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A Review: The Buckling Behavior of Cold-Formed Steel Open Section of Beam

Siti Suhaiza Fitriah Mat Daud[1], Norwati Jamaluddin[2,*]

[1]Faculty of Civil Engineering and Built Environment,
Universiti Tun Hussein Onn Malaysia, Batu Pahat, Johor, 86400, MALAYSIA

*Corresponding Author Designation

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Abstract: . Cold-formed steel is available in various types of sections depending on their purpose and function in construction industry. Cold-formed steel sections have a very thin thickness as compared to their width. These parts are prone to buckling as a result of this feature. In case of cold-formed steel members, buckling is one of the most critical design criteria to consider. In this research, the aim of study is to investigate the buckling behavior of cold-formed steel section and to review and evaluate the beam strength from the past researches on analytical approach, FEM and standard code. To achieve the objectives of the study, 45 reviews from the past researches about the flexural behaviour that focus on lateral-torsional buckling of open section steel beams and the design strength was made. The three types of the method used had shown the types of buckling modes that appears in the cold-formed steel structure.

Keywords: Cold-Formed Steel , Buckling Behavior, Open Section Beam

1. Introduction

The application of cold-formed steel in the building construction industry is increasing rapidly where it is a simple to make and assemble. Although it is higher strength to weight ration and ease of construction, cold-formed beams have high tendency for buckling which means they might collapse due to local buckling, distortional buckling, lateral distortional buckling, and lateral-torsional buckling [1].

Cold-formed steel section have a very thin thickness as compared to their width. These parts are prone to buckling as a result of this feature. In case of cold-formed steel members, buckling is one of the most critical design criteria to consider [2]. In this research, the aim of study is to investigate the buckling behaviour of cold-formed steel open-section and to review and evaluate the beam strength from the past researches on analytical approach, FEM and standard codes. Open sections cold formed steel is the section that the opening is relatively wide from one edge to another differentiates open profiles from closed profile and welded sections. To achieve the objectives of the study, some reviews from the past research about the flexural behaviour that focus on lateral-torsional buckling of open section steel beams and the design strength is made.

*Corresponding author: norwati@uthm.edu.my

1.1 Buckling Modes

Buckling is one of the most critical design parameters to keep in mind when working with cold-formed steel components. When these cold-formed parts are compressed, sheared, or twisted, they can buckle before yielding. Local buckling and distortional buckling can also interact with lateral- buckling since cold-formed steel sections are generally thin and flex [2]. The local buckling for such plate elements varies from overall beam buckling. The element begins to deflect out of its original straight or plane shape when the initial buckling stress is reached, but it does not fail. On the contrary, it can withstand much higher compression stresses than those which cause local buckling to develop. [4]

Local buckling of thin-wall structure elements before yielding is well-known, and it can reach extremes where the local buckling stress is a hundredth of the yielding limit. However, it is well acknowledged that such members do not always fail when buckling stresses occur, and that they can typically withstand increased loads above their capacity if local buckling occurs.[5]

2. Methods of the Studies

The methods in this study is reviewed based on the previous researches on cold-formed steel open section beam on analytical approach, experimental works, and FEM models. The outlines below shows the selection and screening method that was used to choose the previous papers that were relevant to this study.

2.1 Experimental Works

In the paper of [6] covered the four different types of beams which consist of C beams, R beams, lipped I beams, and 2R beams 19 as shown in Figure 1. All nominal thickness (2.5 mm), nominal flange width (43 mm) and inside bend radius (2mm) are all same for this type of beam.

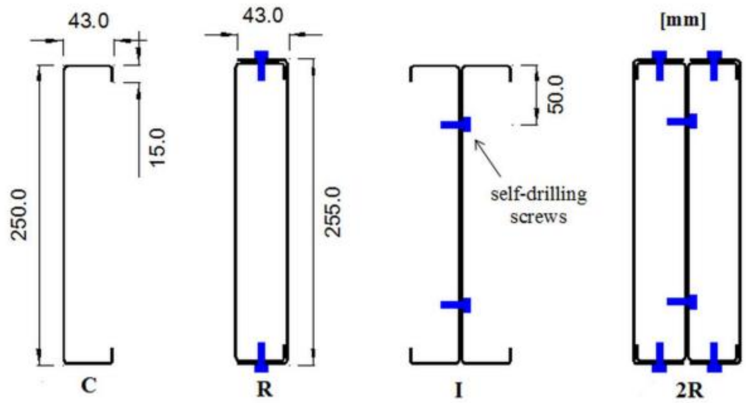


Figure 1: The cross-section of the beams test [6]

In this study, the 295 kN load was applied by hydraulic jack which hanging on two-dimensional reaction frame. In this work, four-point bending tests were utilised to determine the ultimate bending strength of cold-formed steel beams and to investigate the failure mechanisms that led to their collapse. This experiment had applied the load under displacement control at a rate of 0.01 mm/s until the specimen failed and reached its unloading stage where the beam deformation of the lateral rotation of the beam was too large or the maximum stroke of hydraulic jack was reach [6]

In the study [3] had performed an experimental regarding the flexural behaviour of cold-formed steel back-to-back beams. In this study the connections that were used for cold-formed steel C back-to-back section on the web plate were the bolt connection. It is the most suitable and effective in applying to cold-formed steel section with the condition that total thickness should be enough for installation. 12 specimens were fabricated to form C bac-to-back section with the beam length of 4 m. For the testing, two C section were connected each other to performed C backto-back section with different spacing of bolt which were L/2, L/3, L/4 and L/6. The installation of the testing was shown in Figure 2

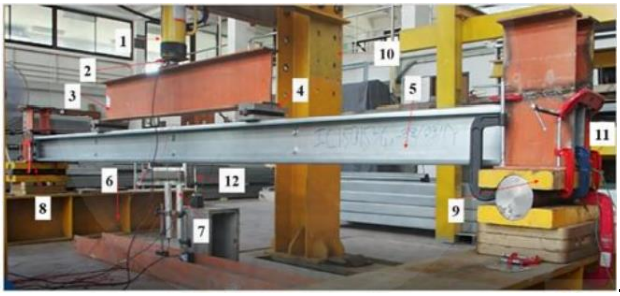


Figure 2: Testing set-up [3]

2.2 Finite Element Model

In paper [7] stasted that ANSYS software was used to construct a finite element model. In order to conduct their investigation, they used a simply supported cold-formed steel beam that was subjected to a mid-span eccentric transverse stress. Lipped channel, lipped Z, and hollow flange channel sections were utilised as cold-formed steel sections. The eccentric load at the mid span is reproduced in the study using an equivalent loading condition, as shown in Figure 3.8. The eccentric load is then substituted by a transverse load (P) applied to the beam web and a couple formed by equal and opposite lateral loads (Q) applied to the beam flanges.

In the paper [3] also had performed the finite element method in determining the flexural behaviour of cold-formed steel back-to-back beams using ABAQUS program version 6.14-1 that was used to simulate the cold-formed steel C back-to-back beams as shown in Figure.3. In this study 12 specimens from the test were used in model. Load were applied at two points of loading bearing plates whose width was cm and it was installedsymmetrically with respect to the mid-span.

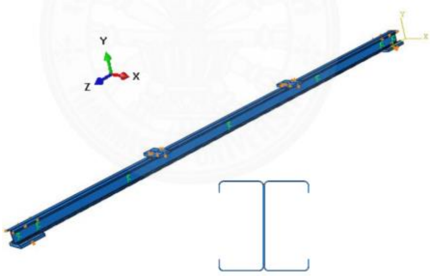


Figure 3: Model of CFS C Back-To-Back Beam [3]

2.3 Analytical Approach

In the paper [8] had performed the lateral-torsional buckling strength of cold-formed stainless-steel lipped channel beams was measured using an analytical model. In addition to yielding, single-symmetric beams may fail due to lateral-torsional buckling. The effective flange widths were calculated using the ASCE stainless steel design specification's criteria for equally compressed stiffened sections..

$$M_n = S_e F_y \quad \text{Eq. 1}$$

Where

S_e = elastic section modulus of the effective section
F_y = yield strength of the material in compression

Or

$$M_n = S_c \left(\frac{M_c}{S_f}\right) \quad \text{Eq. 2}$$

Where

S_c = section modulus of the effective section at a stress M_c/S_f

S_f = section modulusof the full unreduced section

The lateral-torsional buckling strength for a singly-symmetric section in a cold-formed carbon steel design specification is given by the similar equations as mentioned above, with the difference that the plasticity reduction factor is assumed as unity [7]

3. Results and Discussion

The results and discussion section also were divided into three parts which is experimental work, FEM, and analytical approach.

3.1 Experimental works

In the paper [6] presented a mean ultimated load capacity was only 11.72kN while I beam was 41.68 kN compared to the closed sections which were much higher as shown in Figure 4. From the experiment result, the lateral-torsional buckling occurs and the behaviour of the buckling depends on the cross- section shape. C beam and I beam easily showed the lateral rotation at the mid span of beam where the C beams was the most affected. The particular reason for the circumstance was made as the result is the shear center of the cross-section of C beams is not coincide with the centre of gravity and it is obviously because of its cross-section is open. The shear centre is a position on the beam section where no twisting occurs when stresses are applied.

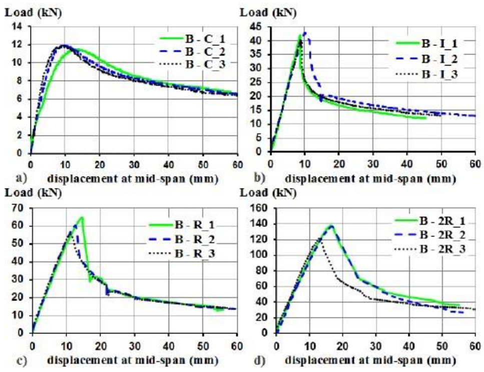


Figure 4: Load-displacement curves of C (a), lipped I (b), R (c) and 2R (d) beams [6]

In paper [3] presented the flexural behavior of cold-formed steel C back-to-back beams using the bolts connection on the web plates. 12 specimens were tested with the different cross-section and different spacing of the connection. The result from the Table 4.1 shows that all the specimens are failed by lateral-torsional buckling for the section C-1 and distortional buckling for the section C-2.

Table 1: Experimental results [3]

No	Specimen name	Max. Load (kN)	Vertical Deflection at max. load (mm)	Failure mode	
				Section C-1	Section C-2
1	IC10012L/2	8.89	47.78	LTB	DB
2	IC10012L/3	8	40.7	LTB	DB
3	IC10012L/4	8.1	41.01	LTB	DB
4	IC10012L/6	6.51	33.48	LTB	DB
5	IC10015L/2	9.16	38.26	LTB	DB
6	IC10015L/3	11.23	50.59	LTB	DB
7	IC10015L/4	9.6	40.26	LTB	DB
8	IC10015L/6	12.89	51.65	LTB	DB
9	IC15015L/2	16.29	26.62	LTB	DB
10	IC15015L/3	18.25	31.21	LTB	DB
11	IC15015L/4	18.12	31.96	LTB	DB
12	IC15015L/6	16.76	28.58	LTB	DB

The Table 4.1 shows that the maximum load of the specimen IC10012L/2 with the depth of 100mm and the thickness of 1.2mm was 8.89 kN which is larger than the connection spacing L/6, 6.51 kN. Meanwhile, the specimen IC10015L/2 shows the maximum load of 9.16 kN which is the lowest value compared to the connection spcing L/3, L.4 and L/6. Similarly, IC15015L/2 shows its maximum load 16.92 kN which is less than the specimen with the connection spacing L/6. From the table, most of the result of the maximum load in case of smaller connection spacing is small compared to the case of the larger connection spacing. The particular reason for the circumstance was it might be due to the eccentricity of applied load on beam during the test. The result shows that all the specimen's beams had failure mode of lateral-torsional buckling on one of the C sections.

3.2 Finite Element Model

In the study of [3] the finite element program ABAQUS was used to simulate cold-formed steel beam double channel back-to-back. The size that had been used of channel back-to-back beam was 7.5 x 7.5 mm and for the loading bearing plates and support bearing plate, the mesh sizes were 10 x 10 x 10 mm and 20 x 20 x 20 mm.the comparison result of the failure mode C back-to-back beam from experimental and FEM is shown in Table 2.

Table 2: Comparison between experimental and FEM result [3]

No	Specimen	Experimental results			FEM results			$\frac{F_{FEM}}{F_{test}}$
		F_{test} (kN)	Failure mode		F_{FEM} (kN)	Failure mode		
			C-1	C-2		C-1	C-2	
1	IC10012L/2	8.89	LTB	DB	7.32	LTB	DB	0.82
2	IC10012L/3	8	LTB	DB	7.88	LTB	DB	0.99
3	IC10012L/4	8.1	LTB	DB	7.72	LTB	DB	0.95
4	IC10012L/6	6.51	LTB	DB	7.88	LTB	DB	1.21
5	IC10015L/2	9.16	LTB	DB	11	LTB	DB	1.20
6	IC10015L/3	11.23	LTB	DB	11.2	LTB	DB	1.00
7	IC10015L/4	9.6	LTB	DB	12.2	LTB	DB	1.27
8	IC10015L/6	12.89	LTB	DB	12.1	LTB	DB	0.94
9	IC15015L/2	16.29	LTB	DB	21.5	LTB	DB	1.32
10	IC15015L/3	18.25	LTB	DB	18.4	LTB	DB	1.01
11	IC15015L/4	18.12	LTB	DB	20.1	LTB	DB	1.11
12	IC15015L/6	16.76	LTB	DB	22.8	LTB	DB	1.36

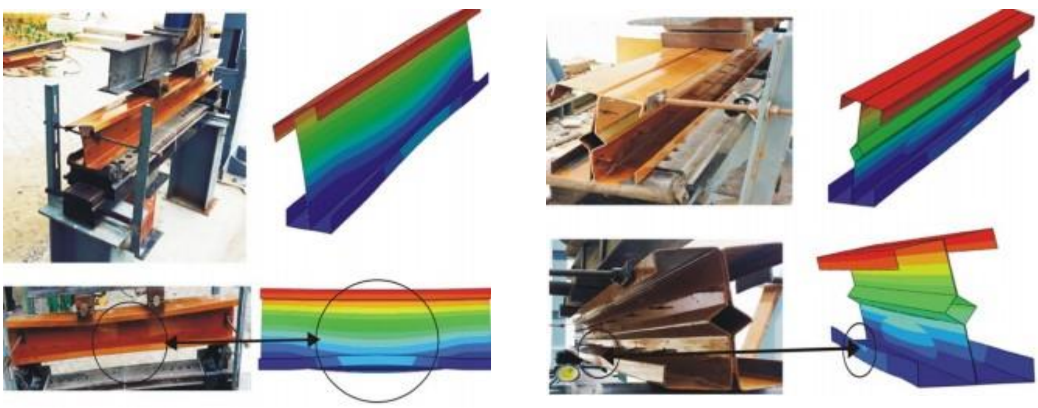
Based on the table, both result for the failure mode were same where for the C-1 section the was had the lateral-torsional buckling mode while for the C-2 section considered as distortional buckling mode. For the ultimate load IC10012 had decrease about 21% and for IC10015 and IC15015 were 27% and 36% respectively.

According to the paper [9] the behavior of cold-formed steel lipped channel built-up-I-section was investigated using ABAQUS software for numerical analysis. Four different sorts of cross-sections are investigated in this study. The findings of the analysis are shown in Table 3. In the experimental, the flexural strength of the specimen SLC, SLC-I, CLC, and CLC-I were 5.06 kN.m, 7.88 kN.m, 7.38 kN.m, and 10.21 kN.m respectively. Meanwhile, according to FEM, the flexural strength for SLC, SLC-I, CLC, CLC-I were 5.23 kN.m, 8.00 kN.m, 7.58 kN.m, and 10.40 kN.m respectively. It may be argued that by improving the geometries section from the simple lipped to the c, the flexure strength was increased.

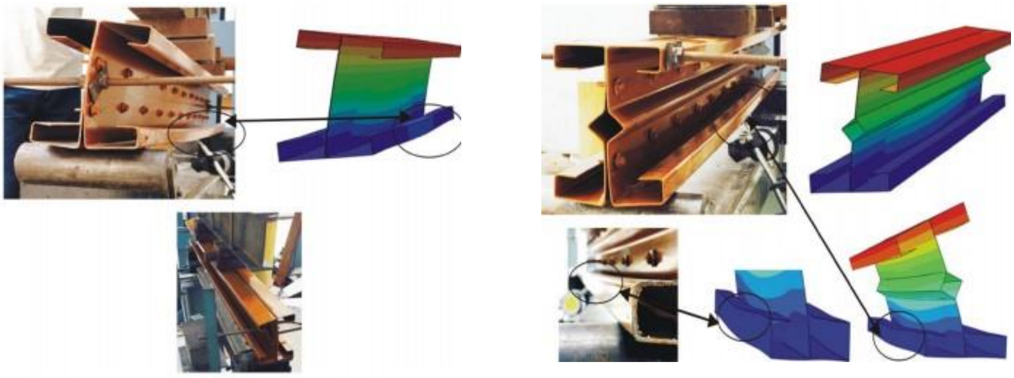
Table 3: Comparison of test and Finite Element Analysis result [9]

No	Specimen ID	Flexural strength (kN.m) M_{EXP}	Flexural strength (kN.m) M_{FEM}	$\frac{M_{EXP}}{M_{FEM}}$	Failure mode
1	SLC	5.06	5.23	0.97	L+LTB
2	SLC-I	7.88	8.00	0.99	L+LTB
3	CLC	7.38	7.58	0.97	L+LTB
4	CLC-I	10.21	10.40	0.98	L+LTB
	Mean			0.98	
	Standard deviation			0.01	

Figure 5 shows the load-deflection behaviour of simple and complex lipped channel section. It had observed that CLC and CLC-I had performed well as long as it improved the torsional rigidity of the section and intermediate web stiffners to reduce the buckling compared to SLC, and SLC-I.



(a) SLC (b) SLC-I



(c) CLC (d) CLC-I

Figure 5: Comparison of failure modes [9]

3.3 Analytical approach

In the study [8], the ASCE Specification was used to compare the experimental and theoretical lateral-torsional buckling strength of doubly-symmetric beams the two different size of lipped I-sections were produced. The experimental results on the lateral-torsional buckling strength of cold-formed lipped I-section beams are shown in Table 4.

Table 4: Experimental and Analytical Beam Strengths [8]

Beam Length (mm)	Beam No.	Flange Width (mm)	M_e (kNm)	M_t (kNm)	M_s (kNm)	$\frac{M_e}{M_t}$	$\frac{M_e}{M_s}$
1000	1	33,3	2,735	2,173	2,680	1,258	1,021
1100	2	33,4	2,813	2,094	2,650	1,344	1,061
1500	3	34,1	2,745	1,821	2,369	1,507	1,159
1700	4	32,8	2,633	1,699	2,196	1,550	1,199
1900	5	33,4	2,186	1,578	2,002	1,385	1,092
2100	6	33,1	1,905	1,456	1,786	1,308	1,067
2300	7	32,9	1,613	1,331	1,548	1,212	1,042
2400	8	33,5	1,665	1,267	1,424	1,314	1,170
2800	9	33,0	1,254	1,012	1,046	1,240	1,199
Mean						1,346	1,112
COV						8,65	6,27
900	10	43,2	4,569	4,981	5,520	1,008	0,909
1200	11	43,1	5,019	4,491	5,520	1,017	0,828
1300	12	42,9	4,675	4,353	5,490	1,074	0,852
1500	13	43,4	5,225	4,103	5,277	1,274	0,990
1700	14	44,0	5,156	3,875	5,033	1,331	1,024
2300	15	43,3	4,523	3,249	4,120	1,392	1,098
2600	16	43,7	3,188	2,937	3,560	1,086	0,895
Mean						1,169	0,973
COV						13,61	15,30

The comparison lateral-torsional buckling moment between the experimental and two theoretical which are by using The ASCE cold-formed stainless-steel design manual uses the tangent modulus notion, while the AISI cold-formed design manual uses the SSRC technique.

4. Conclusion

From the experimental work, it can be said that the failure mode of the cold-formed steel structure depends on its shape and types of section. Open section steel beam had high tendency prone to the lateral torsional-buckling compare with the close section where its stain gauge placed in the compressive flanges of the open section showed a non-uniform increase in the strains and it indicating the lateral-torsional buckling. In general, when a force is applied to a body, the body deforms. In terms of the influence of thickness, when the thickness is increased from 1.2 mm to 1.5 mm, the maximum load increases by 3%, 40%, 19%, and 98 percent, respectively, for connection spacing L/2, L/3, L/4, and L/6. Between two separate loading cases: pure bending and moment gradient, changes in ultimate strength and buckling of cold-formed open-sections were observed. When the beam was subjected to a linear moment gradient, the bending resistance of a part failing by distortional buckling under pure bending increased by 10% on average.

FEM which is run on ABAQUS and ANSYS software in this research, is accurately predicts the strength and behaviour of the cold-formed beam structure. As a result, the FEM developed may be utilised to determine the capacity of the beams with high level of proficiency. Most of the result of FEM and experimental result is quite close where FEM can adapt to meet certain specification for accuracy in order to decrease the need for physical prototype in design process. The numerical simulation failure modes of CFS C back-to-back beams were similar to the ones observed in the experiment. The largest discrepancy between ultimate loads from experiment and finite element analysis for C10012, C10015, and C15015 is 21%, 27%, and 36%, respectively. The failure modes of C back-to-back beams from numerical simulation comparatively agreed with the modes observed in the experiment. The particularly reason for this is the FEM model software has specific parameters for determining failure modes. Meanwhile, due to the experimental work, there may be a small number of inaccuracies.

Beside that, Analytical approach is a method that can be carried out to determined the strength of the cold-formed steel structural material. The calculation of the nominal flexural strength is based on the American Steel Construction Engineering (ASCE) stainless steel design specification. The result that obtained between the ASCE, AISI and experiment results was slightly different. By using the AISI standard had give better result compared to others.

Some recommendations for further research are made which are all the cold-formed steel structure should be reinforced with extra screws that possibly of a greater diameter or for improved steel class. When two or more profiles are used as a beam, the strength to weight ratio was improved. The addition of warping and torsion constraint to the supports significantly improves the flexural capacity. Warping restraint provided to the compression flange has greater impact on the flexural capacity than warping restraint provided to tension flange

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