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Bending performance of cold formed steel structural member with perforated section in housing framing system

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Abstract. The study shows a numerical analysis on bending behavior of cold-formed steel framing system and the effective cost reduction between perforated and non-perforated steel section in steel framing system. The results are presented in the form of displacement and yield moment. Using finite element analysis software, a total of 26 set of nonlinear analysis were executed to determine the effects of opening spacing, edge distance and thickness of section on bending behavior. The result shows that the increasing of the opening spacing and edge distance would increase the bending capacity. C-channel steel section showed better moment resistance in thicker section. The result was then compared to the C-channel steel section without perforation. From the analysis, it was observed that C-channel steel section without perforation had higher bending capacity than C-channel steel section with perforation in major axis. However, there is a small difference in terms of yield moment when comparing C-channel section with 0.4D of square opening and 0.3L edge opening as well as 0.1L opening space with C-channel section without perforation while reducing the volumes up to 7.28%. Thus, C-channel section with 0.4D of square opening, 0.3L edge opening and 0.1L opening space give a very effective cost reduction.

1. Introduction

Over the past decades, constant population growth happened in Malaysia especially in states such as Penang and Kuala Lumpur. In year 2000, population in Malaysia was registered with around 23 million people and density of 71 population per km2, while in 2017, population in Malaysia has increased to around 31 million people and density of 95 population per km2. With the increasing population and limited land area, there will be lack of housing area to withstand the high population. Due to inflation and unstable oil price, the rise of cost of building materials also caused the increase of average cost of houses. This caused the high cost of properties which may not affordable by middle-income households, especially in Penang and Kuala Lumpur.

Besides, Malaysia had experienced flood on December 2014 in the state of Kelantan. Therefore, house with fast construction speed is more demanding in natural disaster-prone area. Due to highly demand of housing, the usage of cold formed steel section as framing system was introduced.

Cold-formed steel (CFS) sections are generally used as framing members in construction. With quick installation and construction, cold-formed steel framing construction is faster and cheaper. The cost analysis in the design of beams has been studied by Estrada et al. (2006) and the result shows that the application of openings can cut down substantial materials and construction costs.

Perforation is the holes made by boring or piercing. For perforated steel section, it means that there are holes on the steel. For perforated section, the shape configuration, size of web opening and distance of opening from the support have large impact on the structural performance of the perforated section. Tsavdaridis and D Mello, (2009) indicated that perforated section with vertical and rotated elliptical web openings have better behavior in terms of performance compared to hexagonal and circular web perforated. The decreasing in the shear capacity is more definite when compared to the reduction in the moment capacity, as the presence of the perforation in the web reduces the shear area of the section significantly whilst the reduction of the bending modulus is small.

2. Problem statement

While the price of steel remained fluctuated throughout the years, the construction cost of cold formed steel framing homes is comparable with conventional homes built with reinforced concrete. This is due to cold formed steel framing homes are built with prefabricated cold form steel and 15% cheaper due to the accuracy and speed while reinforced concrete homes normally are casted in-situ and building speed is slower compare to cold form steel framing homes. Thus, the actual construction cost of both house with cold formed steel and reinforced concrete using the same framing systems will be compared.

Besides, perforation in steel beams will reduce the raw material required. Therefore, the cost of cold formed steel framing system can also be further reduced by making openings on the web surface of steel beam to produce perforated steel section.

3. Objectives

The purpose of this research are to study the bending behaviour of cold form steel framing system. Secondly, the research also was to compare the effective cost reduction between perforated and non-perforated steel section in steel framing system.

4. Numerical study on bending of C-Channel steel section

This research was conducted using finite element software to develop models for finite element analysis using perforated section, to analyse the bending behaviour of cold formed steel structural member with perforated section in house framing system. Cold formed steel structural members without opening were used as a control specimen. The yield load was obtained through nonlinear load deflection graph. The table of section properties for the section used is provided in Table 1.

Table 1. Table of Section Properties.

D		152mm	I_x	2.42E6mm^4
B		51mm	I_y	0.1797E6mm^4
R		22mm	c	12.02mm
T		3.0mm	Z_x	31.9E3mm^3
Section Area (mm^2)		735	Z_y	4.47E3mm^3
Mass per unit length	Galv. (kg/m)	5.86	r_x	57.4mm
	Black (kg/m)	5.77	r_y	15.64mm

C-Channel section with 0.4D of square opening referred to the research from (Ling, 2015) will be constant throughout the whole research. Material for the model is referred to the research from Hashim, (2013) as in Table 2. The Poisson ratio is 0.3 for all models. The deformation is only considered in the elastic zone of the materials. In this study, thickness of section, t = 1.0 mm, 1.5mm, 2.0 mm, 2.5 mm, and 3.0 mm was investigated. The type of meshing is thin shell (QSL8).

Convergence study was implemented to determine the optimum meshing of finite element model and to get more accurate solution. Apart for that, convergence study can also minimize the computational effort. From Figure 1, it is shown that the result converged when the number of element is more than 700. The mesh element size of 20 was chosen.

Table 2. Material properties from the result of tensile test (Hashim, 2013).

Young's modulus, E	226.53 GPa
Poisson's ratio	0.3
Yield Stress	387 N/mm^2
Hardening Gradient	5.664kN/mm^2
Plastic Strain	0.481

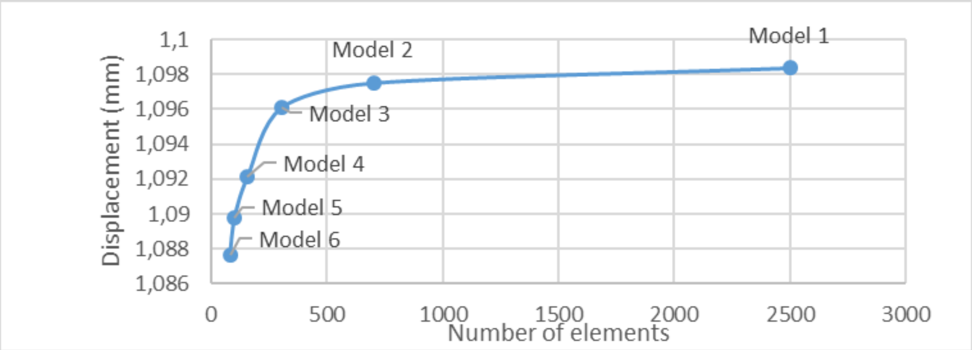

Figure 1. Graph of resultant displacement against number of elements.

This mesh size was used for all sections with and without openings throughout the research.

5. Result and discussion

The whole house framing system with non-perforated C-channel steel is constructed and analyzed using Staad Pro software. The most critical beam section with the highest bending moment need to be determined and the analysis will be carried out using finite element software, LUSAS. Then, the analysis will be carried out to compare with the most critical beam section. From the analysis, the highlighted beam, Beam 233 showed the highest bending moment with 0.99kNm as shown in Figure 2 and Figure 3. This beam has the most critical bending moment and will be used in the following analysis. The variables used in this study are edge distance, spacing of opening, and thickness of steel section.

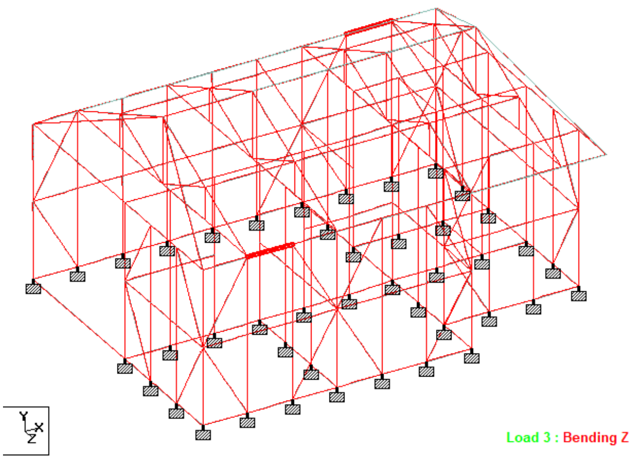

Figure 2. Result of analysis on bending moment of house framing system.

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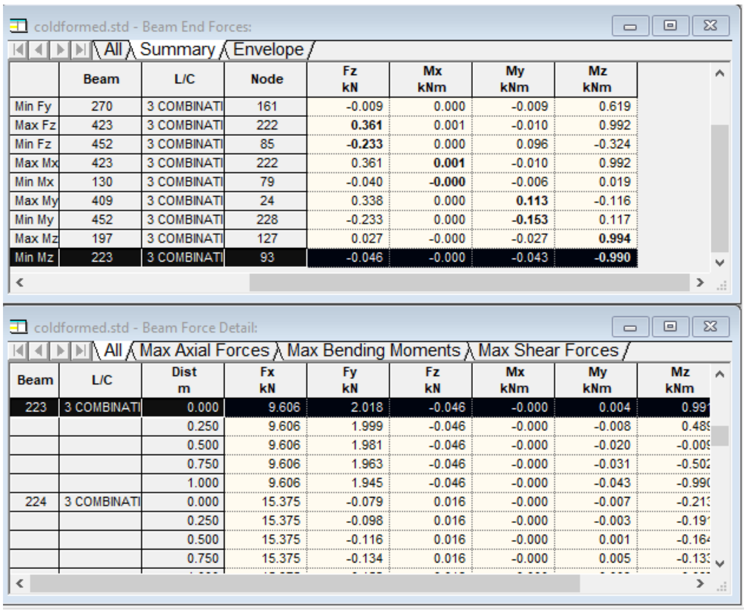

coldformed.std - Beam End Forces:

All | Summary | Envelope

	Beam	L/C	Node	Fz kN	Mx kNm	My kNm	Mz kNm
Min Fy	270	3 COMBINATI	161	-0.009	0.000	-0.009	0.619
Max Fz	423	3 COMBINATI	222	**0.361**	0.001	-0.010	0.992
Min Fz	452	3 COMBINATI	85	**-0.233**	0.000	0.096	-0.324
Max Mx	423	3 COMBINATI	222	0.361	**0.001**	-0.010	0.992
Min Mx	130	3 COMBINATI	79	-0.040	**-0.000**	-0.006	0.019
Max My	409	3 COMBINATI	24	0.338	0.000	**0.113**	-0.116
Min My	452	3 COMBINATI	228	-0.233	0.000	**-0.153**	0.117
Max Mz	197	3 COMBINATI	127	0.027	-0.000	-0.027	**0.994**
Min Mz	223	3 COMBINATI	93	-0.046	-0.000	-0.043	**-0.990**

coldformed.std - Beam Force Detail:

All | Max Axial Forces | Max Bending Moments | Max Shear Forces

Beam	L/C	Dist m	Fx kN	Fy kN	Fz kN	Mx kNm	My kNm	Mz kNm
223	3 COMBINATI	0.000	9.606	2.018	-0.046	-0.000	0.004	0.99
		0.250	9.606	1.999	-0.046	-0.000	-0.008	0.48
		0.500	9.606	1.981	-0.046	-0.000	-0.020	-0.00
		0.750	9.606	1.963	-0.046	-0.000	-0.031	-0.50
		1.000	9.606	1.945	-0.046	-0.000	-0.043	-0.99
224	3 COMBINATI	0.000	15.375	-0.079	0.016	-0.000	-0.007	-0.21
		0.250	15.375	-0.098	0.016	-0.000	-0.003	-0.19
		0.500	15.375	-0.116	0.016	-0.000	0.001	-0.16
		0.750	15.375	-0.134	0.016	-0.000	0.005	-0.13

Figure 3. Results on Beam 223 (Most critical beam section with highest bending moment).

C-channel section with D = 152 mm, B = 51 mm, t = 3 mm and length, L = 1000mm was considered to determine the moment resistance. Line load of 3N/mm was applied on the flange of C-channel section in y direction. 0.4D of square opening was used as constant, where D is the depth of section, was opened on the web of section with 0.1L opening spacing and 0.1L of edge distance. Figure 4 shows load deflection curves of C channel section with and without opening. Yield load, Py is obtained from the graph to calculate the yield moment, My. Yield load is the load at which the section begins to deform plastically. Ultimate load, Pu is obtained from the graph to calculate ultimate moment, Mu in order to compare the results in clearer way. Ultimate load is taken at the peak of the load deflection curve.

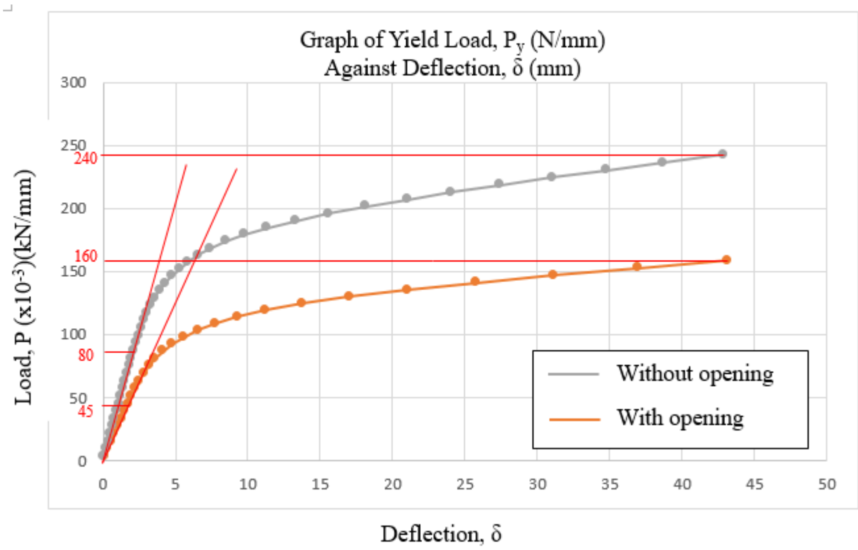

Figure 4. Load deflection curves of C-Section with and without openings.

Calculations of moment capacity of C-channel section without perforation:

Yield load obtained from graph,
Py = 0.080 kN/mm

Yield moment,
My = Py x L2/8
= 0.080 x 10002/8
= 10.0 kNm

Ultimate load,
Pu = 0.240 kN/mm

Ultimate moment,
Mu = 0.240 x 10002/8
= 30.0 kNm

Calculations of moment capacity of C-channel section with perforation:

Yield load obtained from graph,
Py = 0.045 kN/mm

Yield moment,
My = Py x L2/8
= 0.045 x 10002/8
= 5.625 kNm

Ultimate load,
Pu = 0.160 kN/mm

Ultimate moment,
Mu = 0.160 x 10002/8
= 20.0 kNm

From the calculation, it shows that the yield moment of C-channel section without opening is larger than that of the C-channel section with opening.
The difference of yield moment between C-channel section with opening and without opening is:

Difference % = (10 - 5.625)/10 x 100
= 43.75%

The difference of ultimate moment between C-channel section with opening and without opening is:

Difference % = (30 – 20)/30 x 100
= 33.33%

Furthermore, the maximum deflection of C-channel section with openings is larger than C-channel section without opening.

Volume of section without opening

Volume = Area x span length of section
= 762 x 1000
= 762000 mm^3

Volume of section with opening

Volume of openings = 762000 – ((0.4D)2 x t x no. of opening)
= ((0.4(152))2 x 3 x 9)
= 662190.72 mm^3

Reduction in volume
% volume = (762000-662190.72) / 762000 x 100
= 13.098%

5.1. Effect of spacing and edge distance of opening

In this case, the dimension of section is fixed with D = 152 mm, B = 51 mm, and t = 3 mm. Line load of 0.003 kN/mm is applied on the flange of section. Both opening spacing and edge distance is varied by 0.1L, 0.2L, 0.3L, 0.4L, and 0.5L. While, the Table 3 shows the comparison between the nonlinear analysis results of C channel section without opening and C-channel section with different edge distance for various opening spacing.

From the result, the edge distance is directly proportional with the yield moment. The yield moment of C- channel section without opening is larger compared to that of C-channel section with opening. Nevertheless, from the calculation of ultimate moment, Mu, it is shown that, C-channel section without opening have higher bending resistance compared to that of C-channel section with opening.

Table 3. Comparison between the nonlinear analysis results of C channel section without opening and C-channel section with different edge distance for various opening spacing.

Edge distance	Opening Space	Max Deflection (mm)	Yield Load, P_y (kN/mm)	Yield Moment M_y (kNm)	M_y Difference %	Ultimate Load, P_u (kN/mm)	Ultimate Moment, M_u (kNm)	M_u Difference %	Volume (mm^3)	Reduction in volume %
0.1L	0.1L	43.17	0.045	5.625	44.44	0.158	19.809	34.58	99809.28	13.10
	0.2L	42.85	0.063	7.875	22.22	0.194	24.210	20.04	55449.60	7.28
	0.4L	42.93	0.063	7.875	22.22	0.200	24.999	17.44	33269.76	4.37
0.2L	0.1L	44.06	0.063	7.875	22.22	0.200	24.972	17.53	77629.44	10.19
	0.2L	40.68	0.075	9.375	7.41	0.218	27.308	9.81	44359.68	5.82
	0.3L	41.72	0.075	9.375	7.41	0.225	28.074	7.28	33269.76	4.37
0.3L	0.1L	41.35	0.081	10.125	0.00	0.218	27.305	9.82	55449.60	7.28
	0.2L	43.51	0.081	10.125	0.00	0.230	28.799	4.89	33269.76	4.37
	0.4L	40.72	0.081	10.125	0.00	0.230	28.794	4.90	22179.84	2.91
0.4L	0.1L	42.97	0.081	10.125	0.00	0.231	28.815	4.83	33269.76	4.37
	0.2L	41.62	0.081	10.125	0.00	0.230	28.805	4.86	22179.84	2.91
0.5L	-	41.57	0.081	10.125	0.00	0.236	29.558	2.38	11089.92	1.46
Non perforated	-	42.82	0.081	10.125	-	0.242	30.278	-	762000	

5.2. Effect of Thickness

The effect of the thickness of section on bending resistance was investigated in this study. The depth, width and height of lip were fixed while the thickness of section was considered in this case. Figure 5 shows the load deflection curves of C-channel section without opening with various thicknesses while Figure 6 shows the load deflection curves of C-channel section with opening with various thicknesses.

Comparison result between yield moment of C-channel section with opening and without opening is tabulated in Table 4.

Based on Figure 5 and Figure 6, the results showed that the yield moment for both sections increases when the thickness of section increases. In Figure 7, C-channel section without opening has the same yield moment as that of C-channel section with opening for thickness of 1.0mm, 1.5 mm and 2.0 mm. However, from t = 2.5 mm, C-channel section without opening has higher yield moment than C-channel section with opening. The increasing of the thickness of section may increase the stiffness of structure.

Table 4. Comparison between yield moment and ultimate moment of C-channel without opening and C-channel with different thickness.

Thickness (mm)	Without Opening				With Opening				M_y Difference %	M_u Difference %
	Yield Load, P_y (N/mm)	Yield Moment M_y (kNm)	Ultimate Load, P_u (kN/mm)	Ultimate Moment, M_u (kNm)	Yield Load, P_y (N/mm)	Yield Moment M_y (kNm)	Ultimate Load, P_u (kN/mm)	Ultimate Moment, M_u (kNm)		
1.0	0.027	3.375	0.079	9.844	0.027	3.375	0.073	9.123	0.00	7.32
1.5	0.039	4.875	0.118	14.717	0.039	4.875	0.112	13.977	0.00	5.03
2.0	0.051	6.375	0.159	19.832	0.051	6.375	0.145	18.071	0.00	8.88
2.5	0.069	8.625	0.200	24.962	0.063	7.875	0.182	22.734	8.70	8.92
3.0	0.081	10.125	0.242	30.278	0.081	10.125	0.218	27.304	0.00	9.82

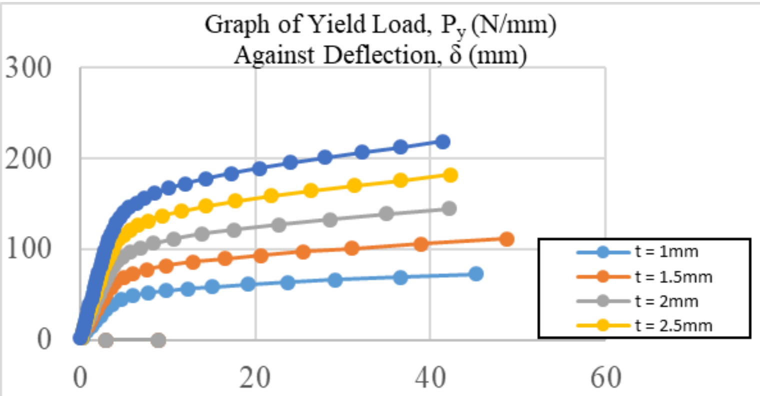

Figure 5. Load deflection of non-perforated C-channel section with various thickness.

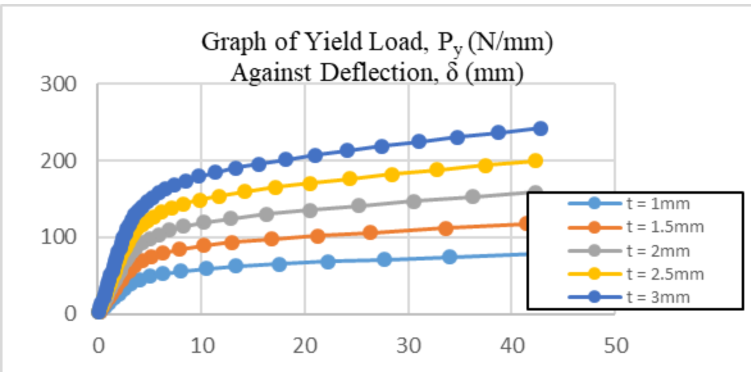

Figure 6. Load deflection of perforated C-channel section with various thickness.

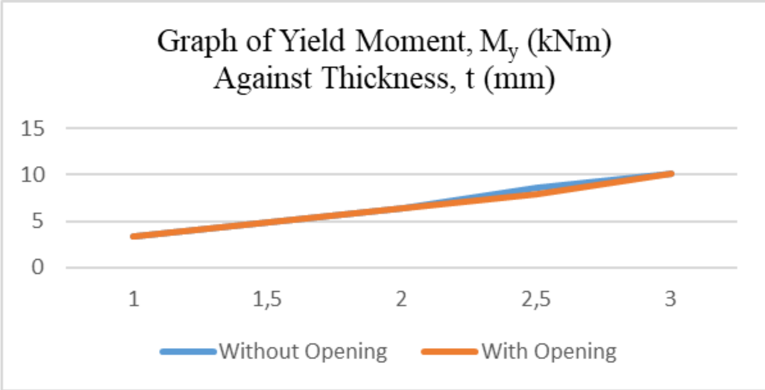

Figure 7. Graph of yield moment against thickness of section.

5.3. Deformation shapes

Based on the result from finite element analysis, the displacement of the model in y direction can be observed from the contour result. Figure 8 and Figure 9 shows the finding of contour of displacement for C-channel section with and without openings subjected to nonlinear loading for comparison. Figure 10 shows result of contour of displacement for C-channel section with 0.4D of square opening. The differences are insignificant.

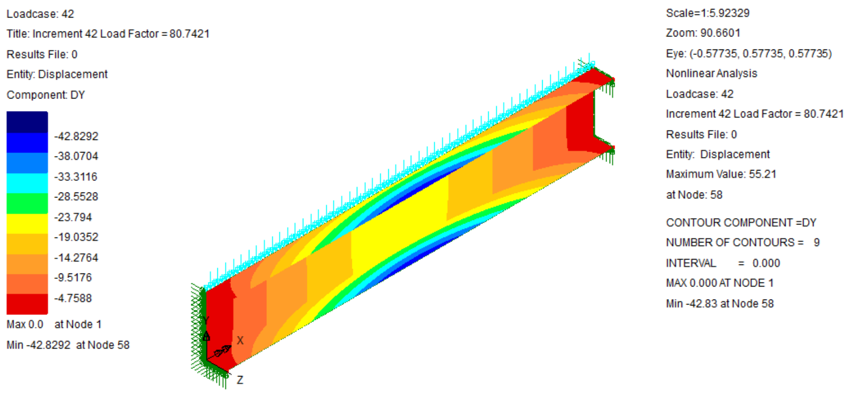

Figure 8. Result of contour of displacement for C-channel section without opening.

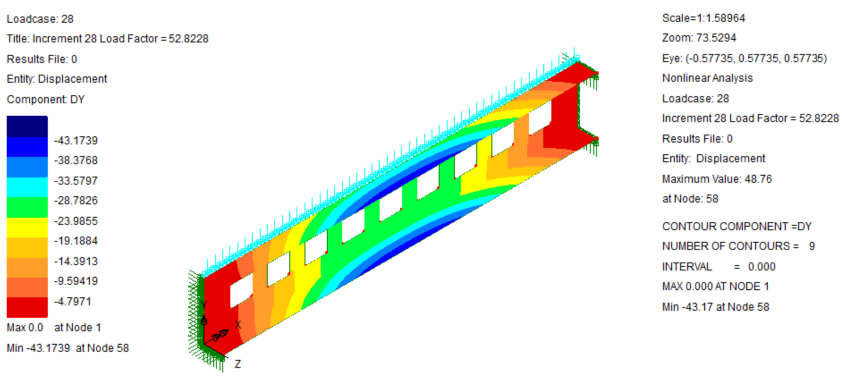

Figure 9. Result of contour of displacement for C-channel section with opening.

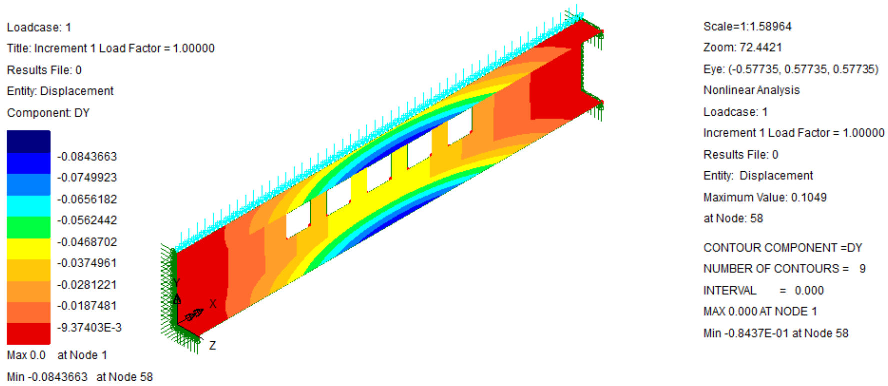

Figure 10. Result of contour of displacement for C-channel Section with 0.4D of square opening.

5.4. Discussion
Bending behavior and performance of C-channel steel section with opening were studied by the finite element analysis. The analysis was based on the changes of three variables such as opening spacing, edge distance, and thickness of section. Comparison was made between C-channel section with opening and without opening in terms of nonlinear bending capacity. From the results obtained above, it was found that the increasing of the opening spacing and edge distance will decrease the yield moment. Furthermore, thicker section and deeper web were proposed for the optimum design in bending since the results show that the thicker the section, the higher the bending capacity. C-channel section without openings appears to have the same or higher bending capacity than C-channel section with opening when the effect of thickness and depth of section were studied. Finally, in terms of bending behavior, C-channel section with 0.4D of square opening and 0.3L edge opening as well as 0.1L opening space can replace the C-channel section without opening because there is no difference of yield moment between both model but the volume reduction is significant, with 7.28%.

6. Conclusions
Nonlinear finite element analysis on various openings and geometric properties of C channel steel section compared to C-channel steel section without opening under bending. From this study, the bending behavior of C-channel steel section can be concluded as:

a) The C-channel section without opening has higher yield moment than C-channel section with opening.

b) The yield moment increases when the opening spacing increases, similar to the edge distance.

c) Thicker section can resist more bending. The thickness of the section was direct proportionate with the yield moment.

Secondly, comparing the effective cost reduction between perforated and non-perforated steel section in steel framing system, the results can be concluded that:

a) In terms of bending behaviour, C-channel section with 0.4D of square opening and 0.3L edge opening as well as 0.1L opening space can replace C-channel section without opening because there are no difference of yield moment between both model but the volume reduction is significant, with 7.28%.

b) C-channel section with 0.4D of square opening and 0.3L edge opening as well as 0.1L opening space can give a very effective cost reduction.

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