers contribute to the stiffness and strength, the bidirectional layer primarily contributes to confining the former in addition to increasing the resistance to lateral torsional buckling (LTB) of the specimens. The results indicate that the CFRP-strengthened closed sections confined by bidirectional fabrics are effective in enhancing the strength and stiffness compared to CFRP skin–strengthened sections (perimeter of bare steel channel sections overlayed with CFRP). The effectiveness of the closed section can be further improved by increasing the unidirectional CFRP layers prior to the final wrapping by bidirectional fibers. The variation in stiffness for all the CFRP configurations from the initial loading of specimens up to the ultimate is also investigated. This paper demonstrates that the strength and stiffness of steel channel sections can be significantly enhanced by means of appropriate CFRP wrapping configuration.**

Author keywords: Experimental study; Carbon fiber–reinforced polymers (CFRPs); Structural steel channel section; Lateral torsional buckling (LTB); Flexure; Strengthening; Stiffness.

I. INTRODUCTION

Recently, existing steel structures have been demolished and re-placed by larger capacity steel structures due to increased require-ment in structural loading or as a result of thickness degradation due to corrosion. The failure of a structure due to increased loading or corrosion typically results in a localized individual member failure. This can be overcome by adopting local strengthening techniques with lower cost instead of replacing the entire structure, which is expensive and time consuming. In general, there are a couple of ways of strengthening a steel structure; one is by addition of more material (as in the case of welding a steel plate), which increases the self-weight, and the other by using a high-strength material, but in lesser quantity [as in the case of carbon fiber– reinforced polymer (CFRP) wrapping], which increases the strength and stiffness without increasing the self-weight of the structure. In addition, other techniques such as making noncomposite structures composite, adding internal supports to beams and thereby making them continuous rather than simply supported, replacing shear connections with moment connections, and adding bracing are also available but are not considered in the present in-vestigation. The focus of the study is restricted to strengthening using CFRP.

Sen and Liby (1994) and Mertz and Gillespie (1996) pioneered research on flexural strengthening of steel and steel-composite girders using CFRP. Their research showed the potential of CFRP in enhancing the flexural strength and stiffness. The use of CFRP is quite common in strengthening of concrete structures in part due to the availability of a design guideline ACI 440.2 R-08 (ACI 2008). Such design guidelines are not readily available for application in structural steel, although the state-of-the-art reviews (Bakht et al. 2000; Bakis et al. 2002; Zhao and Zhang 2007; Teng et al. 2012; Schnerch et al. 2007) on the research work carried out in more than a decade indicate that CFRP can be successfully used for strength and stiffness enhancement of steel structures. In addition, many projects in the United States, the United Kingdom, Japan, and Switzerland have shown that there is a great potential for CFRP to be used to retrofit steel structures (Zhao and Zhang 2007).

The use of CFRP for retrofitting steel tubular sections under flexural behavior has been studied extensively by various research-ers in the last decade (Zhao and Zhang 2007). Prominent among them are Haedir et al. (2006), Hollaway and Teng (2008), Haedir et al. (2009, 2010, 2011), Haedir and Zhao (2012), and Gao et al. (2013). While the externally bonded CFRP over structural steel in general increases the strength and stiffness of the composite struc-ture due to high strength and stiffness offered by the CFRP layer, the effectiveness of the same for lateral rigidity is minimal because the cross section is already a closed configuration. This is not the case for open structural steel sections, especially for channels and angles where the application of externally bonded CFRP over an internal formwork significantly increases the lateral or rotational rigidity of the specimen in addition to the strength and stiffness enhancement in the in-plane (loading) direction (Madhavan et al. 2015). The following papers are focused on the use of CFRP in an open steel section.

Ekiz and El-Tawil (2008) proposed a strengthening system for enhancing the buckling behavior of the steel members in which the open steel section was converted to the closed cross section by sandwich mortar and PVC core block with CFRP wraps. The ex-perimental research demonstrates that the adequate numbers of CFRP layer and sufficient core materials can improve the behavior of the steel members. The similar practice was investigated through large-scale tests for double-angle braces under cyclic axial loading by El-Tawil and Ekiz (2009). The test results prove that the double-angle braces could be made to reach their full strength in compression by converting the open cross section into the closed one. Feng et al. (2013a) carried out an experimental study of a total of 18 specimens for increasing the buckling resistance of an axially loaded cruciform, I-shaped section, round hollow section, and square hollow section. All the open cross sections were transformed into a closed cross sec-tion by packing the bundled bamboo sticks. The FRP fabrics were wrapped over the bamboo sticks. The axial load capacity and duc-tility increased by 25–114% and 6.4 times, respectively, with respect to the control specimen. Feng et al. (2013b) replaced the bamboo sticks with mortar for transforming the open section into the closed one. The FRP tubes were used as a strengthening material. The re-sults indicate that the axial load capacity increased by 44–215% and ductility increased by 877% with respect to control specimen.

Deng et al. (2015) experimentally explored the enhancement of open steel section stability using lightweight glass fiber–reinforced polymer (GFRP) buckling restrained braces (BRBs). Parameters like GFRP layer thickness and wrapping configurations were studied. Two major methods of reinforcements were studied: wrapping a GFRP layer over the pultruded tube profiles, and filling the pultruded tube profiles with mortar. While the GFRP layer with pul-truded tube profiles increases the overall stability, the failure occurs due to local buckling of the steel brace. This was overcome when the pultruded tube profiles were filled with mortar, providing adequate stiffness against local buckling. This research shows that the open cruciform section stability was significantly enhanced by transforming the open section to a closed one by GFRP strengthening. Ritchie et al. (2015) experimentally studied the effect of CFRP reinforcement for axially loaded S sections. A total of 12 specimens were tested, which includes three control specimens and nine CFRP-reinforced specimens. The results indicate that both initial axial stiff-ness and axial load capacity of the member was increased due to CFRP strengthening.

The present research addresses the preceding concerns (bidirectional CFRP and skin strengthening of inner surfaces) for the structural enhancement of channel sections that are extensively used as flexural members in transmission towers, electrical transformer support structures, and in overhead storage structures, which are an important need in the construction industry. Fig. 1 shows the deteriorated channel member in an electrical transformer support structure that is in need of retrofitting. The objective of the current research is to fulfill the need for carrying out experimental testing of channel sections retrofitted by various CFRP configurations and to identify the optimal configuration that leads to improvement in structural behavior.

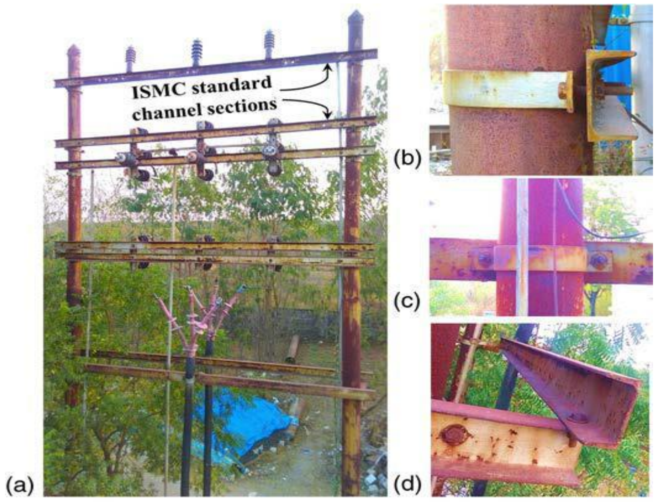

Fig. 1. View of the deteriorated electrical substructure (a) elevation view of the full structure;
(b) U-clamp connection (bolted): sectional view; (c) U-clamp connec-tion (bolted): back view; (d) flange-to-flange bolted connection

EXPERIMENTAL PROGRAM SPECIMEN PREPARATION

A total of 21 structural steel C-channel specimens were tested in this study, which includes three control specimens and six CFRP strengthening configuration specimen sets with three specimens under each set. The specimens were 1.4-m-long Indian standard ISMC 75 (ISMC 1989) steel sections. Fig.

2(a) shows the cross section of a typical ISMC 75 specimen, the dimensions of which are given in Table 1. The surfaces of the steel specimens were cleaned using a steel wire brush to create roughness, for bond-critical application between steel and CFRP. The idea of using a wire brush to clean the surface of the steel structure prior to appli-cation of CFRP layers was to ensure that specimen preparation can be made in situ. In addition, the use of sophisticated equipment (for example, grit blasting) may not be feasible in elevated struc-tures due to access restrictions. To create an internal formwork over which the CFRP can be wrapped (Configurations C_1U, C_1B, C_1U1B, and C_2U1B), cardboard was placed inside the channel section. In addition to being relatively light in weight (density ap-proximately 600 kg=m^3), the cardboard sheet provided accurate geometry to give it a rectangular shape. The cardboards were packed parallel to the web of the steel channel section as shown in Fig. 2(b) to avoid the splitting failure of the packed cardboard sheets and to ensure proper bonding be-tween the cardboard sheet and CFRP wrap.

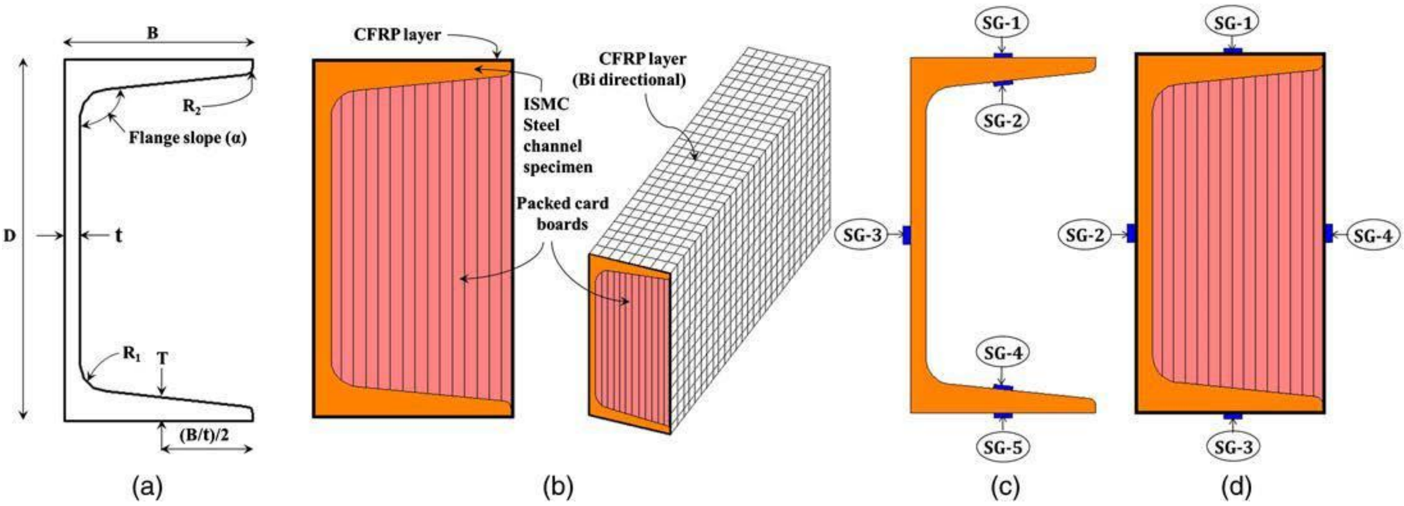

Fig. 2. Test specimen: (a) cross-sectional dimensions of ISMC 75 specimen; (b) view of the ISMC specimen packed with cardboard and CFRP wrapping; (c) location of strain gauges at midspan for wrapping configurations B, S_1U, and S_1B; (d) location of strain gauges at midspan for wrapping configurations C_1U, C_1B, C_1U_1B, and C_2U_1B

Table 1. Cross-Sectional Dimensions of ISMC 75

Description	Dimension
Depth, D (mm)	75.40
Breadth, B (mm)	40.50
Thickness of web, t (mm)	3.90
Thickness of flange, T (mm)	7.42
Flange slope degree, α	96
Radius 1, R_1 (mm)	8.5
Radius 2, R_2 (mm)	2.4

Table 2. Properties of Carbon Fibers Supplied by Manufacturer

Description	Unidirectional	Bidirectional
Fiber type	TC-35	TC-33
Tensile strength (MPa)	4,000	3,450
Tensile modulus (GPa)	240	230
Thickness per layer (mm)	0.25	0.2
Elongation (%)	1.8	1.5
Filament diameter (μm)	7	7

An adhesive was also applied to the inner side of the steel channel sections before packing the cardboards to ensure adequate bonding. The resin [EPOFINE-556 (Fine Finish Organics, Navi Mumbai, India), epoxy content is equivalent to 5.30–5.45 per kg and the density 25°C is 1.15–1.20 g=cm^3] and hardener [FINE-HARD-951 (Fine Finish Organics, Navi Mumbai, India)] were mixed in proportion of 10:1 for CFRP wrapping application. The CFRP fiber layers were cut for a required length and width before the application of epoxy to the specimen. Table 2 represents the mechanical properties of carbon fibers supplied by manufacturer. For the skin wrapping configurations (S_1U and S_1B), the epoxy coating was applied throughout the surface of the specimen by brushes and smeared by steel rollers for uniform thickness. For the inner area of the channel, the smaller diameter steel roller was used. For packed cardboard specimens, the manner of application of epoxy was the same as skin wrapping specimens, but in places where steel surface and cardboard surfaces come in contact, the epoxy was applied by small thickness brushes to ensure the bond integrity. Figs. 3(a–c) show the application of epoxy to the specimens followed by wrapping of first layer of CFRP. Fig. 3(d) shows the wrapping methodology of the second layer and third layer. The CFRP wrap configurations are graphically represented in Fig. 4.

TEST SETUP

Fig. 5 shows the experimental test setup of a four-point bending test with simply supported end conditions. A computer-controlled MTS Landmark (MTS Systems, Eden Prairie, Minnesota) Servo hydraulic Testing Actuator Series 244 with a capacity of 250 kN was used for the four-point bending test. All 21 specimens were tested in displacement control mode at a rate of 0.01 mm=s. The specimens were loaded by two loading points with an intermediate distance of 400 mm. The span between the two supports was kept at 1,200 mm with an overhang of 100 mm on both sides for proper seating of specimens over the support and to ensure that the specimen would not slip during the test. Neither the loading point nor the supports were designed to provide lateral restraints, thereby preventing any stresses that might arise due to warping of the cross section. This was done to ensure that the boundary conditions of the experiments carried out were similar to the actual boundary conditions in the field as shown in Figs. 1(b–d). From Figs. 1(b–d) it can be observed that the web of the channel sections were bolted to the pipe (tubular) member in the structure by means of a U-clamp, which will have the least amount of restraint for lateral torsional buckling (LTB) because the flange was not restrained, thereby allowing uninhibited warping to take place. The vertical and lateral displacement was measured at midspan by a LVDT. The readings from the strain gauge placed longitudinally (along the length of the specimen) were extracted at the midspan of the specimen at the locations shown in Figs. 2(c and d). HBM (Darmstadt, Germany) strain gauges (K-216.00-2128 linear strain gauge, 6-mm grid length) with 350-Ω resistance were used in this work. The load, displacement, and strain readings were recorded by a data acquisition system.

RESULTS AND DISCUSSION

As discussed previously, a total of 21 structural steel channel sections with six sets of different CFRP configurations and one set of control (bare steel) specimens were tested. Table 3 shows the ultimate load attained by each tested specimen, mean strength of the corresponding set of configurations, and percentage increase in strength due to CFRP strengthening with respect to control specimens. The increase in ultimate load ranged from −4 to 25%, depending on the type of CFRP wrapping configuration.

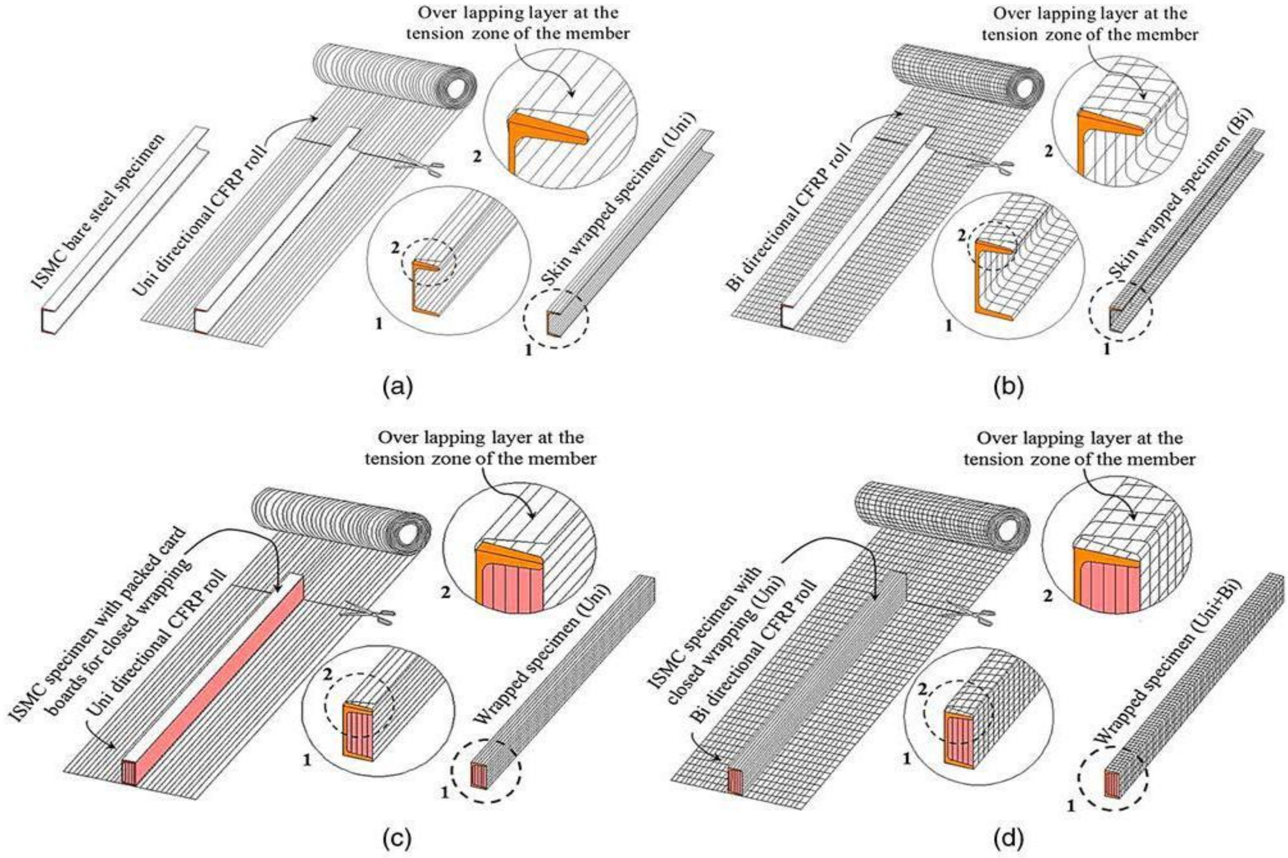

Fig.3 CFRP wrapping procedure: (a) skin wrapping unidirectional CFRP layer (S_1U); (b) skin wrapping bidirectional CFRP layer (S_1B); (c) closed wrapping I layer (C_1U and C_1B); (d) closed wrapping II and III layers C_1U_1B and C_2U_1B

The con-version of an open section to a closed section using unidirectional CFRP layers followed by bidirectional layers enhances the torsional rigidity, thereby increasing the resistance to LTB as shown in Table 3 for closed sections after CFRP wrapping. Such a behavior was not observed in skin reinforced open section whose failure characteristics were similar to the bare
steel (control) specimen due to low torsional resistance offered by such sections resulting in the LTB mode of failure.

LOAD VERSUS VERTICAL DISPLACEMENT

Fig. 6(a) shows the load versus vertical displacement plot for the control specimen and six different CFRP-strengthened specimens. The vertical displacement values for all specimens were taken at the midspan of the specimen (Fig. 5). The CRFP wrapping for closed-section configuration C_2U_1B (closed configuration with two unidirectional layers followed by one layer of bidirectional CFRP wrapping) resulted in the maximum ultimate load (25% higher than the control specimen). The next highest ultimate load was achieved by C_1U_1B (closed configuration with one unidirectional layer, followed by one layer of bidirectional CFRP wrapping), followed by C_1B (closed configuration with one layer of bidirectional CFRP wrapping) and C_1U (closed configuration with one layer of unidirectional CFRP wrapping). In skin reinforced specimens, Configuration S_1B (skin strengthened configuration with one layer of bidirectional CFRP wrapping) resulted in a higher ultimate capacity, followed by Configuration S_1U (skin strengthened con-figuration with one layer of unidirectional CFRP wrapping) and B (control, bare steel) specimens. The

results indicate that in addition to the reinforcement of channel sections by CFRP, the orientation of fibers in CFRP plays an important role in achieving higher stiff-ness and strength.

Fig. 6(a) also shows that while the initial stiffness is steep for all specimens, Specimens B-2, S_1U-1, S_1B-3, and C_1U-3 experience a sudden decrease in stiffness after they reach approximately 80% of their ultimate load as indicated by open circles in the plot. This is because the bare steel specimen (B-2) and skin strengthened (S_1U-1 and S_1B-3) and closed-section specimens with unidirectional fibers only (C_1U-3) will not experience a sustained increase in stiffness as the applied load approaches the ultimate capacity of the specimen. This may be attributed to the fact that during testing, when the specimen starts experiencing sagging deflection, the open-section configuration (B-2, S_1U-1, and S_1B-3) with low torsional resistance undergoes LTB, thereby resulting in a loss in flexural stiffness. In a similar fashion, Specimen C_1U-3 also undergoes LTB because the unidirectional layers are unable to maintain a closed-section cross-section configuration due to lack of confinement from bidirectional fibers. Such a phenomenon was not observed in C_1B-3, C_1U_1B-3, and C_2U_1B-1 where the stiffness in Fig. 6(a) remains same until the specimens reach 95, 91, and 97% of the load, respectively. However, all three specimens for each CFRP configuration did not result in an increase in stiff-ness and strength compared with control specimens. For example, Specimens S_1B-2 (open-section configuration) and C_1U-2 (closed section with only unidirectional fibers) experienced delami-nation of the specimen at early stages of loading, resulting in loss in composite action, and behavior similar to the bare steel specimen was observed. This resulted in lower ultimate load than the mini-mum ultimate load of the control specimens by 2.7 and 4.2%, re-spectively, for Specimens S_1B-2 and C_1U-2. This small deviation may be attributed to geometric imperfection of the rolled channel specimen.

In general, for such specimens wrapped with a final layer of bidirectional CFRP layer over unidirectional layers, the hoop directional fibers in the bidirectional layer provide the confinement effect to the unidirectional (longitudinal) fibers, thus delaying de-bonding during deflection. This leads to an increase in stiffness and change in failure mode from LTB to flexural failure due to a significant increase in torsional resistance, which can be attributed to the conversion of a singly symmetric open steel section to a double-symmetric closed shell over open steel section by CFRP wrapping.

The variation of stiffness along the entire loading path is described in the “Stiffness comparision” section.

Load versus Lateral Displacements

Fig 6 (b)shows Load versus Lateral Displacement response of control and six differents CFRP – Strengthened specimens are taken from the neutral axis of the web and at the midpoint of the span. The load to the lateral displacement response of each CFRP configuration is further explained subsequently.

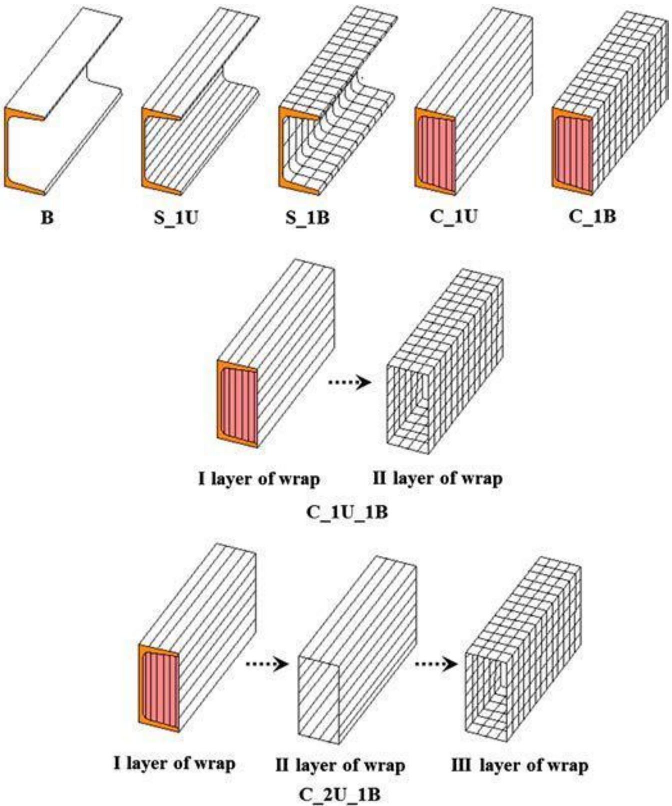

Fig. 4. CFRP wrapping configurations

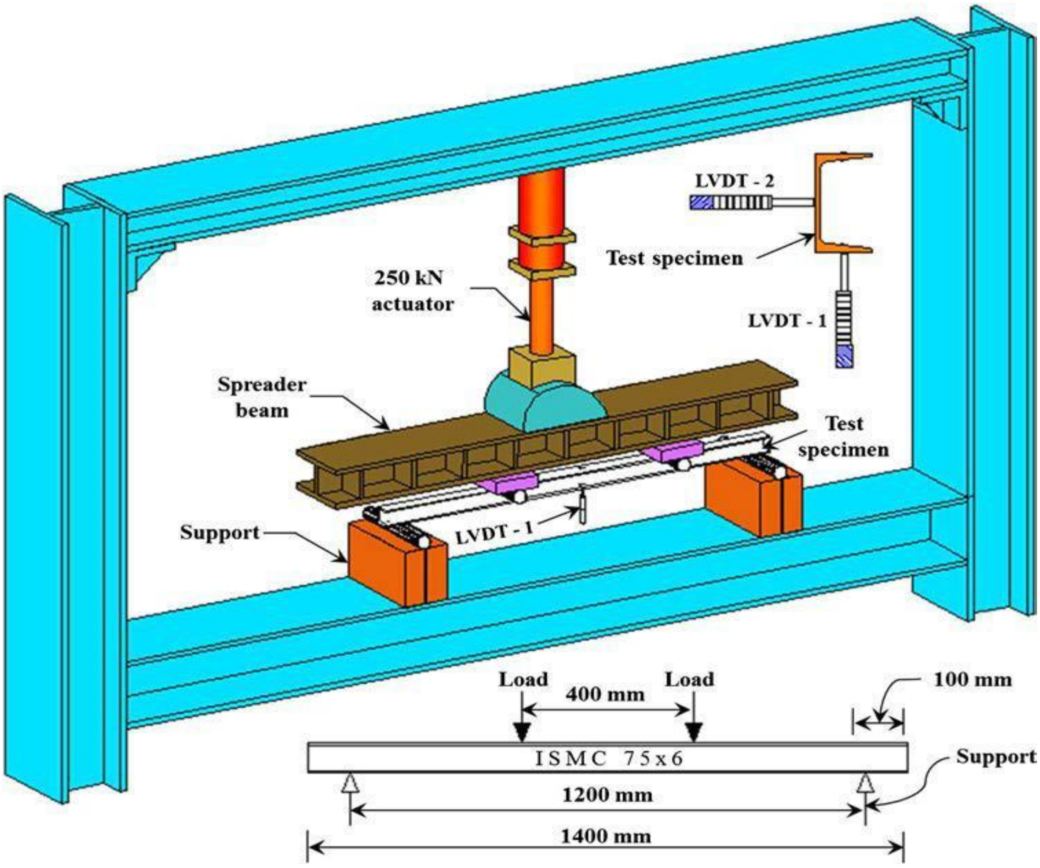

Fig. 5. Experimental setup for four-point bending test

Table 3. Labeling of Test Specimens and Experimental Test Results

Specimen nomenclature	CFRP wrapping configuration	Failure load (kN)	Mean strength (kN)	Percentage increase compared with the bare specimen	Coefficient of variation for the group	Failure mode, load in percentage[a]	Flexural stiffness (kN=mm)
B-1[b]	Bare ISMC 75 steel specimen	40.41	38.23	—	—	—	—
B-2		37.63		—	0.051	LTB, 80	1.77
B-3		36.65		—	—	—	—
S_1U-1[b]	Unidirectional wrapping, skin	41.27	40.58	—	—	—	—
S_1U-2		41.25		6.14	0.039	LTB, 80	2.01
S_1U-3		39.22		—	—	—	—
S_1B-1[b]	Bidirectional wrapping, skin	38.86	37.78	—	—	—	—
S_1B-2		35.65		−1.15	0.057	LTB, 80	1.70
S_1B-3		38.85		—	—	—	—
C_1U-1[b]	Unidirectional wrapping, closed	37.85	36.73	—	—	—	—
C_1U-2		35.10		−3.91	0.029	LTB, 80	1.50
C_1U-3		37.25		—	—	—	—
C_1B-1[b]	Bidirectional wrapping, closed	40.06	39.05	—	—	—	—
C_1B-2		36.48		2.15	0.027	LTB, 95	2.41
C_1B-3		40.62		—	—	—	—
C_1U_1B-1[b]	Unidirectional + bidirectional wrapping, closed	42.97	41.55	—	—	—	—
C_1U_1B-2		40.97		8.71	0.048	LTB, 91	2.63
C_1U_1B-3		40.74		—	—	—	—
C_2U_1B-1[b]	Unidirectional + unidirectional + bidirectional wrapping, closed	46.32	47.81	—	—	—	—
C_2U_1B-2		48.87		25.05	0.029	LTB, 97	2.87
C_2U_1B-3		48.24		—	—	—	—

Note: CFRP wrap configurations are graphically represented in Fig. 4.
[a]Numerical value in percentage indicates the attainment of LTB mode of failure.
[b]Specimens instrumented with strain gauge.

Specimen Configurations C_2U_1B, C_1U_1B, and C_1B

The load versus lateral displacement plot for C_2U_1B was steep until 43 kN (93% of ultimate load), which has the maximum ulti-mate load (47.81 kN) compared with other configurations tested. After reaching 43 kN, the lateral displacement increases at a faster rate, leading to sudden loss in lateral stiffness. Similarly, the load versus lateral displacement plot for C_1U_1B was steep until 40.5 kN (92.5% of ultimate load), after which the lateral displacement increased rapidly. The sudden increase in lateral displacement corresponds to the change in failure mode from flexural to lateral rapidly. The sudden increase in lateral displacement corresponds to the change in failure mode from flexural to lateral

torsional. Likewise, the load versus lateral displacement plot for C_1B was steep until 97% of ultimate load (39.53 kN); thereafter the lateral displacement suddenly shifted to the opposite direction and increased at a higher rate. These results indicate that the closed-section specimen configurations C_2U_1B, C_1U_1B, and C_1B

with bidirectional layers are able to sustain higher loads compared with skin strengthened open sections and provide adequate lateral stiffness to the specimen as can be observed by the steep slope until the load reaches very close to the ultimate load.

Specimen Configurations C_1U, S_1B, S_1U, and B

The load versus lateral displacement plot for wrapping configura-tions C_1U, S_1B, S_1U, and B indicate that all four configurations exhibit similar behavior in lateral displacement. Configurations

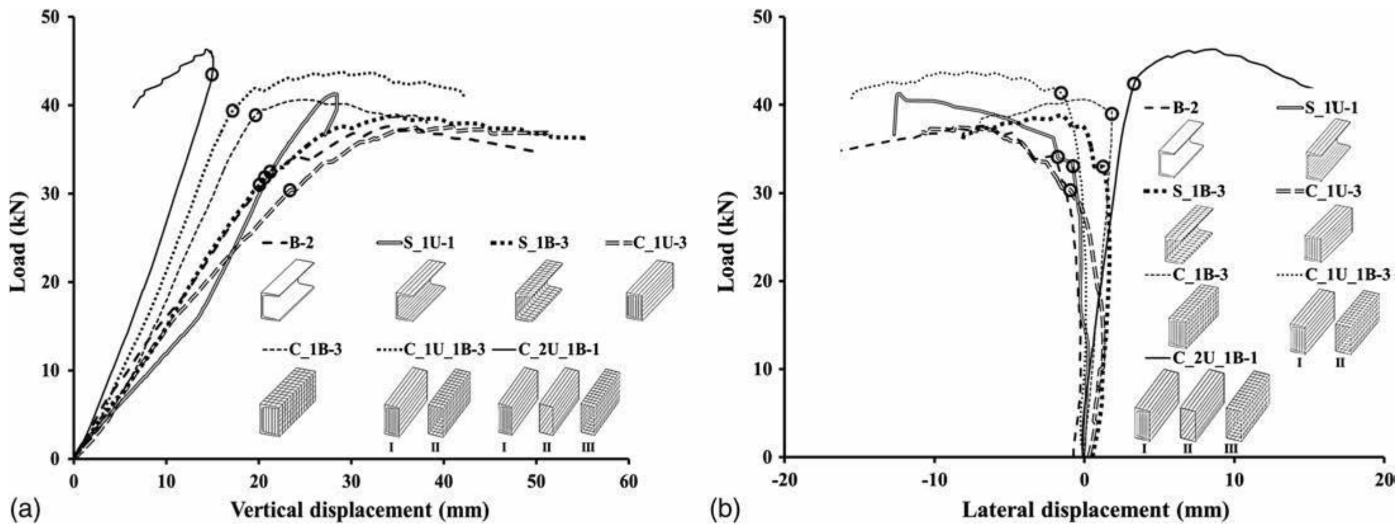

Fig. 6. (a) Load versus vertical displacement plot for all configurations; (b) load versus lateral displacement plot for all configurations

C_1U, S_1B, S_1U, and B show a steep increase in lateral stiffness until they reach 80, 84, 77.5, and 84% of their corresponding ultimate load, respectively. However, the increase in the ultimate capacity with respect to control specimen is in the range of 0–6%.

Unlike all other specimen configurations, which twisted toward the observer (top flange was moving inward and bottom flange was moving outward), C_2U_1B resulted in the twisting of the specimen away from the observer at midspan. This may be due to the shift in the center of gravity due to higher thickness of CFRP layers (two layers of unidirectional CFRP followed by one layer of bidirectional CFRP) causing a change in twisting pattern.

EFFECT OF PACKED CARDBOARDS AND CFRP WRAPPING

Fig. 11 shows the deformation behavior of bare steel (control), CFRP skin strengthened, and closed-section specimens with packed cardboards wrapped with CFRP under a four-point bending test. The pictures were taken after the specimens attained the ulti-mate load. The control (bare steel) specimens failed under lateral torsional mode [Fig. 11(a)] due to unsymmetrical open section at the ends of the specimen and by local bucking under the load-ing point.

While the CFRP skin strengthened specimens (S_1U and S_1B) also failed in lateral torsional mode as shown in Figs. 11(b and c) (due to unsymmetrical open section), specimens with packed cardboards wrapped with unidirectional CFRP followed by con-finement provided by bidirectional CFRP failed in flexure mode alone as shown in Figs. 11(f and g). In addition to the change in failure mode of specimen configurations C_2U_1B and C_1U_1B, the torsional and flexural resistance also increased due to the change in section from open to closed, thereby increasing the torsional constant and moment of inertia, and consequently the torsional and flexural rigidity of the configuration.

For specimens with packed cardboards and single CFRP wrap-ping (C_1U and C_1B) the failure mode was flexural accompanied by a slight twist [Figs. 11(d and e)]. The results indicate that the CFRP single wrapping added little value to the closed cross-section configuration. The failure mode of the C_1U configuration was due to debonding of the CFRP layer (Fig. 10), which occurred from the initial stages of loading [Fig. 8(a)] due to unidirectional fibers that could not offer adequate confinement of cardboard sheets during twisting of specimens that occurred while testing due to lack of fiber in other directions. Such a behavior was not observed in bidi-rectional fibers because the fibers are oriented in longitudinal and hoop direction in equal measure [Fig. 8(b)].

STIFFNESS COMPARISON

Many researchers have studied the stiffness enhancement in steel structures due to the CFRP strengthening (Wu et al. 2012; Dusicka and Tinker 2013; Madhavan et al. 2015; Ritchie et al. 2015). How-ever, a detailed stiffness variation along the entire loading path is required to study the stiffness improvement due to different wrap-ping configurations in addition to the degradation in stiffness with increase in load due to failure of adhesive at the interface between the steel and CFRP.

Fig. 12 shows the stiffness of the member along the loading path for bare steel specimen, CFRP skin strengthened specimen, and closed (packed cardboard) CFRP strengthened specimen. The stiff-ness values were calculated up to the ultimate load point and post-peak stiffness degradation is neglected. Specimens B-2, S_1U-1, S_1B-3, and C_1U-3 have no significant variation in stiffness and experience similar load versus vertical displacement response up to 60% of their ultimate load. As the load increases beyond 60%, these specimens experience a significant decrease in stiffness due to lateral torsional mode of failure. This can be attributed to less tor-sional resistance offered by the open sections (B-2, S_1U-1, and S_1B-3) and weak confining exhibited by unidirectional layer for Specimen C_1U-3.

Specimens C_1B-3, C_1U_1B-3, and C_2U_1B-1 show a significant increase in stiffness when compared with control spec-imens. While the stiffness of Specimens C_1B-3 and C_1U_1B-3 decrease after reaching 85–90% of their ultimate load, Specimen C_2U_1B-1 shows an impressive stiffness improvement up to 95% of the ultimate load compared with the control specimen.

To better understand the stiffness enhancement of various wrap-ping configurations with respect to control specimens, the mean value of stiffness is plotted with respect to the normalized load as shown in Fig. 13. It can be observed that the control specimens and skin strengthened configurations S_1B and C_1U exhibit sim-ilar behavior with no significant change in stiffness. The maximum stiffness of these specimen configurations is in the range of 1.71–2.14 kN=mm. A slight improvement in stiffness enhancement (23%) can be observed in S1_U compared with B, S_1B, and C_1U because the orientation of the all the fibers in one direction leads to an increase in the resistance offered by the specimen. Further im-provement in stiffness can be observed for Configuration C_1B with a 49% (3.18 kN=mm) increase, followed by Configurations C_1U_1B with a 67% (3.57 kN=mm) increase and C_2U_1B with

a 69% (3.60 kN=mm) increase compared with control specimens. This is because the wrapping of a final bidirectional layer over uni-directional layer(s) ensures that no microbuckling or kinking of unidirectional fibers take place because the unbraced length of those layers is zero due to complete confinement. In general the stiffness enhancement in the closed sections is much higher than open sections due to high torsional resistance, except C_1U, which does not adequately confine the cardboard sheets, thereby losing its closed section profile at the initial stages of loading, leading to loss in torsional rigidity.

Fig. 11. Deformed view of specimens tested under four-point bending (front and cross-sectional view): (a) Specimen B-1; (b) Specimen S_1U-3; (c) Specimen S_1B-3; (d) Specimen C_1U-2; (e) Specimen C_1B-2; (f) Specimen C_1U_1B-3; (g)SpecimenC_2U_1B-2

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CONCLUSION

The flexural behavior of 21 channel specimens, strengthened by six different CFRP wrapping configurations, were studied under a four-point bending test. The findings from this experimental study have shown that the structural steel channel specimens can be effectively strengthened for flexural loadings using adhesively bonded CFRP layers. This improvement in strength is primarily due to the change in cross-section type by converting an open sec-tion such as a channel section to a closed section by means of an internal formwork using packed cardboard for wrapping of unidi-rectional CFRP layers, followed by wrapping of bidirectional CFRP layers to confine the former. The ability of the unidirectional CFRP layer to increase the strength and stiffness of the member can be enhanced by confining the same by means of bidirectional CFRP wrap resulting in no microbuckling or kinking of unidirec-tional fibers due to zero unbraced length. In addition, the bidirec-tional layer also increases the torsional stiffness of the doubly symmetric shell due to CFRP wrapping contributing to the resis-tance against LTB. The role of unidirectional fibers is akin to a main reinforcement (longitudinal) in a reinforced concrete struc-ture. The bidirectional fibers provided over the unidirectional fibers play the role of stirrups, thereby confining the unidirectional fibers to ensure that they stay in place, resisting the axial stress that arises as a result of bending, thus enhancing the load-carrying capacity. In addition, the following conclusions can be drawn:

- The skin strengthened wrapping configurations S_1U and S_1B behave similarly to the control specimen B, indicating that the skin reinforcement has no significant effect in improving the strength and stiffness of open channel sections.

- Configuration C_1U failed due to delamination at the initial stages of loading due to inadequate resistance offered by one layer of unidirectional fiber to adequately confine the cardboard and to maintain the shape of the closed section. Among the six various CFRP wrapping configurations, C_2U_1B (doubly symmetric closed-shell CFRP wrapping with two unidirectional layers followed by one bidirectional layer) have the maximum strength and stiffness gain of 25 and 69%, respectively, compared with the control specimen.

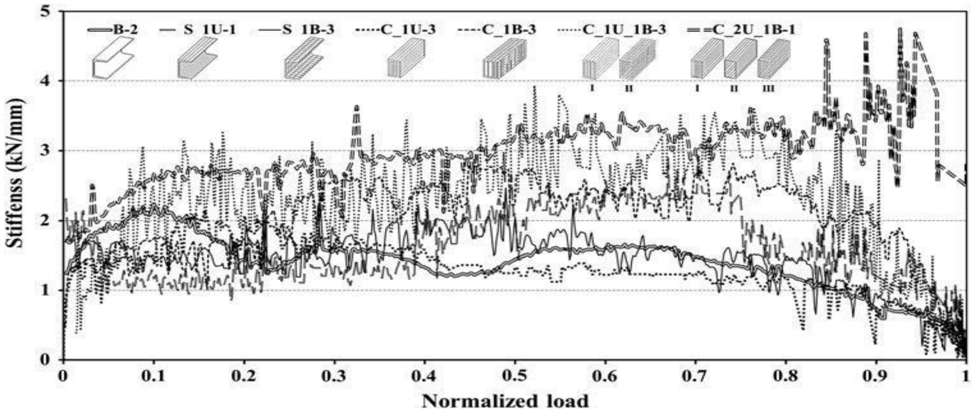

Fig. 12. Stiffness variation along the loading path versus normalized load

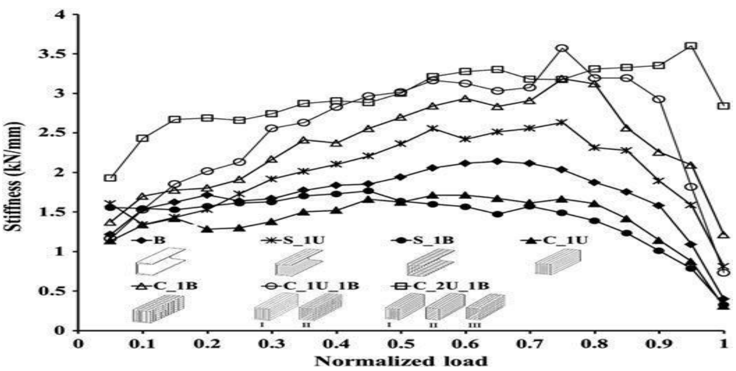

Fig. 13. Mean stiffness variation versus normalized load

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