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STRENGTHENING METHOD AND STRUCTURAL PERFORMANCE OF COLD-FORMED CUT-CURVED STEEL UNDER COMPRESSION

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Graphical abstract

Abstract

Cold-formed steel section (CFSS) is a popular material in the steel structure that has been recognised in construction work. CFSS with curved section is a new section that proposed in the CFSS and still being studied by researchers. Steel curved section, whether by using hot-rolled or cold-formed steel become essential and significant in the design that be suited by the architectural demand. For this reason, the CFSS is recommended to provide the curve in the structure and dispute the use of the hot-rolled steel. In the study, the CFSS is curved by using a clamp, small bender and welding machine. Through this process, CFSS with cut-curved (CFSS-C) is strengthened by welding in particular location at flange and web. The CFSS-C are established into five specimens with different of welding location and added with one normal specimen (CFSS-N) as a control specimen. The CFSS is tested for the structural performance of the column specimens with the height, 1000 mm under compression load and lastly the suitable strengthens method with highest of ultimate load is selected. From the testing, CFSS-C4 is reported to decrease about 32.26 % when compared with normal specimen.

Keywords: Cold-formed steel, cut-curved, structural performance, compression

1.0 INTRODUCTION

Cold-formed steel section (CFSS) is the structural and non-structural material that formed by steel based material. The CFSS has been recognised in Malaysia, especially in the roof truss system, frame, storage rack and highway accessories product. Nowadays, CFSS is studied by researchers for proposing as a beam, wall panel, slab, retaining wall, column and etc. The study of CFSS has become popular due to their performance and advantages when compared with other material. Some example of the CFSS is a lightweight material, fire resistance, termite resistance and corrosion resistance. Whilst, the broadly usage in construction is hot-rolled steel is reported having a lot of disadvantages such as heavy, thick and failure due to corrosion.

CFSS with curve section is still being studied by researchers and tried to replace the traditional material such as hot-rolled steel and timber in the roof truss system and frame. The CFSS with curved is becoming critical and important to propose the best match to the architectural drawing and demand. In the hot-rolled steel, the method of curving section is divided into various methods for instance cold-curving by using rollers, hot-curving by using heat and cut-curving by using cut and weld. Therefore, in the study, the cut-curving method is selected. This is because the cold-curving is not suitable for CFSS because the section is thin, need the sophisticated machine and lastly it's provided the new imperfection for the section. Besides, the hot-curving by using heat also not suitable because the CFSS section is thin and need special tools.

CFSS with curve section provides a lot of advantages in construction due to long span, stability and less deformation. Sometimes, the steel curves can be recognised as curved beam or arch. Steel arch is broadly utilised in the built environment for long-span structure such as airport terminal roof and bridges [1]. Curved steel tubes have been used commonly in large-span and bridge structures, for example stadiums and bridges because of economic and aesthetic issues [2]. Normally, the arch is provided as a good shape of aesthetically and a structure that can eliminate tensile stress to give more open space [3]. In steel arch is separated in different of shapes as shown in Figure 1. In addition, Tran *et al*. [4] has noted the curved panels in structures are offering an aerodynamic potential and attractive aesthetic criterion.

Spoorenberg *et al*. [5] has reported arch is classified as an unstable condition when the local buckling is not considered. The instability of the arch is considered into three circumstances is known as in-plane buckling, out-of-plane buckling and snap-through buckling [6]. They also reported out-of-plane buckling is well considered in elastic buckling behaviour that material non-linearity and imperfection was ignored. El-Mahdy [3] has reported the stability of a steel arch can be depicted by determining the buckling in or out of the plane of the structure. In-plane buckling exists when the steel arch is braced resist out-of-plane displacement and out-of-plane buckling exists with unconnected and separate parts. In-plane buckling is related to combination of compression and bending [3]. Whilst as, out-of-plane buckling is linked with combination of compression, bending and torsion [3]. With lack of sufficient bracing and increased slenderness, the arch is often exposed to instability conditions [6].

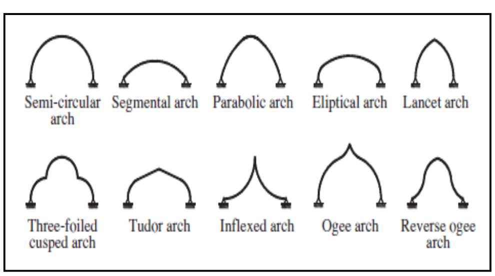


Figure 1 The shapes of arches in construction [3]

There's a lot of research that reported about the steel arch as the structure and also steel arch failed due to buckling phenomena. Guo *et al*. [7] have reported having fifteen arches with constant length and angle of arch from 90^0 to 180^0 are examined under a concentrated load. Virgin *et al*. [8] have examined the structural behaviour of a shallow arch and the sensitivity of it when exposed to changes in the thermal environment. Buckling problems of the arch are normally affected by changes in configuration such as imperfection, load application, boundary condition and lastly symmetry [8]. Buckling loads of the arch are reduced by increasing of rise-span ratio [9]. Dou and Pi [10] have concluded the flexural-torsional buckling of the arch is influenced by the rise-span ratio and also could differentiate arches from the column. Besides, Dou *et al*. [11] have explained in detail about the phenomena of flexural-torsional buckling of steel arch is recognised by a combination of out-of-plane and in-plane deformation and rotation. Sometimes, the steel arch is twisted and warping of cross section [11].

From all information of steel curved and arch, the study of cold-formed cut-curved steel channel section subjected to compression load is started. The main aim of the study is to determine the suitable strengthen method for cut-curved column specimen based on their structural performance especially the mechanical behaviour of the column. The cut-curved specimen has compared the structural performance with the normal section of the column.

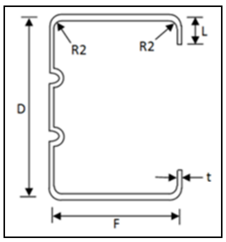
2.0 EXPERIMENTAL ACTIVITY

Cold-formed steel channel section with lipped and intermediate web stiffeners was selected. The section properties of the CFSS are illustrated in Table 1. CFSS was clean and cut to length, 1000 mm for the normal CFSS column. For curved section, Firstly, the CFSS was cut with height, 60 mm from the bottom flange to second intermediate web stiffeners. The length between cut sections to another cut section was recorded 100 mm and with width of cut section, 3 mm. The electric saw was used in the study. Then, CFSS was bended by using the bender machine and directly strengthened by using spot weld and full weld. The location and position of the weld were studied to determine the method that produced the highest ultimate load. The several of method of strengthening the curved section was proposed and shown in Table 2. There are five methods of strengthening the curved section and compared to the normal section as shown in Figure 2. Lastly, the CFSS curved section was ready to test and noted to have length, 1000 mm, 105 mm of rise and 15^0 angle of curved. Rise-to-span ratio of the specimen is approximately 0.105 and this issue can have an effect on buckling of the column. Steel frame with bracing, load cell and hydraulic jack were used in the experiment. Three displacement transducers were used to record the displacement at middle flange, middle web and axial shortening as shown in

Figure 3. The slenderness ratio is calculated 77.28 that more than 40.00 and classified as slender column. Spoorenberg *et al*. [6] has stated the arch is treated as a straight normal column under compression with the same of cross-section and identified the arch length corresponded with the column length in slenderness calculation. Strengthen method of the cut-curved section can be determined by choosing the sample that produced higher of ultimate load and good in deformation. The geometry imperfection and residual stress factor for all specimens is ignored.

Table 1 The section properties of CFSS

Section dimension and properties



Remarks	Units	Value	Remarks	Units	Value
Web, *D*	mm	75.00	Flange, *F*	mm	34.00
Lipped, *L*	mm	8.00	Thickness, *t*	mm	1.00
Area, *A*	mm^2	148.00	Yield Strength, *ys*	MPa	550.00
Mass/unit length	kg/m	1.19	Centroid	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

Table 2 Method of strengthening the curved section with specimen labels

No.	Description of Specimen	Specimen label
1	Straight normal channel section	CFSS-N
2	CFSS cut-curved section and strengthen by full weld along the middle web but without weld at corner flange and bottom web.	CFSS-C1
3	CFSS cut-curved section and strengthen by full weld along the gap of cut section	CFSS-C2
4	CFSS cut-curved section and strengthen by welding at bottom flange and spot weld at every intermediate stiffeners	CFSS-C3
5	CFSS cut-curved section and strengthen by welding at middle web, bottom intermediate stiffeners and bottom flange	CFSS-C4
6	CFSS cut-curved section and strengthen by partial weld	CFSS-C5

Subsequently, the CFSS was cut into the shape of coupon tensile specimens and tested by using Universal Testing Machine with a capacity of 100 kN. The testing was followed the BS EN 10002-1:2001 [12]. The coupon tensile specimens were taken from the flat part of the web and flange. This testing is important to ensure the material properties of CFSS were suited to the design strength material.

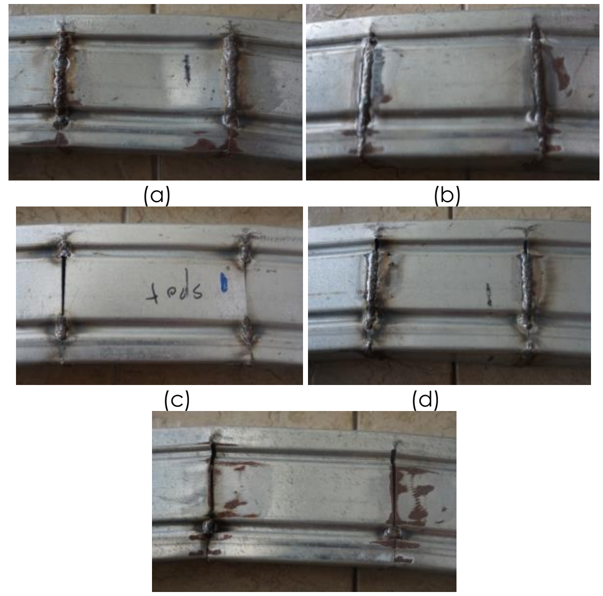


Figure 2 Side elevation of the specimen of a) CFSS-C1 b) CFSS-C2 c) CFSS-C3 d) CFSS-C4 and e) CFSS-C5

(a) (b)

Figure 3 Schematic diagram of compression column testing for a) normal section and b) curved section

3.0 RESULT AND DISCUSSION

3.1 Material Properties

The CFSS flat coupon tensile specimen at web and flange was tested and the result was shown in Table 3. The percentage difference of ultimate load and yield stress between the web and flange were calculated more or less 2.82 % and 3.05 %, respectively. The ductility of the CFSS is determined by using the ratio of *fu/fy* and checked whether the steel is brittle or not. The ratio of *fu/fy* of the web and flange was stated same and more than 1.10 and classified as a good ductility.

Table 3 The material properties of CFSS coupon tensile specimen

Sample	Ultimate Load (N)	Ultimate stress, *fu* (MPa)	Elastic Modulus, *E* (GPa)	Extension at Ultimate Load (mm)	Yield Stress, *fy* (MPa)	Yield Stress factory, *fyf* (MPa)	*fu/fy*	*fu/fyf*
Web	6906.53	603.67	204.00	4.53	550.03	550.00	1.10	1.10
Flange	7106.87	628.48	206.00	5.27	567.38	550.00	1.11	1.14

3.2 Mechanical Properties

A total 18 CFSC columns were tested and average result were taken for difference of all specimens. The result of all specimens, including the normal section is tabulated in Table 4. From the table, CFSS-C4 showed the highest ultimate load among the other cut-curved specimens. This is because the location of weld at web and flange that being cut is considerably supported back the specimen to become strong enough and resist the compression load. The percentage difference between the CFSS-C4 with CFSS-N specimen is calculated approximately 32.26 %. There are two specimens with different percentage of range 62.00 % - 66.00 % is recognized as CFSS-C1 and CFSS-C3 specimen, respectively when compared with normal section. The lowest of ultimate load among the cut-curved specimen is CFSS-C5 and CFSS-C2 with 75.47 % and 76.00 %. CFSS-C5 specimen with partial weld is not enough to sustain the compression load and showed that the location of the weld is not suitable and adequate to strengthen the overall structure. Although the CFSS-C2 specimen with a lower ultimate load is also can't be chosen as a good method because the specimen is having the initial distortion. The cold-formed steel is not suitable to weld along the cut because the material is so thin and probability to distort after weld. The residual stress is existed along the location of full weld and able to reduce the ultimate load radically.

All cut-curved specimens is shown to decrease the value of the compressive extension at ultimate load and remarked as the new solution in compression of the column when compared with CFSS-N. By referring to Table 4 and Figure 4, CFSS-C5 showed the lowest of compressive extension and noted about 78.25 % when compared with normal section. CFSS-C5 is not appropriate as a good in deformation because the specimen curve graphs are not uniform and vary for each load imposed. 49.85 %, 36.35 %, 9.53 % and 47.96 % of percentage difference of CFSS-C1, CFSS-C2, CFSS-C3 and CFSS-C4, respectively when compared with CFSC-N. From Figure 4, the pattern of line graph of CFSS-C1, CFSS-C2 and CFSS-C3 is shown similarly, but CFSS-C5 is illustrated having an inconsistent line. This is because the location of the spot welds at the bottom intermediate stiffeners could not support the specimen to distort in early stage. Furthermore, CFSS-C4 and CFSS-N is reported to have the same pattern and more or less same in initial stiffness prediction.

For verification, the ultimate load of CFSS-N is compared with Eurocode 3 and Direct Strength Method (DSM). The value of DSM is calculated by using THINWALL software. The value of ultimate load is 47.00 kN and 30.69 kN for Eurocode 3 and DSM, respectively. The percentage difference between experimental with Eurocode is 20.21 % and with the DSM is 18.16 %. The failure prediction that occurred from DSM is same as experimental observation. The deformation of the overall element by DSM is shown in the Figure 5. The web and flange are moved out of the origin shape and likely twist to another position. All specimens are stated to have local buckling in beginning and lastly failed due to global buckling as shown in Figure 6. Red circle in the Figure 6 illustrates the highest location of failure for normal and cut-curved specimen. By using the Euler buckling formula, the ultimate load of the CFSS-N is 59.00 kN. Euler buckling is referred to material elastic with consistent cross-section, but the real situation the CFSS-N column may fail due to material yielding and geometrical deformation. Finally, Euler buckling is inappropriate to predict the failure of the CFSS column.

Table 4 Result of normal and cut-curved column section

Specimen labels	Ultimate Load (kN)	Ultimate Stress (MPa)	Compressive extension at ultimate load (mm)	Observation failure mode
CFSS-N	37.50	253.38	10.07	GB
CFSS-C1	12.70	85.81	5.05	GB
CFSS-C2	9.20	62.16	6.41	GB
CFSS-C3	14.00	94.59	9.11	GB
CFSS-C4	25.40	171.62	5.24	GB
CFSS-C5	9.00	60.81	2.19	GB

Note: GB – Global buckling

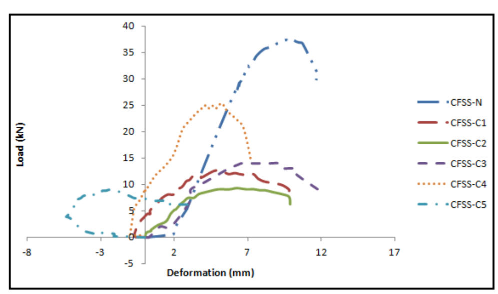


Figure 4 Axial shortening of the specimen

Figure 5 The failure shape of the DSM prediction

Figure 6 The failure mode of global buckling for normal and cut-curved section

3.3 Flange and Web Deformation

Flange and web deformation of the specimen is illustrated in Figure 7 and Figure 8. Flange and web deformation for CFSS-N is recorded to have the higher line graph when compared with specimen with cut-curved. The specimen with cut-curved is shown without any movement in negative sign, but the normal section is moved inward in beginning due to high failure of local buckling. This is because the normal section had a movement in inward and outward that without any welding location at flange element. The CFSS-N and CFSS-C4 is stiffer in flange deformation when compared with other specimen. From observation and graph, CFSS-C4 is reported low value of local buckling failure in the beginning. All cut-curved specimens are more deformed that achieved more than 5 mm while, the CFSS-N is achieved less than 5 mm for ultimate load. All cut-curved specimen exclude CFSS-C4 is showed a similarity in line graph pattern. This can be concluded; the flange deformation for all cut-curved specimens is noted having a superior in deformation until reach the ultimate load. The experimental observation and prediction by DSM and Eurocode 3 that stated a buckling shape of global buckling is proven by the large deformation of the flange. Normally, the global buckling is placed when the flange of the bottom and top is moved out from the origin shape with less of shortened and elongated.

Web deformation of the normal section is more than all cut-curved specimen due to high of sustained load. The web of CFSS-N is deformed linearly from initial load until 30 kN and after that deformed in parabolic shape. This is because the web of the specimen in the initial stage is failed due to local buckling and suddenly is changed to become global buckling. In addition, all specimens exclude the CFSS-C2 is dramatically deflected in positive sign and totally subjected to global buckling. All cut-curved specimen is stiffer when compared with the normal specimen. The line graph pattern still showed similar for all cut-curved section excludes CFSS-C4. This is because the welding location on the web is appropriate to avoid or decrease the local buckling in the early stage of the applied load. Web deformation value of the CFSS-N at ultimate load is more than all specimens of cut-curved.

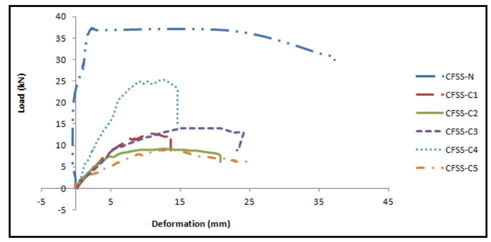


Figure 7 Flange deformation of the specimen

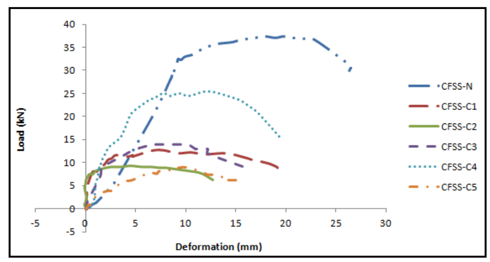


Figure 8 Web deformation of the specimen

3.4 Relationship of the Welds along the Web Element

From the experimental result, the relationship between weld on the web element is discussed. There are two parts of the discussion could be taken for further expression. First part is the location or position of the weld on the web element and the second part is the length of weld along the web element. Location of the weld on the intermediate stiffener whether at the bottom or upper sides is being studied. If the location of the weld at only at the bottom intermediate stiffener, the ultimate load is low when compared with welding at the bottom and upper sides approximately 35.71 %. The middle of the web along flat element from bottom to upper side of intermediate stiffener is discussed. The weld on middle web, upper and bottom sides of intermediate stiffener is decreased the ultimate load around 50 % when compared with the weld on middle web and bottom side of intermediate stiffener. This can be concluded that the weld at the bottom side of intermediate stiffener and middle web is more suitable when compared with other location of the weld.

The relationship of the length weld is broadly discussed based on the ratio of length of weld at web divide with length of weld at the flange. The

CFSS-C1, CFSS-C2, CFSS-C4 and CFSS-C5 only selected in the second part. Length of weld between the specimens is recorded 10 mm for CFSS-C5, 42 mm for CFSS-C4, 52 mm for CFSS-C1 and 60 mm for CFSS-C2. Here, the graph of the relationship between the ratio of length of web per length of flange and ultimate load is calculated and shown in Figure 9. The graph showed the ultimate load of specimen is increased linearly from a ratio of 0.29 to 1.24. Furthermore, the equation of relationship of initial part is established as Eqn 1 for further study. After achieving a ratio of 1.24, the ultimate load of specimen is decreased when the length of the web is greater than before.

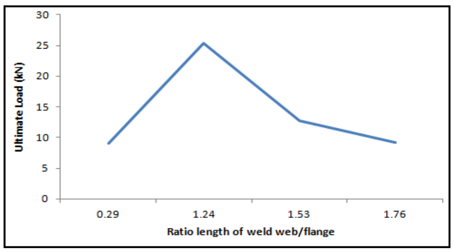


Figure 9 The relationship graph of ultimate load versus the ratio of length of weld at web per flange

$0.29 \leq r \leq 1.24$

Ultimate load, $F_{ULT} = 16.4\,r - 7.4$ (1)

Where, r – ratio of length of weld at web per length of weld at the flange

4.0 CONCLUSION

A series of specimen in experimental tests are carried out to investigate the strengthen method of cut-curved section and column structural performance. Five specimens with different strengthen method of cut-curved and one specimen of the normal section as controlled specimen is tested. From the results and observation, a number of conclusions can be drawn:

1) CFSS-C4 section that strengthened by welding at middle web, bottom intermediate stiffeners and bottom flange with length 42 mm was selected as a better structural performance in cut-curved specimen. The percentage difference between the CFSS-N and CFSS-C4 is approximately 32.26 % and could be taken as a reduction factor when calculating the buckling resistance. In addition, CFSS-C4 was reported having a good performance in web and flange deformation among the cut-curved specimen.
2) All cut-curved specimens exclude CFSS-C4 were recorded about 62.00 % to 76.00 % percentage reduction in ultimate load when compared with normal specimen. Besides, the entire cut-curved specimens were observed to have the global buckling and less of local buckling phenomena when compared to CFSS-N.

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