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# INVESTIGATION ON CFRP STRENGTHEN ALUMINUM, STAINLESS STEEL AND MILD STEEL TUBULAR SECTIONS UNDER END-TWO-FLANGE LOADING

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**ABSTRACT**

Carbon Fiber Reinforced Polymer (CFRP) is one of the most important, effective, potential, and advanced composite materials for strengthening of reinforced concrete (RC) and metal structures. Aluminium, stainless steel and mild steel tubular member may often experience web crippling failure due to concentrated End-Two-Flange (ETF) loading. Strengthening with CFRP can be a better option to overcome this problem. The objective of this research is to investigate the structural strength and behaviour of CFRP strengthened aluminium, stainless steel and mild steel tubular member subjected to End-Two-Flange loading. A series of tests have been conducted to the metal tubular sections which are strengthened by CFRP. Eighteen tubular sections including reference section and CFRP strengthened sections were tested in this study. Hydraulic contorted universal testing machines were used for concentrated ETF loading. The collapse loads, collapse modes and the load-deformation behavior of reference sections and CFRP strengthen section are also presented in this paper. Based on experimental results, it was found that CFRP strengthening aluminium tubular section provides better performance than stainless steel and mild steel tubular sections. The load-carrying capacity increased significantly and it was varied by 28.18% to 43.78% for CFRP strengthening sections. Therefore, it can be concluded that the tubular metal sections can be strengthened efficiently by CFRP.

Keyword: Aluminium, Steel sections, CFRP, ETF, Strengthening

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**INTRODUCTION**

Structural members with tubular sections are being used significantly due to lightness, recyclability easy manufacturing, high strength-to-weight ratio, and availability. But for this member, there may be a risk of undergoing web crippling. Principally, local high intensity of concentrated or point load is responsible for web crippling at the end. There are numerous techniques to counter the web crippling failure by strengthening the web. Attaching plate externally or replacing plating by cutting it's out one of the widespread methods of strengthening (Zhao and Zhang, 2007). The main limitation of the existing techniques is to make the section heavy and bulky. Moreover, it is very hard to match them properly and there's a huge chance of corrosion. Strengthening tubular sections using CFRP externally is proven to be a significant alternative for aluminium and stainless-steel structural members (Islam and Young, 2012). Rectangular light steel beams and carbon steel tube has been strengthened with fibre-reinforced polymer (CFRP) and studied the effects. Then, it was reported as phenomenal (Zhao et al. 2006; Zhao et al. 2009; Fernando et al. 2009). Existing research on web crippling property of the members basically, focused on aluminium and carbon steel members. Structural members made of cold-formed steel subjected to web crippling have been investigated and reported in the previous studies (Young et al. 2004; Macdonald et al. 2011; Chen et al. 2015). Web crippling behaviour of tubular stainless-steel members have been experimented and reported by Zhou and Young 2007 and Zhou and Young 2013. Islam and Young (2018) studied the web crippling strength of aluminium alloy tubular sections strengthened with CFRP subjected to ITF, ETF, IOF and EOF loading conditions by both experimentally and numerically. The research was mainly focused to design the strengthened member. The behaviour of aluminium alloy of channel sections using both finite element analysis and experimental analysis under flanges restrained condition has been studied and reported. From this study for flanges restrained aluminium alloy channels a unified web crippling equation was proposed under ITF and ETF loading conditions (Zhou and Young, 2020). A study of combined crippling-bending interaction behaviour of cold-formed steel channel sections has been conducted and reported (Janarthanan and Mahendran, 2020). The web crippling capacity of fastened cold-formed steel channels with plain webs, un-stiffened and edge-stiffened web holes and under ETF (End-two-flange) loading condition has been tested and reported (Chen et al. 2021). Hareindirasarma et al. (2021) studied the web crippling capacity of cold-formed light steel beams with circular holes under ITF (Interior-Two-Flange) loading condition.

It is now evident that previously the research work on web crimpling behaviour of member of steel structure was limited to cold-formed steel and aluminium. There's a little work on this topic for stainless steel and mild steel. As the use of stainless steel in structures are increasingly being used due to their availability, it is very important to study the response of mild steel and stainless-steel sections to web crippling under ETF loading. A series of web crippling tests of aluminium (Al), stainless steel (SS) and mild steel (MS) tubular structural members at unstrengthened condition and strengthened condition by CFRP was conducted, in this study. The experimental investigation in this article was principally focussed on the effects of different materials and the effect of CFRP strengthening those materials on load resisting against web crippling. The test specimens were subjected to ETF (End-Two-Flange) loading condition.

**MATERIAL PROPERTIES**

External bonded strengthening highly depends on the properties of adhesive and CFRP materials. The effective bond strength, elastic modulus, and elongation are the key mechanical properties of adhesive for strengthening of structures. CFRP material is a composite material that typically consists of fibres embedded in a resin matrix. Epoxy resin is the most widely used resin for the CFRP. Four materials have been used to prepare the specimens such as primer and saturant, CFRP plate, adhesive and RC beam as shown in Fig. 1. In this research, CFRP plate Kor-CLS0214 with 20 mm width, and 1.4 mm thickness was used, and the measured tensile strength and elastic modulus were 3000 MPa, and 165 GPa respectively. Primer and saturant were used having density of 1.14 gm/cm$^3$ and 1.8 gm/cm$^3$: pot life 30 min, 1hr 30 min, tensile strength 1350 MPa, 4875 MPa, modulus of elasticity 99.37 GPa, 238.00 GPa, respectively. Tensile stress was 245 MPa, 434 MPa, and 390 MPa, and the ultimate stress 268 MPa, 464 MPa, and 450 MPa, initial Young modulus 68.3, 201.1, and 198.6 GPa for aluminium, stainless steel, and mild steel tubular sections, respectively. Adhesive Kor-CPA 10 base resin and hardener used in this research have tensile strength of 49.8 MPa, shear strength of adhesive 29 MPa, pot life 70 min.

Fig. 1: Primer, Saturant, adhesive and CFRP Fabric

**EXPERIMENTAL PROGRAM**

A series of tests have been carried out to the metal tubular sections which are strengthening by CFRP. Eighteen tubular section including reference section and FRP strengthen sections were tested in this study. In this study, a number of six specimens were taken for each metal. In total 18 specimens were taken from all other three metals. The specimen lengths ($L$) are determined according to the North American Specification (AISI S100, 2007) and the Australian/New Zealand Standard (AS/NZS, 2005) for ETF. The specimen lengths are $L = N + 1.5d$, where $d$ is the overall depth and $N$ is the bearing length of 50 mm. Out of six specimens of each metal, two specimens were taken for testing without CFRP as a reference test. The other four specimens were taken for testing with FRP plates. The FRP plates are applied on the two sides of the tubular metal members at one end of the members for a length of 50 mm, which is the bearing length. The details dimensions of ETF loading test specimens are shown in Table 1. Definition of symbol, dimension of tubular specimens is shown in Fig. 2.  Figs. 3 and 4 present aluminium, stainless steel, and mild steel specimen for ETF test specimens without and with CFRP strengthening, respectively.

Table 1: Material properties of ETF loading specimens

| Specimen | Length, $L$ (mm) | Thickness, $t$ (mm) | Width, $b$ (mm) |
|---|---|---|---|
| Aluminium | 122.00 | 0.80 | 44.45 |
| Stainless steel | 135.50 | 0.80 | 50.80 |
| Mild steel | 135.50 | 1.10 | 50.80 |

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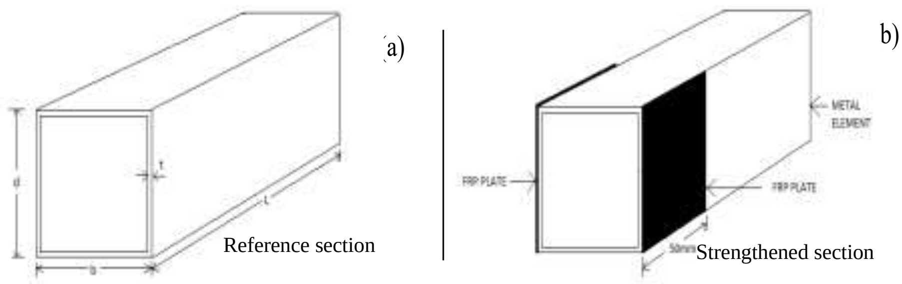


Fig. 2: Dimension of tubular metal section and FRP strengthen specimen for ETF loading

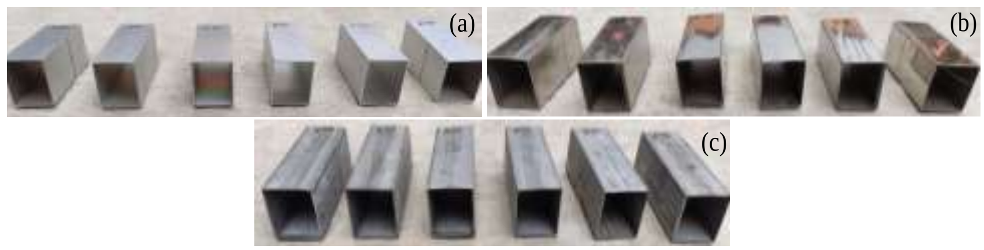


Fig. 3: (a) Aluminium, (b) Stainless steel, and (c) Mild steel specimen for ETF test specimens

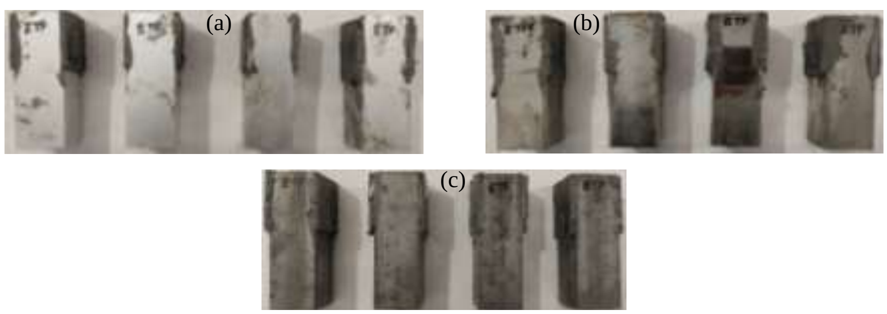


Fig. 4: CFRP plate strengthened (a) Aluminium, (b) Stainless steel and (c) Mild steel specimen for ETF test specimens

Under the application of high amount of concentred loading upon a structural member leads to a localized failure. Web Crippling mainly noticed in steel section with high slenderness. The steel sections like tubular or channel section which has a large ratio of width to thickness undergo web crippling when a high concentrated load is applied on a short length of beam. To achieve the web crippling capacity under these four loading conditions American Iron and Steel Institute (AISI) has proposed a testing procedure recently. The web crippling test was performed by using universal testing machine. In this machine, ETF test specimen was placed. For placing a specimen into the machine to test, two 50 mm bearing plate were used at upper and lower side of the specimen. For avoiding developed moment, half circle plate was provided at both ends. The arrangement is shown in Fig. 5. Although some restrictions, two half circle plates were provided at the top and bottom of the specimen.

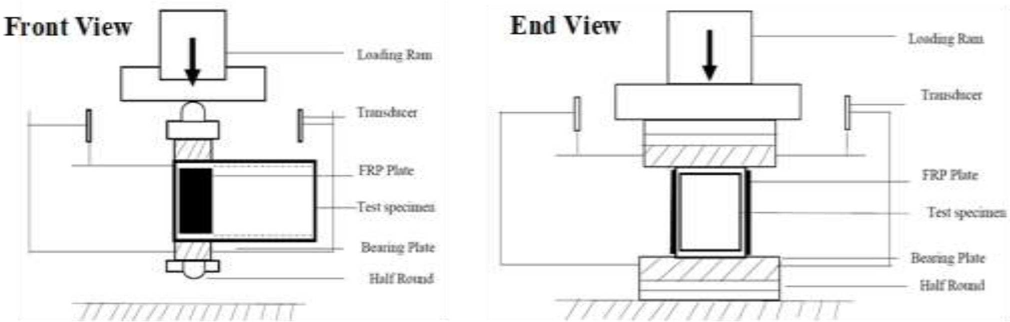


Fig. 5: Schematic view of ETF loading test arrangement

Hydraulic contorted universal testing machine were used for concentrated ETF loading. After completing the setup arrangement, the load was applied and recorded from machine up to the failure occurred. Deflection data were recorded from deflection gauge and corresponding deformation values from deformation gauge as shown in Fig. 6.

Fig. 6: Testing specimen under the arrangment set up

## RESULT AND DISCUSSIONS

In this section, the ultimate capacity and the failure modes has been investigated for strengthening by CFRP. The deformation shapes are shown in Fig. 7. The deformation was occurred at one end in ETF loading test. It is observed that the deformed of aluminium tubular members were higher than those of mild steel and stainless steel. The strength of mild steel is high due to higher thickness. The collapse loads, collapse modes and the load-deformation behavior of reference sections and CFRP strengthen section are also presented in this study.

(a) (b)

Aluminium Stainless Steel Mild Steel Aluminium Stainless Steel Mild Steel

Fig. 7: Specimen after failure (a) reference sections (b) FRP strengthened sections

The ultimate capacity ($P_u$), deflection at ultimate capacity ($\delta$), failure mode and increment of load capacity with respect to reference beam are shown in Table 2. The load-deformation behavior of reference sections and CFRP strengthen section are also presented in Fig. 8. Based on experimental results, it was found that CFRP strengthening aluminium tubular section provide better performance significantly than stainless steel and mild steel tubular sections.

Table 2: The ultimate capacity, deflection at ultimate capacity and increment of load capacity

| Material type | Specimen | $P_u$ (kN) | $\delta$ (mm) | Increment (%) |
|---|---|---|---|---|
| Aluminium | $A_0F_o$ | 5.01 | 4.26 | 00.00 |
| | $A_1F_0$ | 5.02 | 4.26 | 00.00 |
| | $A_3FP_1$ | 7.37 | 5.07 | 43.21 |
| | $A_4FP_1$ | 7.31 | 5.10 | 42.10 |
| | $A_5FP_1$ | 7.40 | 5.10 | 43.78 |
| | $A_6FP_1$ | 7.36 | 5.10 | 42.98 |
| Stainless Steel | $SS_0F_0$ | 8.03 | 4.13 | 00.00 |
| | $SS_1F_0$ | 8.04 | 4.15 | 00.00 |
| | $SS_3FP_1$ | 10.33 | 4.45 | 28.63 |
| | $SS_4FP_1$ | 10.29 | 4.50 | 28.18 |
| | $SS_5FP_1$ | 10.43 | 4.50 | 29.87 |
| | $SS_6FP_1$ | 10.36 | 4.50 | 28.95 |
| Mild Steel | $MS_0F_0$ | 9.24 | 4.98 | 00.00 |
| | $MS_1F_0$ | 9.25 | 4.85 | 00.00 |
| | $MS_3FP_1$ | 12.03 | 5.15 | 30.13 |
| | $MS_4P_1$ | 12.19 | 5.15 | 31.96 |
| | $MS_5P_1$ | 12.03 | 5.25 | 30.23 |
| | $MS_6P_1$ | 10.80 | 5.15 | 31.10 |

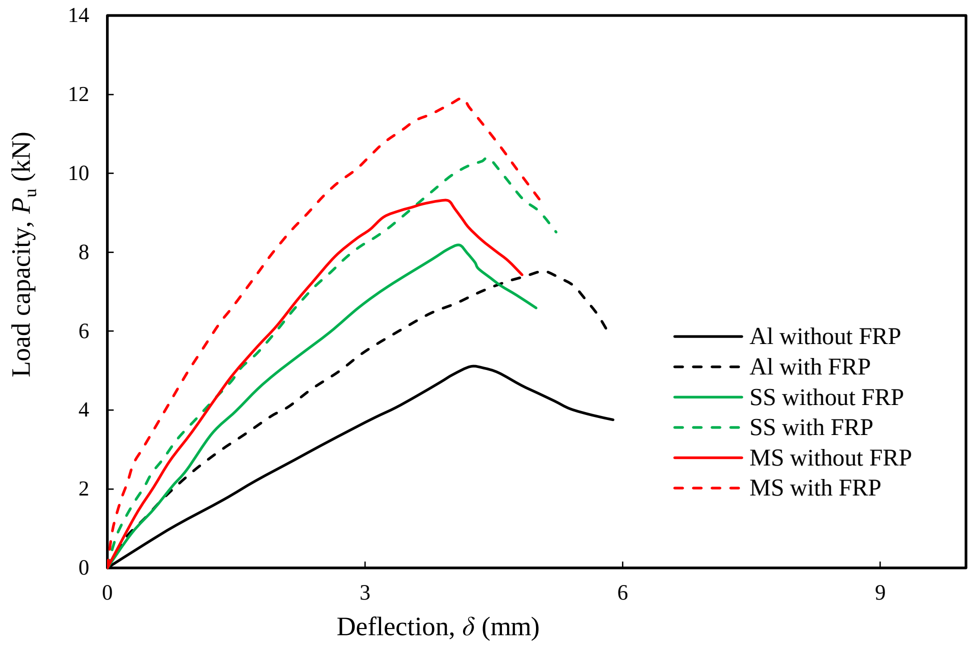


Fig. 8: Comparison of ultimate capacity for reference and strengthened section

A significant improvement in load carrying capacity of each type of specimen is clearly noticeable here. Load carrying capacity is enhanced 43.04%, 28.90% and 30.85 % for aluminium, stainless steel and mild steel, respectively. The percentage of increase in load carrying capacity significantly varied from 28.18% to 43.78% for CFRP strengthening technique. Hence, it can be revealed that the tubular metal sections can be strengthen efficiently by CFRP

**CONCLUSION**

An extensive experimental investigation on CFRP strengthened aluminium, stainless steel and mild steel tubular sections subjected to ETF web crippling loading has been presented. The investigation examined structural strength and behavior of CFRP strengthens aluminium, stainless steel and mild steel tubular member subjected to ETF loading. The ultimate capacity, collapse modes and the load-deformation behavior of reference sections and CFRP strengthen section are also presented in this study. The enhancement of load carrying capacity was found 43.04%, 28.90% and 30.85 % for aluminium, stainless steel and mild steel, respectively. The test results revealed that CFRP strengthening aluminium tubular section provide better performance significantly than stainless steel and mild steel tubular sections. Based on experimental results, it was found that CFRP strengthening aluminium tubular section provide better performance significantly than stainless steel and mild steel tubular sections. The enhancement in terms of percentage of load carrying capacity significantly varied 28.18%-43.78% for CFRP strengthening technique. Therefore, it can be summarized that the tubular metal sections can be strengthening efficiently by CFRP.

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