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Axially Loaded Steel Columns Strengthened with CFRP

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ABSTRACT

During the recent decades, Carbon Fiber-Reinforced Polymer (CFRP) composite materials have proven valuable properties and suitability to be used in the construction of new buildings and in upgrading the existing ones. The objective of this paper is to review the previous work in this area and compare it with the current experimental results to show the design equations for CFRP strengthened steel structural elements. Research findings have shown that CFRP sheets and strips are not only effective in restoring the lost capacity of a damaged steel section, but are also quite effective in strengthening of steel sections to resist higher loads, extend their fatigue life and reduce crack propagation.

KEYWORDS: CFRP, Bond strength, Section capacity, Design rules.

INTRODUCTION

Carbon Fiber-Reinforced Polymer (CFRP) composite materials have experienced a continuous increase in use in structural strengthening and repair applications around the world in the past fifteen years. High specific stiffness and weight combined with superior environmental durability of these materials have made them a competing alternative to the conventional strengthening methods. It was shown through experimental and analytical studies that externally bonded CFRP composites can be applied to various structural members including columns, beams, slabs and walls to improve their structural performance such as stiffness, load carrying capacity and ductility. CFRP composites have enjoyed varying degrees of success in different types of applications as they are extremely flexible, form all kinds of shapes and are easy to handle during construction.

CFRP composite materials have been increasingly employed in the construction industry, mainly in applications dealing with structural strengthening and repair. They are ideally suited for these purposes, due to a combination of (i) very high stiffness-to-weight and strength-to-weight ratios and (ii) an excellent durability in aggressive environments. Indeed, it has been shown, both analytically and experimentally, that the addition of externally bonded CFRP composites significantly improves the performance of a structural member; namely its stiffness, load-carrying capacity, durability and fatigue behavior under cyclic loadings. However, due to limitations from several economical and design-related issues, this strengthening/repair technique has not yet been given a chance to be exploited to its full potential.

Many experimental investigations and theoretical studies have been conducted about CFRP strengthened steel members, dealing with different strength parameters. In this paper, bond strength design equations for CFRP strengthened steel members are presented.

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LITERATURE REVIEW

Bond Characteristics between CFRP and Steel

To enable the use of CFRP composites for strengthening steel structures, an understanding of bonding mechanisms is essential. Bond strength is usually used to determine bond performance. Bond strength can be defined as the ratio of maximum load and interfacial area. However, a local bond–slip relationship is independent of geometric conditions, and therefore a local bond–slip model may be appropriate to measure bond performance. While a great deal of research has been carried out on bond–slip relationships of CFRP sheet/plate bonded to concrete joints, research on CFRP sheet/plate bonded to steel joints is limited. Investigations on bond strength made by Chao et al. (2012), Chen et al. (2001), Dai et al. (2005), Ishikawa et al. (2006), Lu et al. (2007), Nozaka et al. (2005) and Yu et al. (2012) were both experimental and analytical works and proposed effective bond length to achieve perfect bonding for various static and dynamic loading conditions.

Recent studies conducted by Fawzia et al. (2005-2010) investigating CFRP bonded steel plate double strap joints and different numbers of CFRP layers with different bond lengths were reviewed. The load carrying capacity for any bond can be expressed by Eqs. (3 and 4) assuming that the load is linearly propositional to the bond length.

if $l_1 < l_{eff}$

$$P_{CFRP} = l_1 \frac{P_{ult}}{l_{eff}} \quad (1)$$

if $l_1 > l_{eff}$

$$P_{CFRP} = P_{ult} \quad (2)$$

where, l_{eff} is the effective bond length.

P_{CFRP} is the ultimate capacity of bond length l_1.

$Pult$ is the ultimate capacity of bond length l_{eff}.

The imperial mode can be developed by using stress based approach and is expressed in Eq. (3)

$$P_{ult} = 0.8\tau w l_{eff} \quad (3)$$

where, τ is the shear stress.

w is the width of the bonding area.

However, Eq. (3) required experimental computation to identify the shear stress (τ). Fernando et al. (2007) further compared for predictions with the following well known Eq. (4) for bond strength:

$$P_u = b_p\sqrt{2E_p t_p G_f} \quad (4)$$

where b_p is the plate width, E_p is the elastic modulus of the CFRP plate, t_p is the thickness of the CFRP plate and G_f is the interfacial fracture energy.

Example: Manual Verification

From Fernando Specimen Number A-NM-T1-I, b_p=50 mm, E_p=150 Gpa, t_p = 1.2 mm, $P_{u.exp}$ = 30.75 kN, G_f = 1.06 N/mm

$$P_u = 50\sqrt{2X150{,}000X1.2X1.06}$$

P_u = 31 kN.

It is clear from the above example that Eq. (4) can provide an accurate prediction for the bond strength, given that the interfacial fracture energy used is accurate.

In general, applications that allow complete wrapping of the member with CFRP have proven to be effective. Wrapping of columns to increase their load and deformation capacity is the most effective and most commonly used method of retrofitting with composites. CFRP composites are widely recognized for their potential use in seismic retrofitting applications. The use of Carbon Fiber-Reinforced Polymer appears to be an excellent solution for strengthening structural systems.

In the field of thin-walled steel structures, recent investigations on the strengthening of circular hollow sections (CHS) with FRP made by Teng et al. (2007) and Hong et al. (2000) in axial compression, Haedir et al. (2006, 2007) in bending, Doi et al. (2005) in bending and compression, Jiao and Zhao (2004) in tension and Zhao et al. (2005) and Xiao et al. (2005) on concrete filled CHS, have shown significant benefits in strength and stiffness of steel members with externally bonded CFRP. Experiments on steel RHS strengthened with CFRP under transverse end bearing force were described by Zhao et al. (2006) and results are validated with FEM numerical modeling. Research on the strengthening of SHS with CFRP is investigated by Shaat and Fam (2004, 2006 and 2007). CRP strengthening of steel bridges was investigated by Miller et al. (2001), Schnerch et al. (2004) and Mustafy et al. (2010). Most investigations on steel hollow sections were performed on compact sections.

CFRP Strengthening of Channel Columns

Silvestre (2007) investigated non-linear behaviour and load-carrying capacity of CFRP-strengthened lipped channel steel columns, with the aim of assessing how the CFRP strengthening influences (enhances) the nonlinear behaviour and load-carrying capacity of cold-formed steel lipped channel columns. He also proposed design methods to calculate the ultimate load capacity. However, the results might vary if surface preparation and adhesive material change. Thus, unique design procedure should be developed in order to standardize the design equations.

Design of Circular Hollow Steel Section with CFRP

Haedir et al. (2011) investigated design and experimental evaluation of externally bonded CFRP sheets for strengthening circular steel tubular short columns and proposed design methods for cylindrical CFRP-reinforced steel tubular columns under compression.

The concept of modular ratio is applied for calculating the axial section capacities of CFRP-reinforced steel tubular short columns. The thickness of each carbon fiber layer was assumed to be uniform and the bond between the CFRP and the steel to be adequate. The strengthening influence of the CFRP can be gauged by using the effective area of the supplanted and steel cross-sections given in the existing local buckling design procedure. The test results suggest that the use of a combination of hoop and longitudinal CFRP in a slender tube can promote the attainment of the yield capacity of the bare tube. The experimental ultimate capacities were compared with the AS/NZS 4600, AS 4100 and Eurocode 3 provisions. A reasonable agreement was obtained. The investigation has characterized the increase in the design curve with the increase of the reinforcement factor, α. In addition, the variation of the proportioning factor, ξ, provides a quantitative comparison of the strengthening effect of the reinforced columns. The effect of these variables on the capacity of CFRP-reinforced steel tubular columns needs to be considered in order to ensure the effective design of CFRP-reinforced steel tubular columns. The proposed design rules (Eqs. 5 and 6) are for capacity of CFRP-reinforced circular hollow steel section under axial compression.

$$N_u = N_s \qquad (5)$$

$$N_u = A_{es}\sigma_y^s \qquad (6)$$

where:

N_u is the ultimate axial compression.

σ_y^s is the yield strength of steel.

A_{es} is the area of the equivalent steel section.

Design of Square Hollow Section with CFRP

Bambach et al. (2009) investigated axial capacity and design of thin-walled steel square hollow section [SHS] strengthened with externally bonded CFRP. The SHS were fabricated by spot-welding and had plate width-to-thickness ratios between 42 and 120, resulting in plate slenderness ratios between 1.1 and 3.2. Two different matrix layouts of the CFRP were investigated. It is shown that the application of CFRP to slender sections delays local buckling and subsequently results in a significant increase in elastic buckling stress, axial capacity and strength-to-weight ratio of the compression members.

A design method is developed whereby the theoretical elastic buckling stress of the composite steel–CFRP sections is used to determine the axial capacity, and is shown to compare well with the test results. A reliability analysis shows the method that is suitable for design. The proposed design rules are as follows:

f_{cr} is the elastic buckling stress based on load-axial displacement curve, f_y is the yield stress, E is Young's modulus, t is the plate thickness, b is the plate width and υ is Poisson's ratio.

$$\lambda = \sqrt{\frac{f_y}{f_{cr}}} \quad (7)$$

$$f_{cr} = \frac{k\pi^2 E}{12(1-\upsilon)^2}\left(\frac{t}{b}\right)^2 \quad (8)$$

Capacity prediction using composite plate theory

$$t_t = t_s + t_{CFRP} \quad (9)$$

$$E_{CFRP} = \frac{E_a t_a + E_{cf} t_{cf}}{t_a + t_{cf}} \quad (10)$$

$$P_{uc} = \rho_c A_s f_{ys}. \quad (11)$$

Experimental Investigation

The objective of this experimental program is to develop a system to increase the stiffness such that the local buckling can be controlled to some extent of cold formed lipped channel steel members. While previous work has shown strength increases, there is possibility for any shape of steel structures reinforced with conventional CFRP materials. Experimental program is designed to investigate the strength increase due to CFRP strengthening. The experimental program is included in three phases. At The UNITEN-Malaysia University, a series of experimental and theoretical studies are progressing in this area (Sreedhar et al., 2013). In the first phase of tests, a detailed experimental program was conducted to study the proposed strengthening system for ultimate load carrying capacity and buckling behaviour. In phase II, effective bond length for application of CFRP to steel plate by the process of tension coupon tests was studied. The test specimens used in this study are also used to investigate same grade of steel for ultimate load and buckling load calculations in later phases of studies. In order to investigate design equations, several models are developed based on experimental results in which part of the study is investigated with and without wrapped cold formed steel members with CFRP.

In phase I, experimental works were carried out using the standard tension method to calculate bond strength (Fig. 1). The coupon consists of two 200 mm long and 50 mm wide F550 grade steel plates. The dimensions of the tension coupons were decided as specified in available research guidelines (Zhao, 2007). The tests were carried out by using a testing machine in the UNITEN Structural Testing Laboratory (Fig. 1).

The results from Table 1 and Fig. 2 clearly show that 100 mm bond length gives optimum load carrying capacity compared with bond length of 75 mm, 150 mm and 200 mm. The failed test specimens are clearly showing the peeling due to debonding failures explained in Fig. 3.

Table 1. Maximum tension load for different bond strengths

Specimen Thickness (mm)	Max. Load (N) at 75 mm	Max. Load (N) at 100 mm	Max. Load (N) at 150 mm	Max. Load (N) at 200 mm
0.75	13731.3	14307.6	13948.1	14951.4
1	15665.8	16967.6	15318.5	16216.1
1.2	12584.3	7522.01	9778.09	8708.8

Figure (1): Tension coupon test with CFRP strengthened specimen

In phase II, experimental and analytical investigations are conducted for cold formed steel lipped channel sections strengthened by CFRP (Fig. 4).

The test and analytical results showed that the strengthening effect may increase the load-carrying capacity up to 16.75%. The proposed design equations for CFRP strengthened cold formed steel-lipped channel sections subjected to pure axial compression are described in Sreedhar et al. (2013). The elastic modulus of the CFRP with steel is determined from the modular ratio concept, E_{cfrp} given by Eq. (13).

$t_t = (t_{cf}) + t_s$ (12)

$$E_{cfrp} = \frac{E_s t_s + E_{cf} t_{cf}}{t_s + t_{cf}}. \quad (13)$$

The modified composite elastic modulus in Eq.(13) is incorporated into the design equations of the North American Specification for the Design of Cold-Formed Steel Structural Members-AISI -2007 and Euro Code for Cold-Formed Members and Sheeting-EC3-EN1993-1-3:2006. The results are graphically represented in Fig. 5.

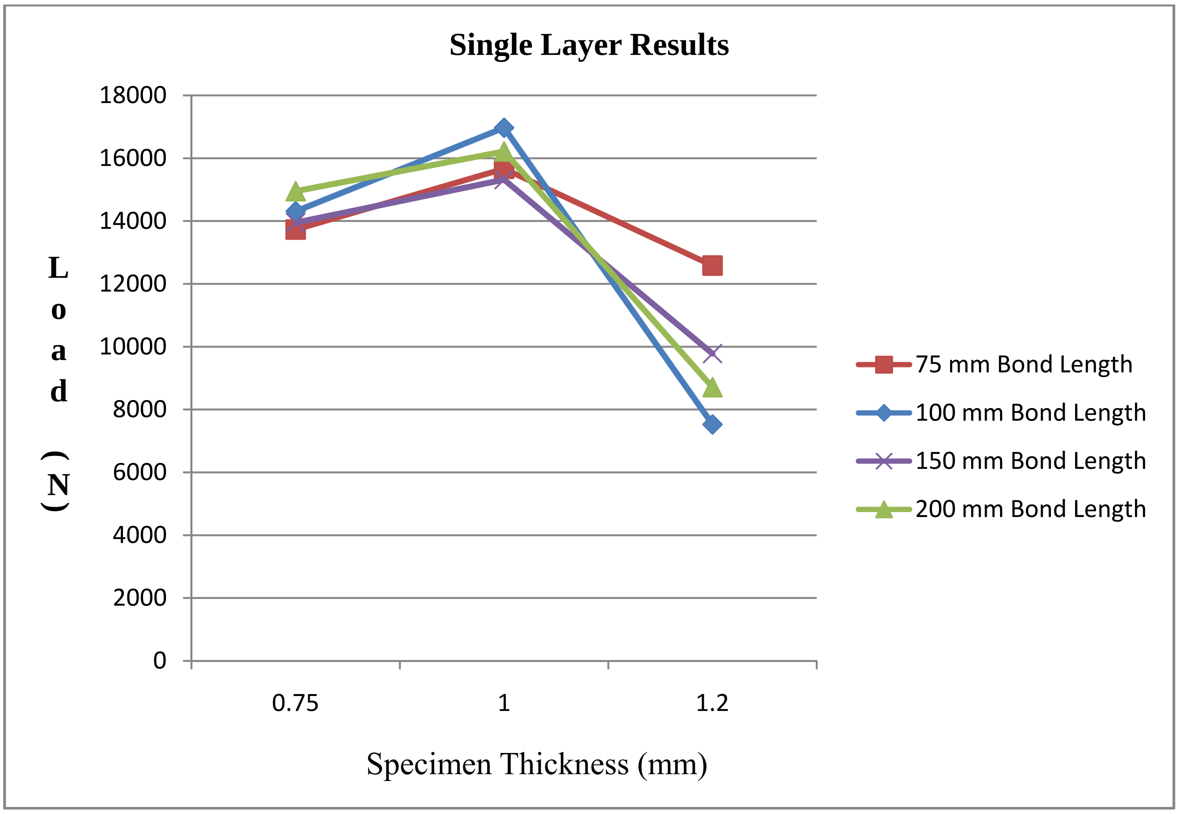

Figure (2): Bond strength *vs.* Specimen thickness

Two proposed design approaches (AISI and EC3) were compared with the experimental results. In Fig. 5, a comparison is shown between the ultimate load obtained through the experimental tests and that obtained through the proposed design approach. The proposed design equations show good agreement with experimental results and provide conservative estimates.

CONCLUSIONS

This paper focused on recent developments on CFRP strengthening steel structures. The following observations and conclusions can be made.

- Bond characters are studied and proposed empirical load-carrying capacity based on stress-based approach for steel plate strengthened by CFRP is found to be in good agreement with the test results.

- CFRP strengthened lipped channel section reviewed, current experimental results also show that strength estimation is close to the proposed design method.

- CFRP strengthened circular and square hollow steel sections reviewed, the proposed design rules are found to be in good agreement with the test results.

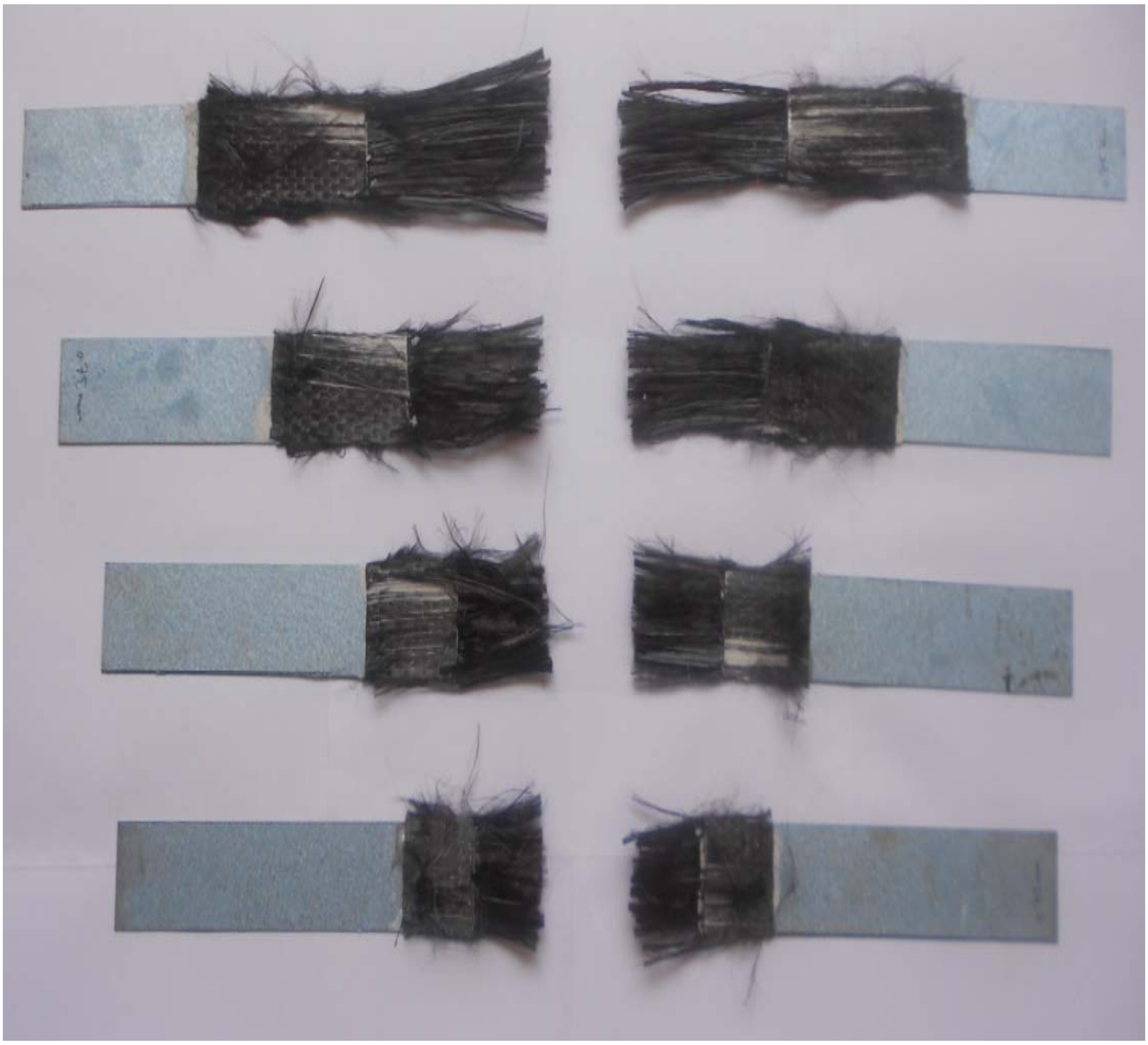

Figure (3): 0.75 mm thick single layered tested specimen

These equations might be considered as interim guidelines for axial compression strength prediction until design code equations are developed. Research is still being conducted to investigate many issues to standardize design code equations for CFRP strengthened thin walled steel structures.

Figure (4): Cold formed steel lipped channel sections strengthened by CFRP

It was also found from the review results that the increase in strength due to CFRP depends on the type of CFRP like high modulus of elasticity, number of layers, thickness, type of the adhesive material and surface preparation. Some research studies consider that only the steel section should be used to calculate the strength. That is, the CFRP is assumed to play an important role in elastic buckling, but not strength. The

CFRP is thus not primarily a load carrying member, but its geometric properties will beneficially affect the elastic buckling of the section. This is also congruent with the fact that the CFRP is not extended to the end of the specimens and is not in contact with the loading platens of the machine, and is thus not directly carrying axial load.

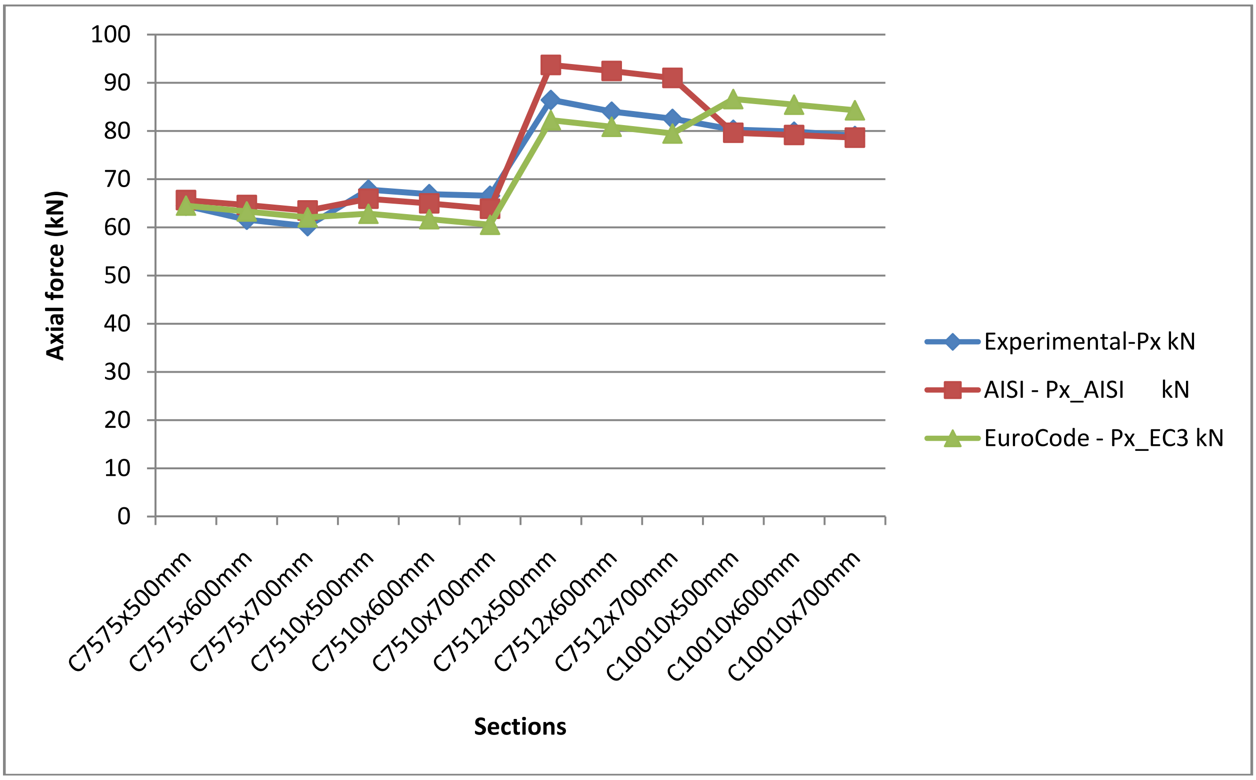

Figure (5): Ultimate load for CFRP strengthened full section: a) experimental b) AISI c) EC 3

In order to validate the proposed design equations, further research should address the following issues:

- Effect of epoxy should be considered for CFRP-reinforced steel columns in order to ensure the effective design of CFRP-reinforced cold formed steel columns.
- Steel surface preparation and characterization should be considered to develop a widely accepted procedure.
- De-bonding failures should be investigated to control the peeling of CFRP from steel.

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