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EXPERIMENTAL STUDY ON FLEXURAL BEHAVIOR OF COLD-FORMED STEEL CHANNELS WITH CURVED SECTION

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ABSTRACT

Lightweight and thin-walled cold-formed steel section has become a popular material in building and engineering application. Cold-formed steel sections are available in a variety of thickness, shapes and steel grade. Continual researches have been carried out world widely for cold-formed steel sections with straight profile. However cold-formed steel section with curved profile, which serves both aesthetic and engineering purposes for arch and truss structures, has not been studied in depth. This study aims to investigate the flexural behavior of cold-formed steel channel section with curved profile. Cold-formed steel channel (CFSC) with lips and intermediate stiffeners is selected. The CSFC is cut and bended by clamps, forming into cold-formed steel channel curved section (CFSC-CS). Six specimens of CFSC-CS with different weld and screw profiles are prepared, together with one CFSC section without curved used as controlled specimen (CFSC-NS). The bending behavior, vertical deformation and horizontal deformation of the seven CFSC specimens are determined experimentally. From the results, the flexural strengths for all CFSC-CS specimens are lower than CFSC-NS, with percentage of strength reduction range from 8.79 % to 38.80 %. Among the six curved sections, CFSC-CS with three spot weld locations (CFSC-CS3) indicated the highest ultimate load, i.e. 6.484 kN. CFSC-CS3 shows a potential to decrease the vertical flange and horizontal web deformation, and is capable to protect the section from the flexural torsional and local buckling.

Keywords: cold-formed steel channel, curved section, flexural behaviour, deformation.

INTRODUCTION

Cold-formed steel with thin-walled profile and lightweight advantage is one type of building material, commonly used for non-structure or secondary structure in engineering application. This material is produced by using rolling, pressing, forming and stamping process from sheet steel. With the generic thicknesses range from 0.5 mm to 3 mm, cold-formed steel is becoming a popular choice for roof truss system, replacing the conventional timber material and relatively thick (≥ 4 mm) hot-rolled steel materials. Cold-formed steel sections are available in various shapes, steel grades, dimensions and thickness. The common shapes that used in construction are channel (cee), zee, angle and hat section. Many researchers study on the alternative or innovation sections such as sigma, built-up, back-to-back and common shape with stiffeners. However there are no notable studies on cold-formed steel curved sections.

Curved structural section is proposed for long-span Bridge, large-span spatial structures, roof truss for stadiums, dome and warehouse because of their esthetic appearance and economic issues (Han *et al.* 2012). The design guide for curved steel section is not adequate due to its complex behavior. Curved steel needs in-depth analysis and advanced calculation to provide sufficient information for the design. The arch and curved beam structure are defined by regarding to their position and elevation as shown in Figure-1. Normally, an arch is a structure that curved in elevation or curved in vertical direction of normal structures. On another hand, curved beam is a structure that curved in plan or known as curved in a horizontal direction from normal straight structure. The structure is regarded as a curved beam when one of the supports shows a change to outward spreading (La Poutre *et al.* 2013). When load is applied, three deformation of curved structure could occurred, i.e. snap-through, in-plane buckling and out-of-plane buckling, as shown in Figure-2.

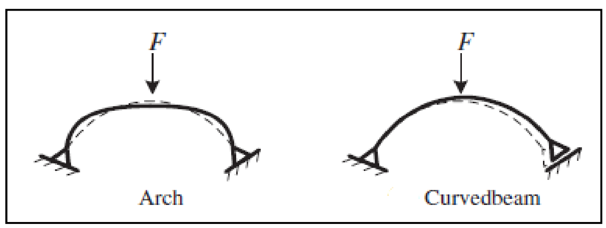

Figure-1. Arch structure and curved beam (La Poutre *et al.* 2013).

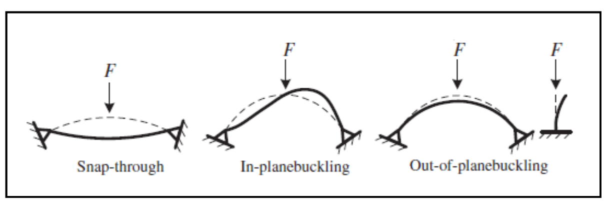

Figure-2. The buckling modes of arch structure (La Poutre *et al*. 2013).

Xu *et al.* (2014) analyzed the bending behavior of the curved concrete filled steel tubular (CCFST) Warren trusses. They found that the CCFST trusses gave larger load-carrying capacity and stiffness when compared with straight concrete filled steel tubular (CFST) trusses (Xu *et al.* 2014). In addition, the CCFST trusses with increment of rise-to-span ratio were showing an increasing elastic stiffness and load resistance as well (Xu *et al*. 2014). Han *et al.* (2012) conducted the axial compression test of curved concrete filled steel tubular (CCFST) built-up section and compared curved hollow tubular built-up column. The study concluded that the stiffness and ultimate strength of CCFST built-up dramatically lessens when the initial curvature ratio and the nominal slenderness ratio are increased (Han *et al*. 2012).

Usually in bridge engineering, the curved section is used as bridge deck by using horizontal curved steel section. Horizontal curved steel bridges are provided aesthetic, cost effective; defend against torsional stresses and deformations through a seismic action (Seo and Linzell 2013). Thanh and Itol (2013) investigated the stability of curved steel bridge railings subjected to the impact of vehicle collisions and also checked the safety of the users. Liu *et al*. (2013) established the non-linear inelastic analysis by using a numerical formula of composite I beams with curved in-plan. Horizontal curvature in plate girders with longitudinal stiffeners was promoted so that the web becomes stable when subjected to flexural loads (Issa-El-Khoury 2014).

Currently there are no notable investigations on cold-formed steel curved sections. Due to insufficient experimental data and research knowledge, this study aims to conduct initial experimental test for cold-formed steel channel curved sections. The study focuses on the bending behavior of cold-formed steel channel with curved sections (CFSC-CS), in comparison to normal cold-formed steel channel section (CFSC-NS) in straight profile. Besides that, the potential of CFSC with curved section is determined to collect the mechanical behavior of the section.

Experimental work

In the study, locally manufactured cold-formed steel channel section with lips and intermediate stiffeners (KS7510) is used, as shown in Figure-3. The section properties are tabulated in Table-1. The same cold-formed steel channel sections were later manufactured into curved section (CFSC-CS). The CFSC normal section was cut with width of 3 mm from the bottom flange until upper stiffeners, i.e. about 60 mm from the bottom of CFSC. In addition, the CFSC was proposed with cut 100 mm lengths centre to centre to produce curved section. The length of each beam is 250 mm following a previous study Kankanamga and Mahendran (2012) which reported that the moment capacity can be taken from the short span beam such as 100 mm, 500 mm and 800 mm. Then, the CFSC cut section was bent and curved by using G-clamp, hand clamp and fabrication equipment to produce CFSC curved section as shown in Figure-4(a). To strengthen the CFSC-CS, weld and self-drilling screw process were established for each CFSC-CS as illustrated in Table-2. CFSC curved section with spot weld of 5 mm diameter on the bottom of the flange by using gas metal arc welding (MIG Welding). Whereas, CFSC curved section with two 4 mm diameter self-drilling screw and one 5 cm width flange plate (with/without lip) cut from same CFSC material placed on the bottom flange of the curved section.

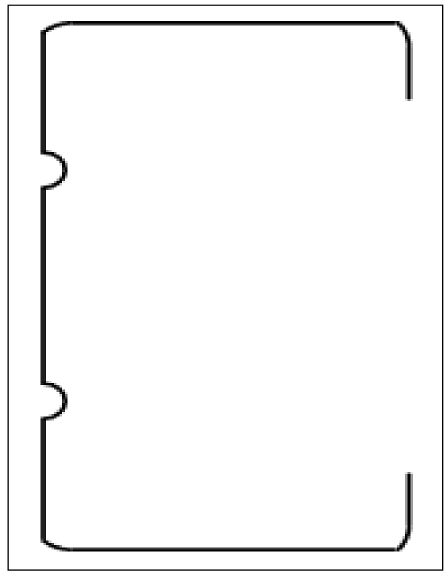

Figure-3. The cross section profile of KS7510.

Table-1. Section properties of KS7510.

Section dimension	**Web, *d*** (mm)	**75.0**
	Flange, *b* (mm)	**34.0**
	Lip, *l* (mm)	**8.0**
	Thickness, *t* (mm)	1.0
Area	A, (mm^2)	148.0
Second Moment of Area	I_{xx} (mm^4)	0.135×10^6
	I_{yy} (mm^4)	0.025×10^6
Second Modulus	Z_{xx} (mm^3)	3.605×10^3
	Z_{yy} (mm^3)	2.240×10^3
Radius of Gyration	R_x (mm)	30.22
	R_y (mm)	12.94
Centroid	X (mm)	11.07
Design Strength	γs (MPa)	550
Dimensional ratio, *b/t*		34
Dimensional ratio, *d/t*		75
Dimensional ratio, *d/b*		2.206

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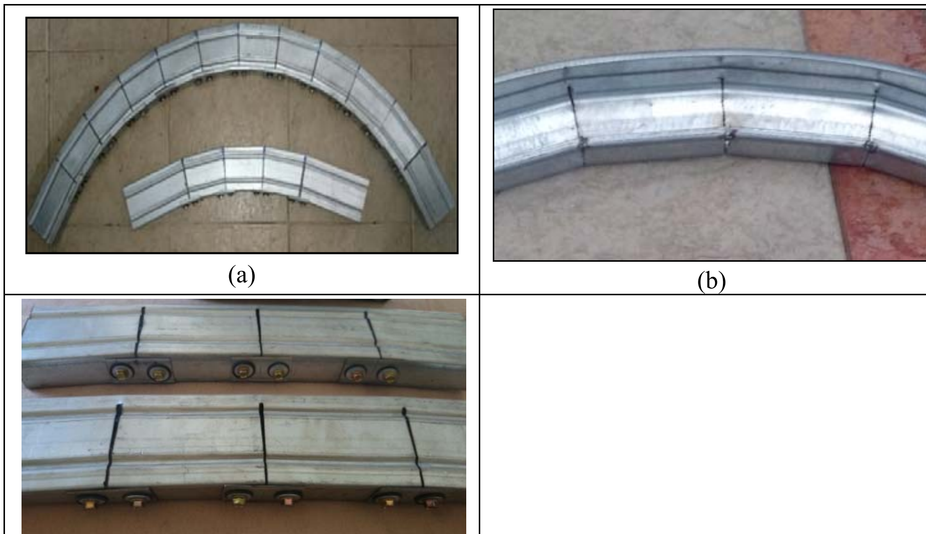

(a) (b) (c)

Figure-4. (a) Example of cold-formed steel channel curved section (CFSC-CS), (b) CFSC curved section with spot weld and (c) CFSC curved section with plate and self-drilling screw.

Table-2. The CFSC curved sections for experimental investigation.

CFSC curved section	Specimen label
CFSC normal section without cut section	CFSC-NS
CFSC curved section without spot weld	CFSC-CS0
CFSC curved section with 1 spot weld	CFSC-CS1
CFSC curved section with 2 spot welds	CFSC-CS2
CFSC curved section with 3 spot welds	CFSC-CS3
CFSC curved section with self-drilling screw and plate without lipped	CFSC-CS-SP
CFSC curved section with self-drilling screw, plate with lipped and 2 spot welds	CFSC-CS-SPW

There are six CFSC-CS were tested in the experimental investigation. The first CFSC-CS was produced by without spot weld, namely CFSC-CS0. The second to fourth specimens are provided with one to three spot welds respectively as shown in Figure-4 (b). Spot weld number one was located at the corner between web and bottom flange. Spot weld number two is placed in middle of bottom flange. Even as, the spot welds number three was sited at the corner between bottom flange and lip. The fifth and sixth specimens were produced by using cold-formed steel plate cut from the identical CFSC section and two self-drilling screws. Plate with lip was used in the sixth specimens, plus additional two different locations of spot weld. The steel plates were cut from the flange with 50 mm length and 25 mm width as shown in Figure-4 (c).

All six CFSC-CS and one CFSC-NS as controlled sample were installed in the universal testing machine and tested for flexural behavior under three point bending. Two pin supports were provided, as shown in Figure-5. Two displacement transducers (LVDT) were used; one placed at the middle of the web, another on the upper flange at 10 mm from the end of specimen. Extensometer and spring deflector was utilized to record the strain on the bottom flange under loading condition. All CFSC-CS was measured with 5^{o} of the horizontal angle.

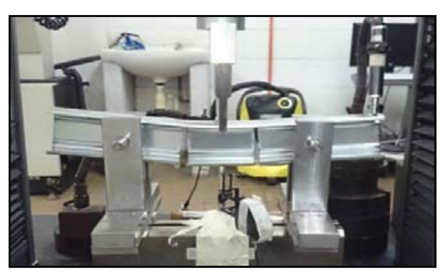

Figure-5. Specimen CFSC-CS0 under bending test.

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RESULT AND DISCUSSIONS

Experimental results of the flexural behavior of CFSC specimens are shown in Table-3. All specimens failed in the mode of Local buckling (L) and Flexural-torsional buckling (FT), as shown in Figure-5. The controlled specimen, CFSC-NS sustained the highest bending load, i.e. 7.109 kN. All curved steel specimens achieved lower maximum as compared to CFSC-NS. Among the curved sections, CFSC-CS3 achieved the highest load resistance, i.e. 6.484 kN, followed by CFSC-CS2 (6.267 kN) and CFSC-CS1 (5.613 kN). Curved specimen with no spot weld (CFSC-CS0) obtained the lowest load resistance, which is 4.351 kN. The results showed that the cuts on the curved sections have weakened the section's robustness. CFSC-CS0 specimen with no spot weld loses up to 38.80% of its flexural strength as compared to normal section, CFSC-NS. However a simple spot weld could regain back the integrity of the curved sections, where the ultimate load resistance of the curved section is increased with the number of spot weld. The percentage reduction of the CFSC-CS1, CFSC-CS2 and CFSC-CS3 was presented 21.03 %, 11.84 % and 8.79% respectively. On the other hand, the load resistance for CFSC-CS stiffened with steel plates and screws are averagely low as compared to CFSC-CS stiffened with spot weld. The maximum load resistance for CFSC-CS-SP and CFSC-CS-SPW are 4.542 kN and 5.069 kN respectively. It showed that the complexity of screwed gusset plate could not effectively maintain the flexural strength of the cut and curved section. The loss of strength ranged from 28.70 % to 36.11 %.

The maximum stress appeared in the CFSC specimens ranged from 29.39 x10^{-3} kN/mm^2 to 49.69 x10^{-3} kN/mm^2. Again, the result has shown that CFSC-NS with no cuts remain the highest stress, while CFSC-CS0 loses its stress up to 40% as compared to CFSC-NS. The steel plate and screws could not sustain the stress in specimen CFSC-CS-SP, for it loses 38.24% of its stress as compared to the controlled sample. Bending deformation for all specimens ranged from 5.78 mm to 9.14 mm; and the time taken for each tests ranged from 632.5 s to 1097 s.

Table-3. Experimental results of CFSC specimens with different profiles

Specimen label	Maximum load (kN)	Maximum stress (kN/mm^2)	Bending deformation at maximum load (mm)	Time taken (s)	Mode of failure
CFSC-NS	7.109	49.69 x10^{-3}	6.28	753.5	L, FT
CFSC-CS0	4.351	29.39 x10^{-3}	7.17	860.5	L, FT
CFSC-CS1	5.614	37.93 x10^{-3}	5.27	632.5	L, FT
CFSC-CS2	6.267	42.34 x10^{-3}	5.61	674	L, FT
CFSC-CS3	6.484	43.81 x10^{-3}	5.78	694	L, FT
CFSC-CS-SP	4.542	30.69 x10^{-3}	9.14	1097	L, FT
CFSC-CS-SPW	5.069	44.36 x10^{-3}	6.53	967	L, FT

Note: L - Local buckling and FT - Flexural-torsional bukling

Figure-6 shows the load-deflection behavior of the seven experimental specimens. The CFSC-CS1 specimen showed the highest initial stiffness, i.e. 3.30 kN/mm. It is closely followed by CFSC-CS2 and CFSC-CS3, with stiffness 3.29 kN/mm and 2.89 kN/mm respectively. The graph has shown that the initial stiffness of curved section is decreased with the number of spot weld applied to the section. However, after the deformation reach at 3.00 mm, their load and stiffness value between CFSC-CS1, CFSC-CS2 and CFSC-CS3 have dramatically changed. Now, the load is increased by increasing the number of spot weld. Surprisingly, specimen CFSC-CS-SP has the lowest initial stiffness, 1.00 kN/mm which slightly lower than of the curved section with two spot weld and plate, CFSC-CS-SPW. This again is supporting the fact that only screwed steel plate is unable to maintain the structural integrity of cut curved beam. Specimen CFSC-CS-SPW is able to sustain initial stiffness of 2.52 kN/mm, which close to specimen CFSC-CS3. Even though suffered an initial slip, the CFSC-NS maintained the highest final stiffness when achieved loads of 6 kN. On the other hand, at the mid load of about 3.80 kN, the specimen experienced a sudden drop of load resistance due to the failure of spot welds in the section. The CFSC-CS-SPW specimen later regained its load resistance and stiffness, with an identical pattern to the CFSC-CS-SP specimen.

Table-3 also showed the time taken of the machine to achieve the ultimate load. CFSC CS SP was indicated the highest time taken and CFSC CS1 was determined the lowest time taken. The percentage difference between CFSC CS SP and CFSC CS1 is about 42.34 %. The higher the ultimate load of CFSC CS was compared with the highest ultimate load; CFSC NS in time taken was illustrated in Figure-7.

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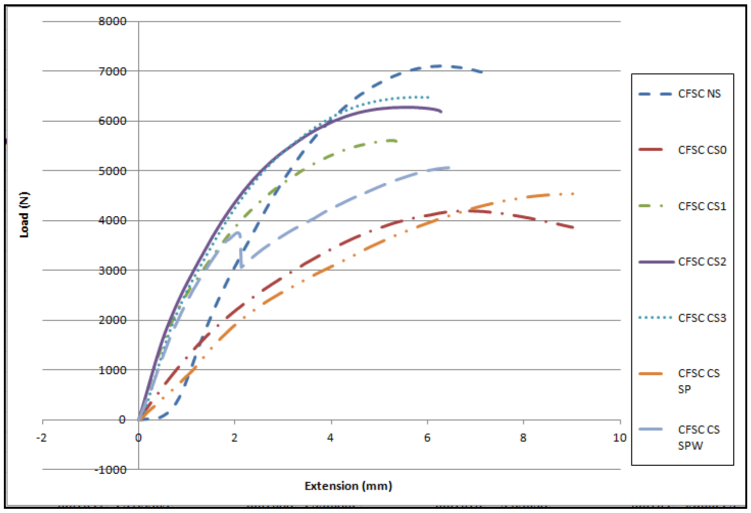

Figure-6. Load-deformation graph.

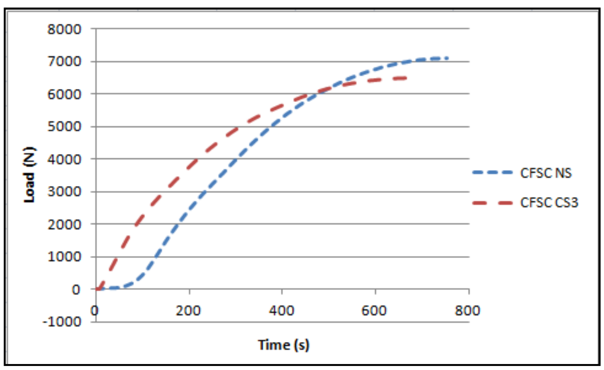

Figure-7. The load versus time taken.

The horizontal web deformation for the seven CFSC specimens is illustrated in Figure-8 and Figure-9. This profile and movement of the lateral-torsional buckling mode are depicted in Figure-9. All sections showed a consistence increment of horizontal web deformation when the load increased. Most section developed lateral deformation about 2 mm or less. However specimen CFSC-CS-SP and CFSC-CS-SPW have suffered more severe lateral deformation, up to 6 mm, as shown in Figure-8. Specimen CFSC-CS0 showed large deformation at the lowest load. CFSC-CS1, CFSC-CS2 and CFSC-NS illustrated similar deformation at initial load. The location of the spot weld is important to be further investigated because it would resist the horizontal movement or deformation of the beam's web. The location of spot welds at the corner of the web and bottom flange proposed a higher resistance to horizontal web deformation. This statement is proven as referring to Figure-8. The location of spot welds on the middle bottom flange was not given any advantage to protect the section from horizontal web deformation. Although, the location of spot welds on the corner of bottom flange and lip established high performance in deformation. The CFSC-CS0 was determined to demonstrate inconsistent of horizontal deformation because the section was unstable.

It is worth taking note that CFSC-CS with steel plate and self-drilling screw as stiffener demonstrated higher horizontal web deformation. Steel plate and screws stiffener was unable to preserve the stability of the curved beams. Specimen CFSC-CS-SPW initially maintains a good resistance against lateral deformation from load 0 kN to 3.5 kN. Between loads 3.5 - 4.0 kN, the spot welds were failed in the specimens, causing large lateral deformation on the section from loads 4.0 kN onwards, with the deformation rate identical to specimen CFSC-CS-SP.

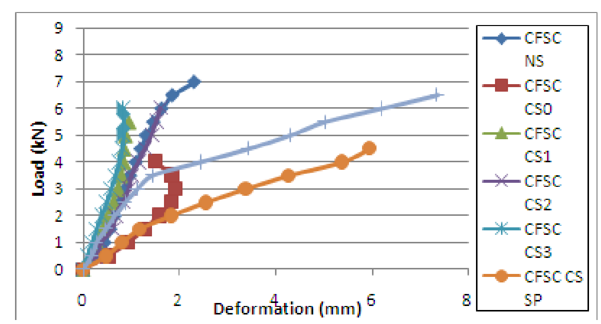

Figure-8. The load versus horizontal deformation of middle height of the web.

Figure-8 also showed that the spot-welds in specimen CFSC-CS3 can reduce the flexural-torsional buckling. Overall of the graph line is experienced that having the deformation on the web and can be acknowledged as flexural-torsional buckling phenomena is exist.

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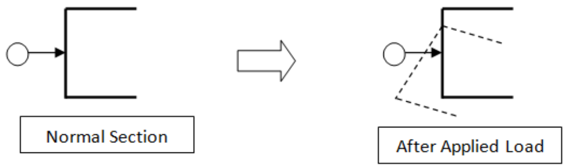

Figure-9. The profile of the horizontal deformation on the web.

The vertical upper flange deformation of 10 mm from the support was determined and shown in Figure-10.

The CFSC-CS0 illustrated the highest vertical flange deformation when compared with other sections. The CFSC-CS with spot weld developed higher vertical flange deformation as compared to CFSC-NS. The CFSC-CS with spot weld was unable to resist the vertical deformation of the flange. In addition, CFSC-CS3 presented low deformation on initial load when compared to other CFSC-CS with and without spot welds. The CFSC-CS with plate and self-drilling screw indicated inconsistence value of flange deformation.

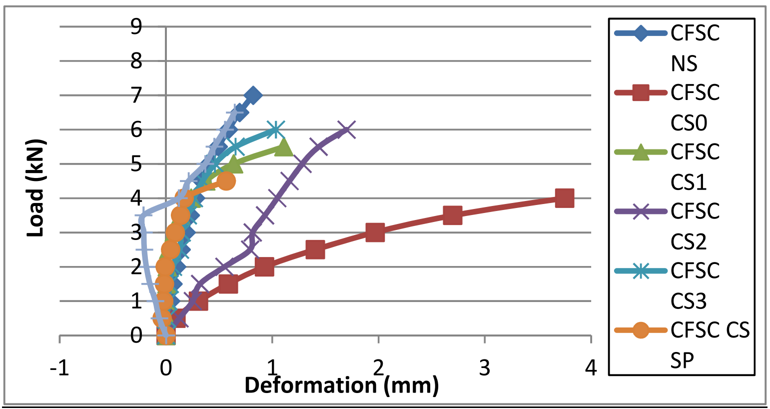

Figure-10. The load versus vertical upper flange deformation of 10 mm from the support.

Figure-11 shows the load versus strain at the bottom flange of the beam specimens. CFSC-CS0 was reported to have the highest strain in initial and final load. This is due to the section was unstable when load was applied. Besides, all CFSC-CS with spot weld showed the best result on initial load when compared with other sections. The location of spot welds on the corner of the flange - web and flange - lipped presented the highest value of strain in initial load. The CFSC-CS with stiffeners of either spot weld or plate with self-drilling screw established strain below 0.05. From Figure-10 and Figure-11, CFSC-CS2 and CFSC-CS3 were able to reduce the local buckling. Overall, all of the graph line experienced the deformation of the upper and bottom flange. This deformation of the flange is known as local buckling of the section.

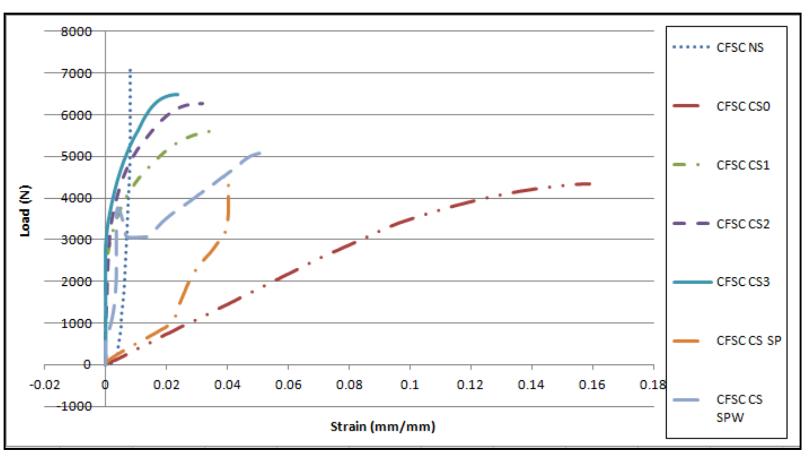

Figure-11. The graph of load versus strain at the bottom flange under load.

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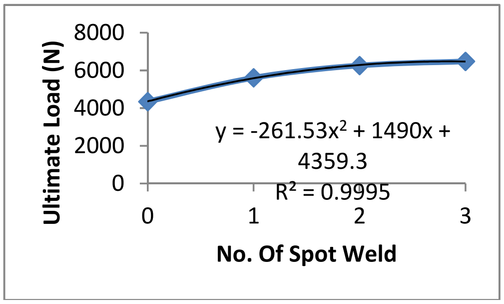

Figure-12. The load versus number of spot welds in CFSC-CS.

The relationship and equation of the ultimate load and number of spot weld was established for CFSC-CS as shown in Figure-12. The equation with the regression of 0.9995 was stated in the study to produce the accurate equation. This equation is a guide to determine the resistance of CFSC-CS by using the number of spot weld:

$$P_u = -261.53\, n^2 + 1490\, n + 4359.3 \quad (1)$$

Where P_u = ultimate load and n = number of spot weld

CONCLUSIONS

A series of experimental tests are carried out to investigate the flexural behavior of cold-formed steel channel curved section. Six cold-formed steel curved channel section (CFSC-CS) with different stiffener profiles and one cold-formed steel normal channel section (CFSC-NS) as controlled sample were tested. From the results, several conclusions can be drawn:

a) The maximum load resistance and stress for the controlled specimen CFSC-NS are 7.109 kN and 49.69 x 10^{-3} kN/mm^2 respectively.
b) All curved steel sections (CFSC-CS) achieved load resistance, stress and stiffness lower than the control sample. The reduction of load resistance range from 8.79 % to 38.80 %, and for stress reduction range from 10.72 % to 38.24 %.
c) Among the curved steel specimens, section stiffened by steel plates and screws give the lower resistances in bending load resistance, stress and stiffness.
d) Curved steel specimens with spot weld stiffeners are more robust in term of flexural strength and stiffness. The maximum load resistance increased with the number of spot weld applied to the curved sections. An equation is formulated to represent the relation between numbers of spot welds to the ultimate load resistance of the curved beams.
e) Among the six curved beam profiles, CFSC-CS3 is chosen to be the best configuration with simple spot-weld stiffener, minimal loss of load resistance and highest stiffness.

The CFSC-CS0 without any stiffener is proven to be unstable section and recorded lowest load resistance, which is below 5000 N. The stiffener that is used in the study such as spot weld, plate and self-drilling screw help the curved beams to sustain flexural load to more than 5 kN. So, the stiffener has achieved the purposes of the study.

The deformation of CFSC is important in the study for checking the buckling of the section. The deformation of flange and web is generally recognized as the flexural-torsional, local and distortional buckling in section.

The use of spot weld gives reasonable value of load resistance; however the spot weld is not a permanent stiffening solution and cannot be used in structure for the long term without proper workmanship and protection. The spot weld is weakened and eventually, the bonding of section will break when the section not able to sustain load anymore. Thus, further studies are inevitably important to identify a potential stiffener profile for cold-formed steel curved channel sections.

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