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Determination on Mechanical Behaviour of Cut-Curved Cold-Formed Steel Channel Slender Compression Member

[1]Mohd Syahrul Hisyam Mohd Sani, [2]Fadhluhartini Muftah,
[3]Cher Siang Tan and [1]Mohd Fakri Muda
[1]Faculty of Civil Engineering, Universiti Teknologi Mara Pahang, Pahang, Malaysia
[2]Faculty of Civil Engineering, [3]Forensic Engineering Centre,
Faculty of Civil Engineering, Universiti Teknologi Malaysia,
Johor, Malaysia

Abstract: Cold-Formed Steel (CFS) that accepted as structural material in civil engineering activity has been studied for solving the instability phenomena. CFS with lipped and double intermediate web stiffener is selected. CFS is cut in certain height and spacing to form curved section that identified as CFS cut-curved section. CFS is separated into two samples with a variety of heights of compression member that known as CFS normal and cut-curved section. The mechanical behaviour of both samples with slender section is determined. From the observation and testing, the percentage difference between CFS normal and cut-curved is stated of 30-39%. This reduction is reasonable and practical because the reduction of ultimate load still below half of the ultimate load of CFS normal section. The web and flange deformation is determined by using transducers, noted to have the large deformation and concluded fail due to local buckling in early stage and global buckling in final stage.

Key words: Mechanical behaviour, cut-curved, cold-formed steel, compression member, global buckling

INTRODUCTION

Cold-Formed Steel (CFS) is a structural material that produced by rolling, pressing and shaping in room temperature. The varieties of shape such as channel, zee, angle and hollow section and dimension of CFS is proposed. The innovative cross-section shape is established and optimised for their particular application (Ma *et al*., 2015). Now a days, a lot of construction and civil engineering work are shifted to CFS because its advantages and lightweight. CFS have been utilised in residential houses, building, highway product, storage racks and steel tower. With the complete reference standard, either by using Eurocode 3 or American Iron and Steel Institute (AISI), CFS becoming more popular when compared with others. The instability issue of CFS is important that must be encountered to ensure the CFS is stiff enough and safe from failure. Most slender CFS with open cross-section is highly exposed to buckling phenomena (Dinis and Camotim, 2011). Consequently, many researchers are studied the new and complex shape and also the manufacturing process to cater the CFS problems especially the buckling issues. The innovative cross-section shape is established and optimised for their particular application (Ma *et al*., 2015). Here, one of the ideas to solve the CFS problem by establishing the CFS with curve section.

CFS with curve section is not popular since there is not suitable equipment and expertise in this area. CFS with curve section is also still being studied by researchers. Normally, the steel curve section is used as a chord member of roof truss, frame, bridge deck and arch. Steel curve is formed by hot-curving, cold-curving and cut-curving method. CFS is curved by cut-curving method that can reduce cost of production with no use of expensive equipment and skilled workers. In addition, the hot-curving method is not suitable for CFS with thin section that can produce initial distortional buckling and high of residual stress. CFS with curve section turns into critical in the analysis and design of structural element that must be follow the architectural demand and ideas. However, there is no information about the design flow, standard and analysis of CFS with a curve that required for steel manufacturer and engineer. Dimopoulos and Gantes (2008) have reported there are no design information and provision about the analysis and design of steel arches in Eurocode 3.

Corresponding Author: Mohd Syahrul Hisyam Mohd Sani, Faculty of Civil Engineering, Universiti Teknologi Mara Pahang, Pahang, Malaysia

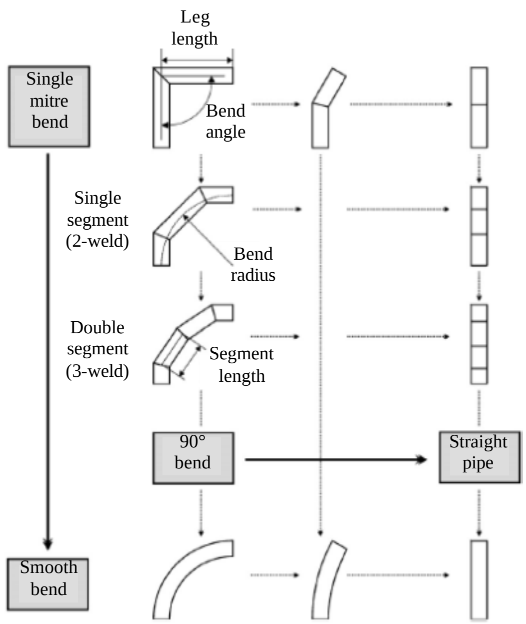


Fig. 1: Comparison between mitred pipe bend and smooth pipe bend (Wood, 2008)

Cut-curving is using the electric saw, clamp and bender machine to curve according to the length and angle of the curve. Usually, the cut-curving process mimics the mitred pipe method that curved by using a large unit of cut segment length to form smooth bend pipe. Figure 1 is the example of the cut-curving that can be a reference in the study. Cut-curving is easy to produce in a construction site or any locations with desirable length and rise of the curve. Sani *et al.* (2015) have studied the cold-formed cut-curved steel channel with 600 mm height of the column and noted having a reduction in compressive strength around 21.26% when compared with normal section.

CFS with cut-curved section is proposed as a compression member to investigate the mechanical behaviour. The compression member is classified as a column, arch or top/bottom chord of a roof truss. Many researchers are studied broadly about the CFS as a column or a compression member to check the buckling failure or other failure that occurred. They are studied with different shape, size, height and dimension that be used as a reference guide in design and analysis. A CFS column of stub column is failing due to local buckling and slender column fail due to global buckling or sometimes known as flexural-torsional buckling. Martins *et al.* (2015a) have reported the failure of the channel with lipped column is related to local, distortional and global buckling as shown in Fig. 2.

Madeira *et al.* (2015) have studied the optimal design of CFS columns of lipped channel and z-section due to

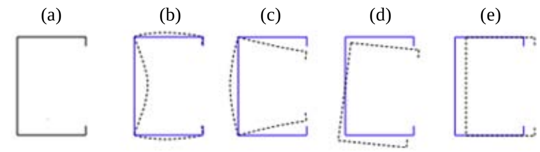


Fig.2: The buckling shape of the channel with lipped column: a) Normal; b) Local; c) Distortional; d) Flexural-torsional and e) Flexural buckling (Martins *et al.*, 2015b)

the effect of local, distortional and global buckling load. The second moment of area of the cross-section is the most important parameter in determining the maximum of the local-global strength (Madeira *et al.*, 2015). Many researchers have studied about the CFS channel section without or with lipped or stiffeners that effected to local, distortional and global buckling such as (Martins *et al.*, 2015; Ellobody, 2013; Camotim and Dinis, 2011; Gunalan and Mahendran, 2013; Leng *et al.*, 2014; He and Zhou, 2014). Furthermore, several researchers also have investigated the steel curve beam members and arch that be applied in civil engineering work for instance (Pi and Bradford, 2014; Guo *et al.*, 2015, 2016; Spoorenberg *et al.*, 2012; Heidarpour *et al.*, 2012; Pi and Bradford, 2004). Pi and Bradford (2003) have mentioned the steel arch could be buckled in flexural-torsional buckling when subjected to uniform compression and the central torsional restraint is created torsional and also out-of-plane bending restraint actions. Lastly, the main objective of the study is to determine the mechanical behaviour of compression member of CFS cut-curved section and compare with CFS normal section.

MATERIALS AND METHODS

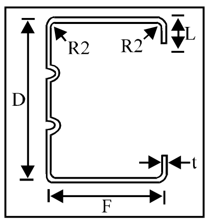
Cold-Formed Steel Channel (CFSC) with web (D) of 75.0 mm, Flange (F) of 34.0 mm, Lipped (L) of 8.0 mm and thickness (t) of 1.0 mm was selected. CFSC with grade 550 Mpa and elastic modulus of 200 Gpa was used. The section properties of the CFSC with double intermediate web stiffeners were illustrated in Table 1.

The CFSC normal section was cut to length 1000 mm, 1500 and 2000 mm. Although, the CFSC normal section was cut to a width of 3 mm, depth of 60 mm and spacing 100 mm was produced to form CFSC pre-cut-curved section. Then, the pre-cut-curved was bended by using a G-clamp, hand bender and strengthens the curved section by using welds. The location of the weld was situated along the bottom flange and spot welds on the double intermediate web stiffeners as shown in Fig. 3 and 4. For the spot weld, 4 times tapping of spot weld was located

Table 1: The six samples of description and labels

Description of samples	Sample labels
CFSC normal section with length 1000 mm	CFSN1
CFSC cut-curved section with length 1000 mm with partially weld	CFSPCC1
CFSC normal section with length 1500 mm	CFSN1.5
CFSC cut-curved section with length 1500 mm with partially weld	CFSPCC1.5
CFSC normal section with length 2000 mm	CFSN2
CFSC cut-curved section with length 2000 mm with partially weld	CFSPCC2

Section dimention and properties



Remarks/units	Values	Remarks/units	Values
Area (A) (mm^2)	148.00	Yield strength (ys) (mPa)	550.00
Mass/uni+length (kg/m)	1.19	Centriod (mm)	11.07
F/t = b/t	34.00	D/t = h/t	75.00
D/F = h/b	2.21	L/t = c/t	8.00

Fig. 3: The section properties of CFS channel

Fig. 4: The location of the weld at bottom flange and double intermediate web stiffeners

at the bottom and top intermediate web stiffeners for strengthening the curved section. Total sample for the testing is six samples including CFSC normal and cut-curved section. Table 2 was tabulated the description of sample and labels. The CFSC cut-curved section was noted to have a rise and the angle of curved is shown in Table 3. Rise-to-span ratio was also shown in Table 3 that can be checked the effect on buckling of the column. The work flow of production of CFSC cut-curved is illustrated in Fig. 5.

CFSC normal and cut-curved section was placed on steel frame with lateral bracing and added with load cell and hydraulic jack were used in the testing. The steel plate and angle was situated on the bottom and top of the column sample and recognised as semi rigid end support. The self-drilling screw was used as a fastener to joint between the end support and sample. Three of Linear Variable Displacement Transducers (LVDT) were utilised to measure the axial shortening of the compression member, displacement of the centre of the web and flange element. The slenderness ratio was calculated and recorded as 77.3, 115.9 and 154.6 for 1000, 1500 and 2000 mm, respectively. All samples were classified as slender column because the value of the ratio is >40.0. The geometry imperfection and residual stress of all samples was neglected.

Table 2: The rise and angle of CFSC cut-curved samples

Sample	Height H (mm)	Rise of curved r (mm)	Angle of curved, θ (°)	Rise-to-Height ratio (r/H)
CFSPCC1	1000	105	15	0.105
CFSPCC2	1500	185	20	0.123
CFSPCC3	2000	300	25	0.150

Table 3: The experimental result of CFSC normal and cut-curved column

Sample	Ultimate load (kN)	Percentage difference	Compressive extension at ultimate load (mm)	Failure mode
CFSN1	39.20		9.04	GB
CFSPCC1	24.00	38.78	6.16	GB
CFSN1.5	31.20	30.77	9.57	GB
CFSPCC1.5	21.60		13.10	GB
CFSN2	25.20	38.10	6.36	GB
CFSPCC2	15.60		19.38	GB

GB = Global Buckling

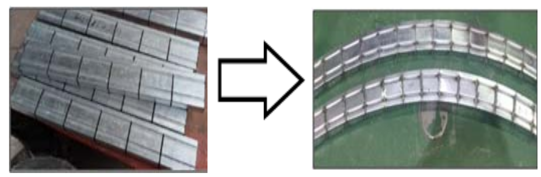


Fig. 5: The workflow of the CFSC cut-curved section

RESULTS AND DISCUSSION

Mechanical behaviour of compression member: There are total of 18 columns were tested and average for every sample were occupied for discussion. The result of all samples was tabulated in Table 4. From Table 4, percentage different of ultimate load between the CFSN1 and CFSPCC1 was recorded about 38.78, 30.77 and 38.10% of percentage different of ultimate load was noted between CFSN1.5 with CFSPCC1.5 and CFSN2 with CFSPCC2, respectively. All percentage different between normal and cut-curved section was distinguished <50.00% and reported reasonable strength reductions. The ultimate load of normal section was decreased when the height of the column increased. The reduction percentage of CFSN1

Table 4: The comparison result between experiment and other codes

Sample	Experimental (Exp) Ultimate load (kN)	Direct Strength Method (DSM) Ultimate load (kN)	Comparison P_{Exp}/P_{DSM}	Eurocode 3 (EC3) Ultimate load (kN)	Comparison P_{Exp}/P_{EC3}
CFSN1	39.20	47.84	0.819	44.73	0.876
CFSN1.5	31.20	41.34	0.750	36.84	0.847
CFSN2	25.20	28.69	0.878	30.94	0.814

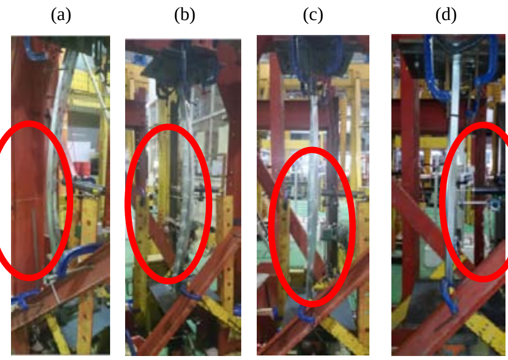


Fig. 6: Example of the failure shape on experimental activity: a, b) cut-curved section of 1.5 m; c, d) normal section of 1.5 m

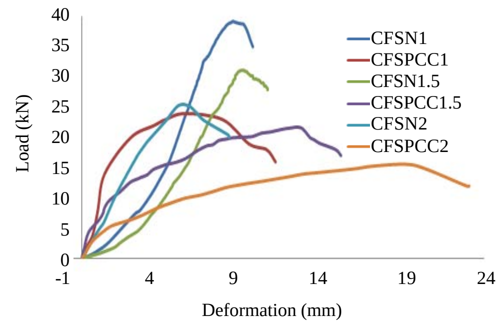


Fig. 7: The axial shortening of the compression member

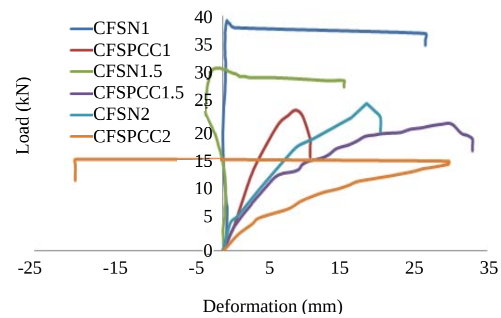


Fig. 8: The load versus deformation of flange element when subjected to compression load

with CFSN1.5 and CFSN2 was determined about 20.41 and 35.71%, respectively. Additionally, the ultimate load of cut-curved section also reduced when the height of compression member was increased. The percentage different of ultimate load was decreased approximately 10.00% when compared between CFSPCC1 with CFSPCC 1.5 and 35.00% when compared between CFSPCC1 with CFSPCC2.

The compressive extension at ultimate load of CFSN1.5 was noted the highest value and CFSN2 was shown the lowest value among the normal section. Furthermore, the highest and lowest value of compressive extension at ultimate load was reported of CFSPCC2 and CFSPCC1. This is because the probability of the sample with highest height to twist and fail due to global buckling was determined very high. From the observation, the compressive extension at ultimate load of cut-curved section was reported increased with increasing the height of the compression member. All samples are failed due to global buckling as shown in Fig. 6 and the red circle line showed the failure on the middle of the height.

Figure 7 shows the load versus axial shortening of the compression member based on LVDT. It showed that the graph pattern of all samples of the normal section is same but the CFSN2 is slightly showed highest of initial stiffness when compared with CFSN1 and CFSN1.5. Graph pattern of all cut-curved section also showed a same pattern among them.

Deformation of flange element of the compression member: Figure 8 is shown the load-deformation of a flange element of compression member. The CFSN1 is illustrated very stiff when subjected to compression load before achieved ultimate load. After meeting the ultimate load, the CFSN1 is becoming weak and fail due to global buckling. The flange element was gone out of the origin shape. CFSN1.5 and CFSPCC2 was stated to have the positive and negative way and sign due to the unstable flange element. Flange element was moved inside and outside of the origin cross-section.

Deformation of web element of the compression member: The load-deformation graph based on LVDT is illustrated in Fig. 9. All samples are noted to deform positive or tension by subject to compression load. CFSPCC2 sample is only reported to have the negative and fluctuated line when load is set between 5.0-15.0 kN. This is because the cut-curved with highest height was failed due to extremely local buckling. After achieving 15.0 kN, the sample is changed from local buckling to global buckling with moving to the other side of the web origin surface. The line pattern of the CFSN1 and CFSN1.5 is same but the

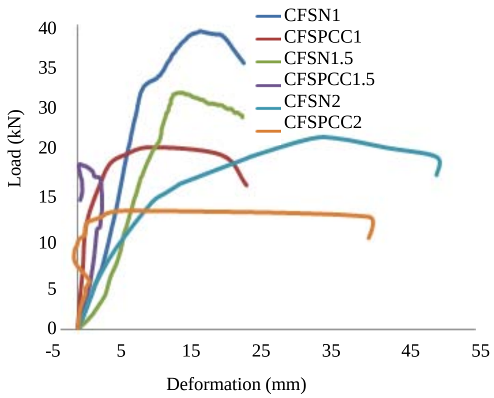


Fig. 9: The load versus deformation of web element when subjected to compression load

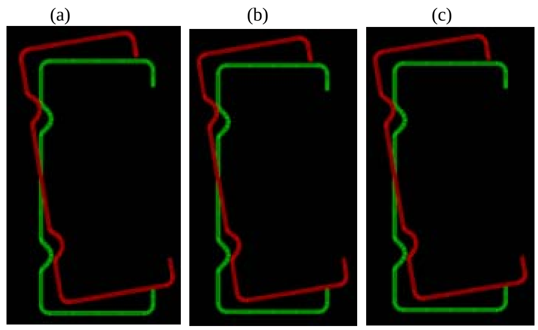


Fig. 10: The failure mode of CFS normal section from the DSM prediction of: a) 1000 mm; b) 1500 mm and c) 2000 mm

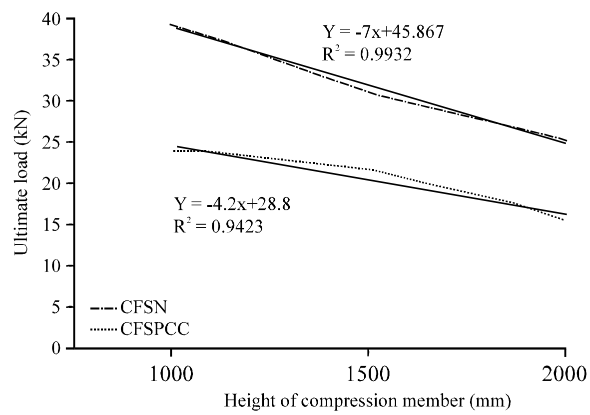


Fig. 11: The relationship graph between the ultimate load and height of compression member

CFSN2 is changed of initial stiffness of the web element due to the high value of height. This can be concluded, the CFSN1.5 was selected as the optimum height that produced the initial failure of local buckling and stated the good performance in web deformation. CFSPCC1.5 was stated to have the web deformation in different position and way of buckled, it moved inside of the cross-section. Therefore, another sample is moved outside of the cross section. CFSPCC1 was noted to have the highest value of initial stiffness when compared with normal section. This is because the strengthen method of the weld was appropriate to prevent initial local buckling and influence the restrained on web deformation in early stage. So that the CFS with cut-curved could be the new method to resist the local buckling when compared with normal section.

CFSPCC1 with welding on both sides of intermediate web stiffeners was reported solving the local buckling on the early stage. As reported by Ma *et al.* (2015) the intermediate web stiffeners could be diminished the effect of local buckling but still can't interacted of local-global buckling.

Comparative study of the compression member: The CFSC normal section was compared with the Direct Strength Method (DSM) prediction that acquired by using software THINWALL and Eurocode 3. The comparison ratio between experimental data and DSM was reported 0.819, 0.750 and 0.878 for 1000, 1500 and 2000 mm, respectively as shown in Table 4. Besides, the ratio of experimental with Eurocode 3 was reported 0.876 for 1000 mm, 0.847 for 1500 mm and 0.814 for 2000 mm. All samples either experiment or DSM or Eurocode 3 was stated having global buckling. Figure 10 was illustrated the failure shape of the CFSC normal section of DSM. It showed that the CFSC normal section moved out from the origin but the centre of the section still in position. Flange element was noted to have the large deformation on both flanges. Web element was observed to have large deformation in early stage because due to local buckling and lastly fail headed for overall buckling. By referring of DSM, the nominal strength of CFS columns is investigated through the minimum among three strengths which are determined by the elastic critical and yielding load. Elastic critical loads are including local, distortional and global.

If compare the result of experimental Gunalan and Mahendran (2013) result for lipped channel section with web of 55 mm, flange of 35 mm, lipped of 8 mm, thickness of 0.95 and a grade of 550 MPa, the percentage difference is approximately 1.98% for length 1800 mm and 36.90 % for length 2800 mm. It showed that the result of the experiment was noted reasonable and practical result.

The relationship between the CFS normal and cut-curved along the height of the compression member was illustrated in Fig. 11. Both sections were demonstrated having the linear relationship. The equation for checking the ultimate load of CFS normal and cut-curved section was proposed. For CFS normal section of slender compression member:

$$\begin{aligned} &1000 \leq H \leq 2000 \\ &\text{Ultimate load, } P_{ULT} = -7H + 45.867 \end{aligned} \quad (1)$$

For CFS cut-curved section of slender compression member:

$$\begin{aligned} &1000 \leq H \leq 2000 \\ &\text{Ultimate load, } P_{ULT} = -4.2H + 28.8 \end{aligned} \quad (2)$$

where, H = height of the compression member.

CONCLUSION

From the study, a number of conclusions can be drawn: CFS normal and cut-curved section of slender compression member can be determined the percentage different of ultimate load of range 30.00-39.00% for 1000-2000 mm. The ultimate load of CFS normal and cut-curved decreased when the height of the compression member increased. Compression extension of CFS cut-curved for 1000 mm is reported smaller than the CFS normal section. All samples are noted failing due to global buckling and verified by using DSM and Eurocode 3 for the CFS normal section. The experimental result showed the reasonable and appropriate data when compared with the previous researcher result. The prediction of ultimate load of CFS normal and cut-curved can be determined by using Eq. 1 and 2.

Web and flange deformation of CFS normal and cut-curved section is reported having tremendous deformed after achieving the local buckling phenomena. CFSPCC of 1000 mm is illustrated having good restrain of local buckling when compare with CFS normal section.

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