Research Article
Experimental Study on CFRP Strengthened Cold Formed Channel Columns

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Abstract: Cold-formed steel members usually display local-global buckling interaction which strongly effects the structural strength of columns. Through strengthening web of the members this buckling can be controlled to some extent. In this investigation, Carbon Fibre Reinforced Polymers (CFRP) is used for strengthening cold formed steel channel member. This paper presents compression tests of cold-formed plain and CFRP strengthened steel channel section columns. This paper also proposes a design method based on Direct Strength Method provisions specified in American Iron and Steel Institute (AISI), for determining the axial compression strength. Results obtained from the proposed design method are compared with experimental test data and are found to be in good agreement.

Keywords: Axial compression, CFRP, CFRP strengthened, cold formed steel, design methods

INTRODUCTION

In the last decade, Carbon Fibre-Reinforced Polymer (CFRP) composite materials have been increasingly employed in the construction industry, mainly in applications dealing with structural strengthening and repair. The rehabilitation of steel structures is usually in the form of strengthening of structural members or retrofitting the seismic deficiencies. Carbon fibre reinforced plastics have proven to be an excellent option as an external reinforcement because of their high tensile strength, resistance to corrosion, high durability, and ease of installation. The applicability and cost-efficiency of the CFRP strengthening concept depends largely on the material behavior of the member to be strengthened. Until now, the research activity in this area has been mainly focused on bond characteristics, local-plate and/or distortional buckling behaviors', design method, fatigue behaviour of tensile steel/CFRP joints.

Bond between steel and CFRP: Specific design of the adhesive bond is dependent upon many variables such as surface preparation, specific epoxy, strip thickness, and environmental conditions that make general recommendations for adhesive bond design very difficult. Xiao-Ling and Lei (2007) presented an interesting state of the art on cold-formed steel structures. In real life, structures like bridges. Buildings are subjected to dynamic loads. Therefore, it is necessary to understand the bond behaviour between steel and the strengthening materials for both static and dynamic loads, Haider *et al.* (2012) investigated bond characteristics between CFRP fabrics and steel plate joints under impact tensile loads. It was observed that the effective bond length is insensitive to loading rate for both joints.

Ochi *et al*. (2011) and Yu *et al*. (2012) studied the strengthening using the high modulus CFRP is brought about 15.8% increment in the flexural rigidity and about 26% enlargement in the yield strength of the I-shaped steel girders. Even if the adhesive lengths of the CFRP strips isn't sufficient, the strengthening effect is fully obtained by installing the debonding prevention plates. Although laboratory experiments by several researchers have proven the effectiveness of using a CFRP-bonded reinforcement technique to improve the load carrying capacity and service life of metallic members, bonded reinforcement systems suffer from several drawbacks generally associated with the long-term performance of the adhesive bond between the metallic substrate and CFRP plate.

CFRP strengthening effect: In general, applications that allow complete wrapping of the member with CFRP have proven to be effective. Regarding thin-walled steel members with CFRP strengthening, there has been a lot of research aiming at predicting the improved strength capacity under various loading conditions with existing design rules. In the field of thin-walled steel structures recent research on strengthening of beams with CFRP by Haedir *et al.* (2010) and Zhao and Al-Mahaidi (2009), in web buckling, Ghafoori *et al.* (2012) in Fatigue, Nuno *et al.* (2008) and Jimmy and Xiao-Ling (2011) in compression members, have shown significant benefits in strength and stiffness of steel members with externally bonded CFRP.

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Table 1: Section dimensions and properties

Component	Thickness (mm)	Yield stress (Mpa)	Area (mm^2)	I_{xx} x10^4 (mm^4)	I_{yy} x10^4 (mm^4)	Section modulus, Z_x x10^3 (mm^3)	Section modulus, Z_y x10^3 (mm^3)	Radius of Gyration R_x (mm)	Radius of gyration R_y (mm)
C7575	0.75	550	122	11.6	2.28	3.03	0.91	30.8	13.60
C7510	1.00	550	137	12.2	2.85	3.25	1.02	29.84	12.67
C7512	1.20	550	204	18.9	5.2	5.14	1.84	30.43	15.96

CFRP strengthened beams: Haedir *et al.* (2010) studied an analytical approach for calculating the ultimate strength of CFRP-reinforced steel CHS tubular beams under flexure. The effects of key variables on the moment capacities of CFRP-steel composite beams were investigated. The ultimate bending moment resistance of individual cross-sections was calculated using strain compatibility between CFRP, steel and force equilibrium requirements. Using available experimental data, the methods for calculating the ultimate strength of CFRP-reinforced CHS tubular beams was evaluated. Jimmy and Xiao-Ling (2012) design method has been presented for predicting the capacity of CFRP-Strengthened steel circular hollow sections which take into account strengthening parameters. The ultimate capacities obtained from tests were compared with those predicted by the AS/NZS 4600, AS 4100 and Eurocode 3 provisions.

CFRP strengthened columns: Design approaches for CFRP-strengthened cold-formed steel is proposed by Nuno *et al.* (2009) for Channel column section, Xiao-Ling and Lei (2007) for tubular column sections, Bambach *et al.* (2009) for square hollow sections. Other then AISI most of the standards follows Effective Width Method (EWM). In order to account for the local buckling effects the EWM requires the determination of an effective area of the cross-section. This depends on slenderness λ which directly based on mechanical properties of the section. Design methodology for load carrying capacity of CFRP strengthened sections are proposed with modified slenderness λ to account elastic buckling. Since the elastic buckling and Winter strength equations are generally applicable to other metals, the design method is also applicable to other metals and other CFRP materials, so long as the bond between the metal and CFRP may be achieved.

However, most of the investigations proposed many design methods based on several assumptions. In this investigation cold formed steel channel section strengthened web only to determine strength behavior. The test results are compared with proposed design method.

MATERIALS AND METHODS

To understand the axial compression load capacity of cold formed lipped channel section strengthened with CFRP, a two phase experimental programmer was conducted. In Phase 1, a total of 18 specimens of plain cold formed steel sections were tested. In Phase 2, a

Fig. 1: Test setup

total of 18 specimens of CFRP strengthened cold formed sections were tested under concentrically axial load. The compression test specimen dimensions are shown in Table 1. A schematic view of the test setup is shown in Fig. 1. Simple lipped channels of 0.75 to 1.0 mm thickness and 500, 600 and 700 mm length were chosen for the compression tests. The different types of lipped channels, designated here as C7575 (75×33×7×0.75 mm), C7508 (75×33×7×0.8 mm), C7510 (C75×33×7×1.0 mm), were tested. Two samples were used in each test and the average value was taken.

Bonding is more important to achieve good results for composite structures. To ensure proper bonding between CFRP and Steel, surface preparation of the steel must be used to enhance the formation of chemical bonds between the CFRP-Steel and the adhesive (Fig. 2). The surface of the steel was grooved with an abrasive disc and then removed oils and other contaminates. Carbon fibre sheet was prepared according to the required dimensions and mixed high-

Fig. 2: Surface preparation and application of CFRP

modulus epoxy adhesive MC-Bauchemie was smeared uniformly on the surface of the fibre sheet. Unidirectional high-strength carbon fibre sheets namely MBrace CF 130 of 3790 MPa ultimate tensile strength 230Gpa elastic modulus with a thickness of 0.176 mm were used in this investigation. The composite sheet was then placed around the exposed external surface of the column web and gradually pressed along the fibre axis.

To ensure that the two supporting ends were parallel to each other and perpendicular to the loading axis, they were wire eroded normal to the loading axis. This ensured full contact between specimen and steel end plates. The specimens prepared length is greater than three times flat width of the section and its length/radius of gyration in the direction of the least radius of gyration was kept to less than 50. It is done to prevent failure of the column due to column flexural buckling rather than local buckling. The specimens were tested in a 500 kN capacity hydraulic testing machine at a displacement controlled rate of 0.25 mm/min set to investigate the failure modes of the CFRP strengthened steel sections. The ultimate load carrying capacity results are tabulated in Table 2.

RESULTS AND DISCUSSION

Design method for CFRP strengthened channel section proposed to axial compression based on AISI standards (AISI, 2007). To account CFRP, the Direct Strength Method (DSM) modified to estimate the

ultimate strength of cold-formed steel columns experiencing flexural or flexural - torsional, local and distortional buckling. CFRP is assumed to play an important role in elastic buckling, slenderness ratio. The nominal axial strength P_n determined as minimum of (P_{ne}, P_{nl} and P_{nd}) based on DSM method is in Eq. 3, 4 and 5, proposed by Schafer (2006). Total thickness of CFRP layered plate (t_t) considered as CFRP thickness (t_{cf}) + steel plate (t_s) neglecting adhesive layer thickness (as this is week in strength and bucking) given by Eq. (1). The elastic modulus of the CFRP with steel is determined from the modular ratio concept and given by Eq. (2):

$$t_t = (t_{cf}) + t_s \tag{1}$$

$$E_{cfrp} = \frac{E_s t_s + E_{cf} t_{cf}}{t_s + t_{cf}} \tag{2}$$

Flexural, Torsional, or Torsional-Flexural Buckling (P_{ne}):

$$P_{ne} = \begin{cases} \left(0.658^{\lambda_c^2}\right)P_y & \lambda_c \leq 1.5 \\ \left(\frac{0.877}{\lambda_c^2}\right) & \lambda_c > 1.5 \end{cases} \tag{3}$$

where,

$$\lambda_c = \sqrt{P_y \big/ P_{cre}}$$

P_{cre} = Minimum of the critical elastic column buckling load in flexural, torsional, or torsional-flexural buckling.

Local Buckling (P_{nl}):

$$P_{nl} = \begin{cases} P_{ne} & \lambda_l \leq 0.766 \\ \left[1 - 0.15\left(\frac{P_{crl}}{P_{ne}}\right)^{0.4}\right]\left(\frac{P_{crl}}{P_{ne}}\right)^{0.4} P_{ne} & \lambda_l > 0.766 \end{cases} \tag{4}$$

where,

Table 2: Plain cold formed steel ultimate load: Experimental Vs theoretical

Section	FY Mpa	Ultimate Load-Experimental-kN	Ultimate load -theoretical-AISI- kN
C7575×500 mm	550	54.23	55.35
C7575×600 mm	550	53.86	54.63
C7575×700 mm	550	53.13	53.78
C7510×500 mm	550	57.97	62.03
C7510×600 mm	550	57.88	55.84
C7510×700 mm	550	56.75	55.00
C7512×500 mm	550	72.65	84.31
C7512×600 mm	550	71.08	83.28
C7512×700 mm	550	69.5	82.08

Table 3: CFRP strengthened cold formed steel-ultimate load: Experimental vs. theoretical

Section	FY Mpa	Ultimate load-experimental-kN	Ultimate load-theoretical-ISI-kN
C7575×500 mm	550	59.85	61.19
C7575×600 mm	550	60.21	60.34
C7575×700 mm	550	58.45	59.31
C7510×500 mm	550	64.26	61.87
C7510×600 mm	550	64.01	61.02
C7510×700 mm	550	64.05	60.04
C7512×500 mm	550	80.05	89.64
C7512×600 mm	550	79.64	88.50
C7512×700 mm	550	78.92	87.16

Table 4: Increase of strength due to CFRP strengthening

| Section	FY Mpa	Ultimate load-plain section-experimental-kN	Ultimate load-CFRP strengthened sections experimental-kN	Change in strength-%
C7575×500 mm	550	54.23	59.85	10.36
C7575×600 mm	550	53.86	60.21	11.78
C7575×700 mm	550	53.13	58.45	10.01
C7510×500 mm	550	57.97	64.26	10.85
C7510×600 mm	550	57.88	64.01	10.59
C7510×700 mm	550	56.75	64.05	12.86
C7512×500mm	550	72.65	80.05	10.18
C7512×600mm	550	71.08	79.64	12.04
C7512×700mm	550	69.5	78.92	13.55
Average increase of strength due to CFRP strengthening				11.36
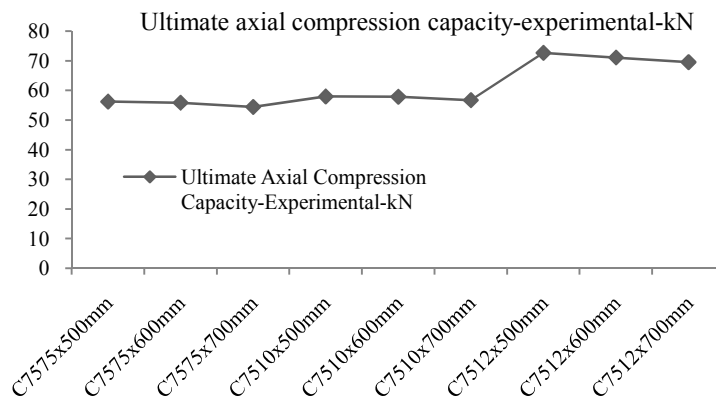
Fig. 3: Ultimate axial compression capacity Vs section length

$$\lambda_l = \sqrt{P_{ne}/P_{crl}}$$

P_{crl} = Critical elastic local column buckling load.
Distortional Buckling (P_{nd})

$$P_{nd} = \begin{cases} P_y & \lambda_d \leq 0.561 \\ \left[1 - 0.25\left(\frac{P_{crd}}{P_y}\right)^{0.6}\right]\left(\frac{P_{crd}}{P_y}\right)^{0.6} P_y & \lambda_d > 0.561 \end{cases}$$

(5)

where,

$$\lambda_{cd} = \sqrt{P_y/P_{crd}}$$

P_{crd} = Critical elastic distortional column buckling load.

The theoretical ultimate loads determined from AISI provisions for design of compression members with and without CFRP strengthening cold-formed steel columns are presented in Table 3. The experimental CFRP strengthened cold formed steel channel section ultimate loads were compared with theoretical a ultimate load that is determined from AISI provisions, as shown in Table 4. The proposed design method results are good agreement with experimental test results. Ultimate load verses length of the member are plotted in Fig. 3, the results shows slight decrement of the load carrying capacity for slender members of same cross sections. Also noted strengthening using CFRP results in increasing the yield capacity of the sections.

CONCLUSION

In this study, Ultimate load of CFRP strengthened cold formed steel channel column was investigated. Each column with the column length ranged from 500,

600 and 700 mm were tested, the column ultimate strength obtained from test results compared with the strengths calculated using the AISI specifications for cold formed steel sections. Comparison of the analytical and experimental study indicates that the flexural capacity of CFRP strengthened steel channel columns can be predicted within a reasonable accuracy. The strengthening using the high modulus CFRP brought about 11% increments in axial compression strength. However the proposed design method is valid ensuring a proper bond between CFRP laminates and steel. Further investigation is needed for better understanding of bond/debonding failures in CFRP-Adhesive-Steel system. This proposed design method also applicable for open sections with single axis symmetrical shapes.

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