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Research paper

Investigation on the use of cold formed perforated steel sections as columns and purlins

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Abstract

Perforations are required in columns and purlins of a trussed building for making connections, for fixing electrical fixtures etc. An investigation was undertaken to study the effect of perforations in cold-formed C and Z sections used as columns and purlins. For this purpose, finite element model was developed using ANSYS software. Six different shapes of perforations were considered to investigate the shape that gives maximum buckling load. The perforation pattern which is optimum for the individual section was applied to frames and then to the building and optimum type of perforation is suggested. Buckling loads of frames and building with and without perforation was done separately and results were compared. By considering perforations with equal area, linear buckling analysis was done and stress pattern around perforation was studied. Even though the area reduction was equal, differently shaped perforations gave different buckling load. In this case, stress concentration has an important role; buckling load is higher for the shape with least stress concentration.

Keywords: *ANSYS; Buckling; C and Z Section; Cold Formed Steel; Perforation.*

1. Introduction

During recent years, the use of cold-formed steel members in building construction and other areas has increased vastly, because of their favorable strength to weight ratio, ease of fabrication, and ease of erection and installation. A large number of products, with different shapes, sizes, and applications are produced in steel using cold forming processes such as folding, press braking, and rolling. The cold forming process reduces the cross-section and improves the properties of the material.

The main applications of cold-formed steel are the construction of light steel structures including frame systems, thinly walled steel trusses, grids, and reticulated shell structures. When cold formed sections are subjected to various loading conditions, they tend to buckle locally at stress levels lower than the yield strength of the material. There are different buckling modes such as local, global, distortion and torsional flexural. The buckling mode is influenced by various factors like cross-section geometry, end conditions, loading, material etc. Also, introducing perforations to structures has a significant effect on the critical buckling load and buckling mode.

Cold-formed steel members are typically manufactured with perforations to facilitate various services in building construction. These perforations are varied with respect to their position, size, shape, number of perforations, and orientation as shown in figure

Introduction of these perforations helps in reducing the overall cost of the project by reducing the total weight of the structure. Also, perforations in the roof system reduce the load transferred to the supporting members, so that the size of these member sections can be reduced.



Fig. 1: Perforated Cold-Formed Steel Sections Used as Framing Members.

Numer- ous researchers on perforated cold-formed steel members have carried out a large number of investigations. Most of the researchers used C sections or Z sections for the investigation purpose as these are the commonly used sections in frame works. The direct strength method, effective width method, and finite element methods have been used in investigations related to cold-formed steel structures. MP Kulatunga and M Macdonald carried out a detailed investigation on the perforated channel members and found out that reduction in stiffness associated with the sections with circular perforations was higher than that for slotted perforation with the same cross-sectional area. From their study, they concluded that design code predictions of load carrying capacity of cold-formed steel sections with perforations are inadequate and still there are no reliable equations or models for predicting the ultimate buckling strength. Some studies on cold-formed steel sections with web opening has been carried out by Sivakumaran and discovered that circular opening and square opening does not alter the strength significantly. Perforations affect the ultimate capacity. The ultimate load capacity decreases with increase in opening size and increasing the length of perfora-

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tion. After carrying out the analysis using finite element method, J Y Ling concluded that the factors affecting buckling are edge distance, number of opening, and also the opening spacing. Ling used five different shaped openings and found out that hexagon shaped perforation has higher buckling load compared to other shapes. Cristopher D. Moen conducted an experimental study to evaluate the influence of industry-standard slotted holes on short and intermediate length cold-formed steel structural studs and found out that, slotted web holes were shown a minimal influence on the ultimate strength in the specimens considered, although post-peak ductility was decreased in some cases. A number of investigations on the buckling behavior of the cold-formed section with holes concluded that the effects of material non-linearity, residual stresses, imperfections etc. give the potential for the interaction of buckling modes. In the case of local buckling, any interaction that exists between elements is treated independently.

This paper investigates the effect of various shapes and sizes of perforation on the buckling load capacity of cold-formed C sections used as columns and Z sections as purlin. The perforation pattern which gave maximum buckling load was taken as optimum perforation pattern. This optimum perforation pattern was applied to the selected frame and then to a trussed building, and change in buckling capacity with and without perforation was studied.

2. Selection of cold-formed steel sections

For the study, a building with dimension 36 X 12m is considered and by using relevant codes the building is designed .Plan of the selected structure is shown in figure 2. The Fink type truss is selected and the spacing between the trusses is fixed as 3.6m. By selecting the column height as 6m, loads coming on the truss were calculated as per IS 875 part 1, 2 and 3. The building was analysed in STAAD pro-V8i for designing the cold-formed steel C section for column and Z sections for purlin. Steel design using STAAD results gave sections, C channel section of web depth D=150mm, flange length B=50mm and thickness of section t=5mm (150sCUx50x5) and Z lipped channel section of D=140mm, B=60mm, t=2mm and lipped length x=20mm (140ZSx60x2) and are adapted for this investigation .The rendered view of the trussed building is shown in figure 3.

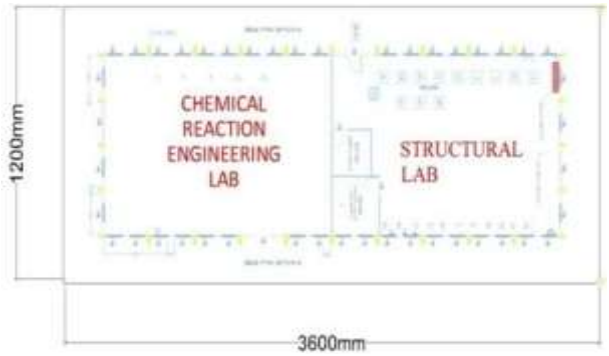


Fig. 2: Plan of the Selected Trussed Building.

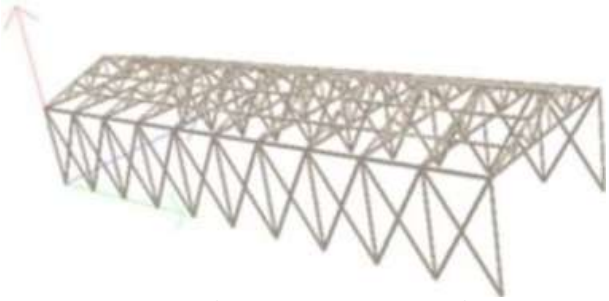


Fig. 3: Rendered View of the STAAD Pro Model of Selected Trussed Building.

3. Selection of the perforation pattern

The following variables are studied:

i) Perforation Shape 6 web perforations of different shapes are considered in this study are,

1) Circle
2) Diamond
3) Elongated circle
4) Hexagon
5) Octagon
6) Square

First 5 shapes of perforation are drawn by referring to the research carried by Jin Ying and Shin Lin. Geometric configurations of web perforations are as shown in figure 4.

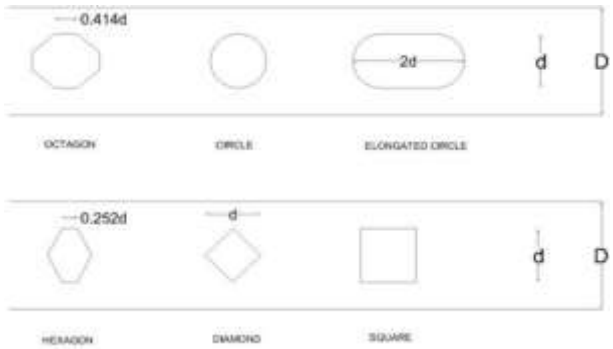


Fig. 4: Geometric Configuration of Perforation. D is the Width of per Foration.

ii) Size of perforation

For the study on various perforation sizes, two perforation sizes are adopted, which are 0.25D and 0.5D. Perforation with 0.25D size is denoted as type (1) and 0.5D as type (2).

iii) Corner profile

The perforations which are having sharp corners are studied with and without rounding the corners.

iv) Perforation with equal area

By keeping the area of perforation as constant the dimensions of the perforation is changed and the effect of perforation under equal area reduction is also studied.

For the entire study, the perforations are centrally placed in the web of the sections to avoid the eccentricity. The effects of equal area perforations are studied with 1m specimens. C sections are analyzed as columns with the fixed-free condition and Z sections as purlins with the simply supported condition. Center to center spacing of the perforations is fixed as 300mm.

4. Modeling and analysis in ANSYS

68 models have been developed for this study to investigate the effect of perforations to the cold-formed sections. In this paper, ANSYS WORKBENCH 16 is used to for the analysis. CAD models of the sections are drawn and imported to ANSYS. The material properties of the model are same for all specimens. For this study, linear elastic properties of the material are taken as 210 GPa for Young's modulus and Poisson's ratio is set to 0.3.

Eigenvalue buckling analysis is used to estimate the buckling load of individual members, frames, and building. Comparison between buckling behavior of models with and without perforation was carried out.

5. Analysis of perforated sections with equal area

Cold-formed steel C and Z section of 1m length were analysed with perforation of equal area. The dimensions of each perforation are as shown in figure 5. Here C section is analysed as the column with fixed free condition and Z section as purlin with the simply

supported condition. Buckling load of perforated sections and Eigenvalues are shown in table 1. The stress distribution around perforation subjected to axial load is also studied. Figure 6 shows the stress distribution around differently shaped perforations.

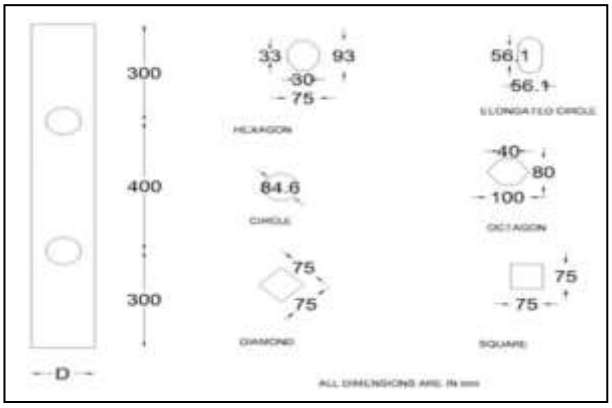


Fig. 5: Dimensions of Perforations with Equal Area.

Table 1: Buckling Load of Differently Shaped Perforations with Equal Area EV is the Eigenvalue; BL is the Buckling Load, So- Same Orientation of Per- Foration as in Figure 8 and Oc- 90o Rotation of Figure 8

Perforation Shape	C Section		Z Section	
	Ev	Bl	Ev	Bl
Without Perforation	12.26	122.67	15.93	159.3
Circle	11.412	114.12	12.936	129.36
Diamond	11.071	110.71	10.577	105.77
So	11.746	117.46	11.924	119.24
Elongated				
Oc	10.773	107.73	13.619	136.19
So	11.232	112.32	13.95	139.5
Hexagon				
Oc	11.418	114.18	14.3	143
So	11.518	115.18	13.162	131.62
Octagon				
Oc	11.017	110.17	13.96	139.6
Square	11.453	114.53	14.808	148.08

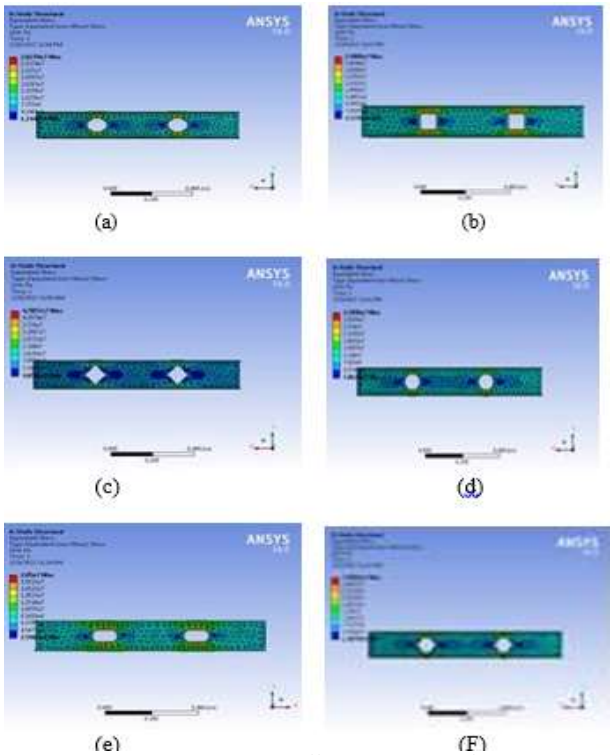


Fig. 6: Stress Distribution around Different Shaped Perforations A) Octagon B) Square C) Circular D) Diamond E) Elongated Circle F) Hexagon.

6. Analysis of individual sections

Finite element analysis of cold-formed C channel section as column and Z section as purlins were conducted with different shape and sizes of perforations. The obtained buckling load of the non-perforated section is kept as the reference and percentage reduction of the buckling loads are calculated and compared. Percentage reduction in the volume of steel is also calculated in each case for finding out an optimum perforation pattern which is having comparatively higher buckling load and volume reduction.

6.1. C Channel section analysis

The length of the column of the selected trussed building is 6m. Buckling analysis is performed for non-perforated channel section and perforated channel sections as shown in figure 7 and figure 8.The end condition is the fixed-free condition. Analysis of C channel steel section subjected to axial load was conducted. Percentage reduction in buckling load of perforated sections compared to the non-perforated section is as shown in table 2. For this study, two opening sizes, which are 0.25D and 0.5D, are considered. ANSYS model of the C section with type (2) circular perforation is shown in figure 7 and the deflected shape of the column is shown in figure 8. For the study on the effect of corner rounding, perforations which are having sharp edges were rounded and ana- lysed separately. The result obtained is shown in figure 9.

6.2. Z section analysis

Cold-formed steel Z sections of 6m length were analyzed as purlins with the simply supported condition. As in the case of C channels here also two opening sizes and six different shapes of perforations are considered. Percentage reduction in buckling load and percentage reduction in the volume are shown in table 2. ANSYS model of the Z section with type (2) circular perforation is shown in Fig. 10 and the deflected shape of the purlin are shown in figure 11.

Table 2: Percentage Reduction in Buckling Load of C and Z Sections BR is the Percentage Reduction in Buckling Load and VR Is the Percentage Reduction in Volume

Perforation Shape	C Section				Z Section			
	0.25D		0.5D		0.25D		0.5D	
	BR	VR	BR	VR	BR	VR	BR	VR
Without Perforation	0	0	0	0	0	0	0	0
Circle	2.14	1.53	7.35	6.134	7.449	1.076	17.068	4.306
Diamond	1.6	1.955	7.812	56.96	1.37	16.214	75.482	
Elongated	3.34	3.481	3.461	3.947	13.764	2.447	20.525	9.78
Hexagon	1.88	1.567	13.6	25	12.29	11.25	17.001	35.47
Octagon	2.2	2.348	8	9.375	4.63	1.79	12.213	7.049
Square	2.46	1.951	0.647	81.256	279	1.37	17.073	5.482

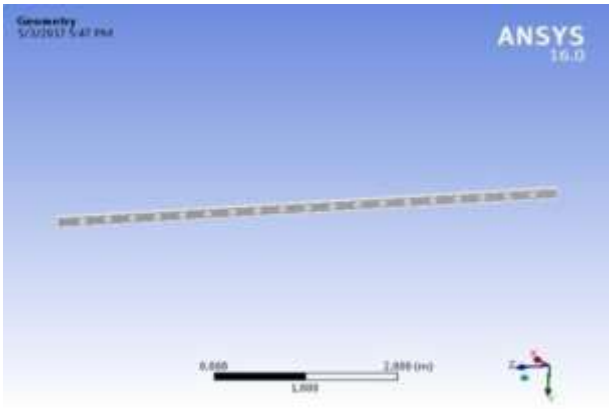


Fig. 7: ANSYS Model of C Section with Type (2) Circular Perforation.

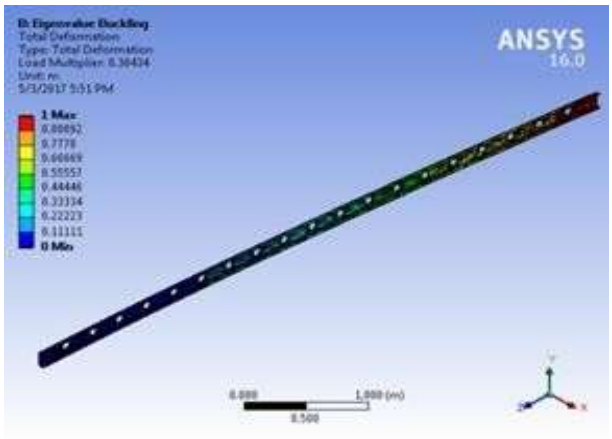
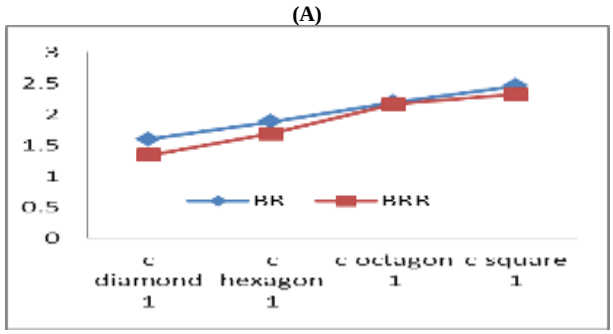
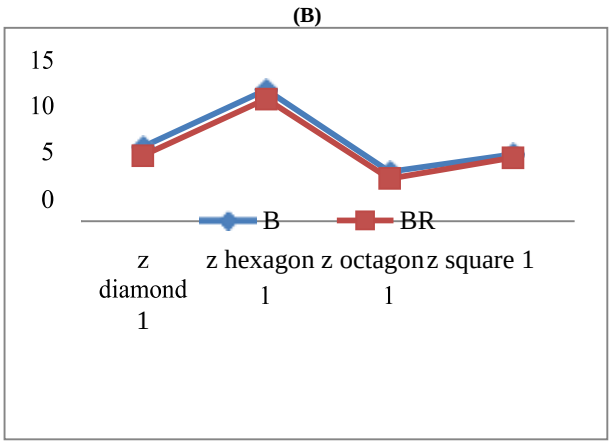
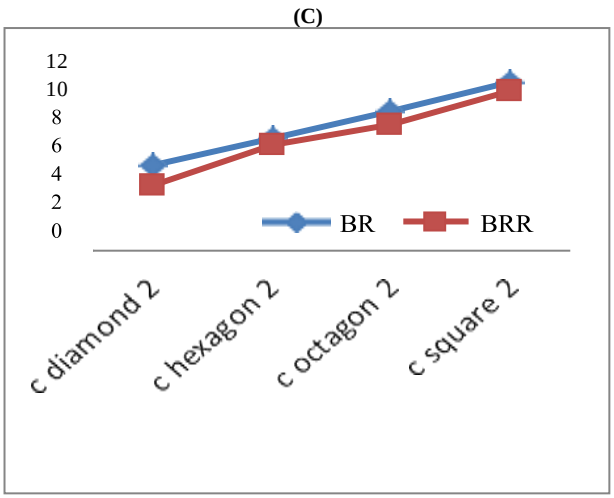


Fig. 8: Total Deflection of C-Section with Type (2) Circular Opening.

Here also analysis of rounded edge perforation was done and the result is shown in figure 9.In figure 9 BR is the percentage reduction in buckling load and BRR is the percentage reduction in buckling load when perforations are with the rounded edge







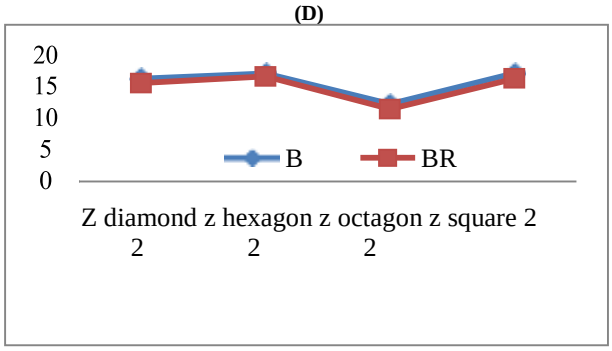


Fig. 9: Percentage Reduction in Buckling Load Due to Corner Rounding For Various Shapes of Perforations (A) C Section with Type 1 Perforation B) Z with Type 1 C) C with Type 2 D) Z With Type 2 (Percentage in Y-Axis).

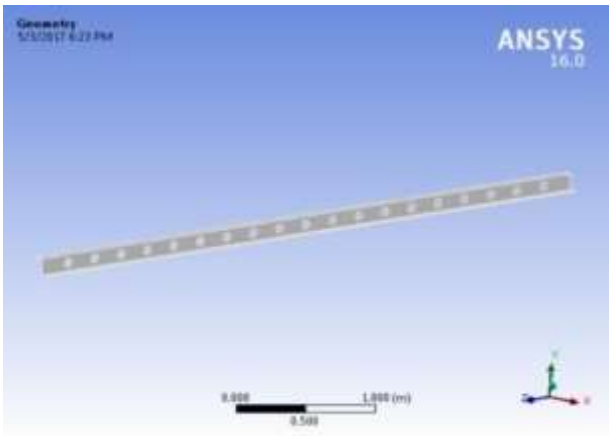


Fig. 10: ANSYS Model of Z Section with Type (2) Circular Perforation.

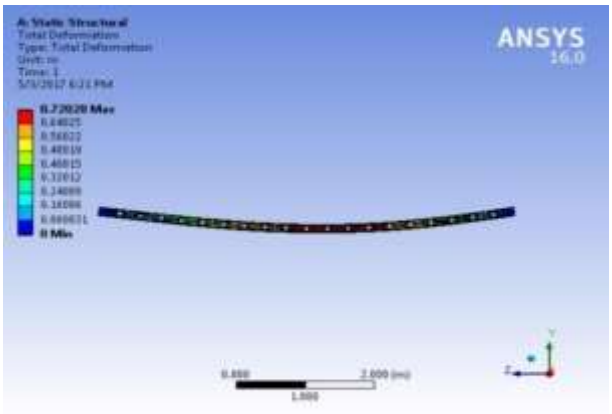


Fig. 11: Total Deflection of Z Section with Type (2) Circular Opening.

7. Analysis of frame with and without perforations

A single frame of the selected steel structure was analyzed with and with- out perforations. For C section diamond-shaped perforation is selected as the optimum pattern as it gave maximum buckling load and relatively higher volume reduction. Similarly for Z section octagon shape is selected as the optimum pattern. Perforation which is selected as the optimum pattern is applied to column members and main truss members. The analy- sis is done for type 1 perforation which is having depth 0.25D in one mod- el and type 2 with 0.5D in another model. The frame without perforation was analyzed first and the obtained Eigenvalue was compared with the Eigenvalues of frames with perforation. A uniformly distributed load is given above the Z section. Eigenvalue and the total volume of steel for each frame are as shown in table 3. ANSYS model of the frame and the resulted total deformation is as shown in figure 12 and figure 13 respectively.

Table 3: Load Multiplier and Total Volume of Steel of Frames

Frame	Eigen Value	Total Volume Of Steel(x $10^{-4}m^3$)
Frame With Out Perfo- ration	113.1	462
Frame With Type 1 Perforation	102.87	437
Frame With Type 2 Perforation	90.424	415

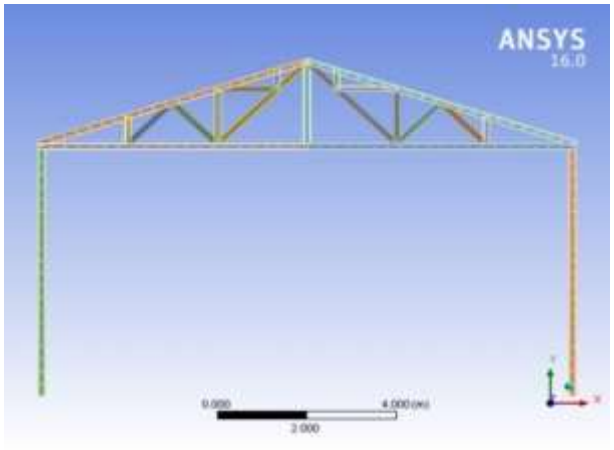


Fig. 12: ANSYS Model of Frame with Type (1) Perforation.

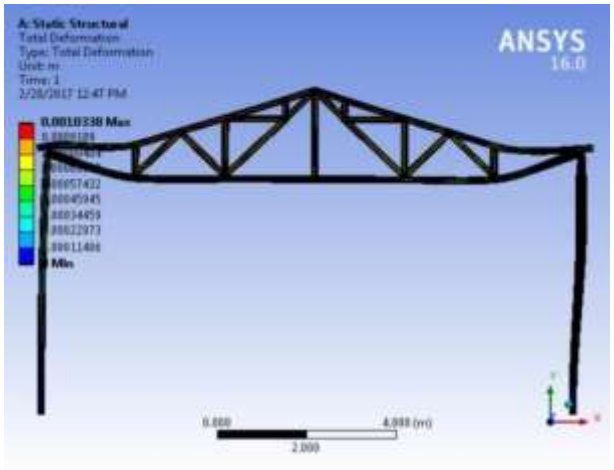


Fig. 13: Total Deformation of Frame with Type (1) Perforation.

8. Analysis of trussed building with and without perforation

The selected steel building is analyzed with and without perforated C and Z sections. The analysis is done with both type 1 and type 2 perforated elements. Perforation is given to the truss, lateral bracings and purlins. A uniformly distributed load is given to the roof cladding. The analysis result of the structure without perforation is compared with the structure with perforated elements. Reduction in buckling load and volume of steel in each case is shown in table 4. ANSYS model of the building and the resulted total deformation is as shown in figure 14 and figure 15 respectively.

Table 4: Percentage Reduction of Buckling Load and Volume of Buildings

Building	Percentage Reduction In Buckling Load	Percentage Reduction In Total Volume
Building With Out Perforation	0	0
Building With Type 1 Perforation	18	12
Building With Type 2 Perforation	35	21

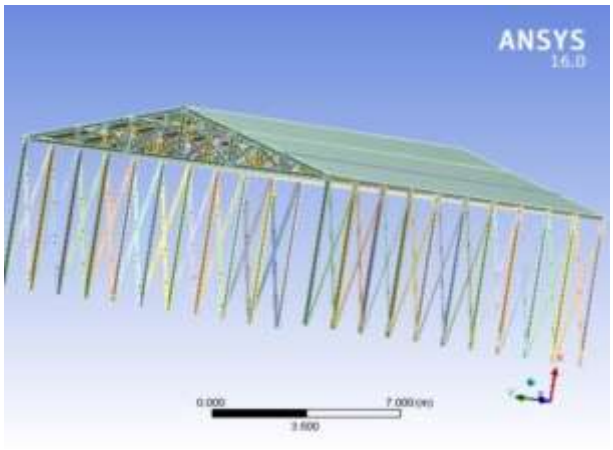


Fig. 14: ANSYS Model of Building with Type (1) Perforation.

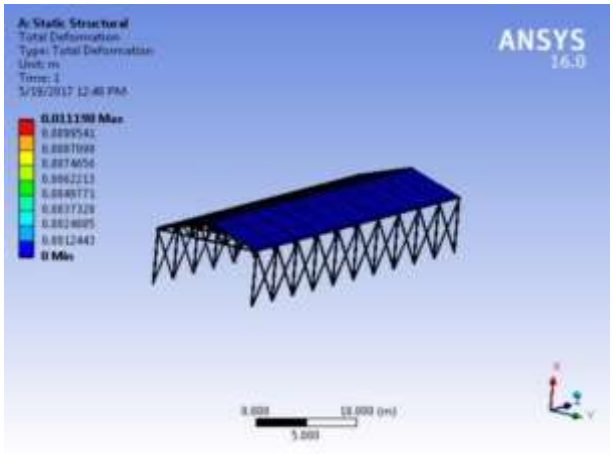


Fig. 15: Total Deformation of Building with Type (1) Perforation.

9. Conclusion

From the analysis results of cold-formed steel C and Z sections, the factors affecting buckling load are the size of the opening, the shape of the opening, number of sharp edges and opening length etc. From table 2 for cold-formed steel C section subjected axial load with opening size 0.25D, it can be seen that section with the diamond opening has higher buckling load compared to other opening shapes such as circle, octagon, square, hexagon and elongated circle. For diamond-shaped perforation percentage reduction in buckling load is 6% for type (2) perforation. And for Elongated circle opening, which is having the lowest buckling load, the percentage reduction in buckling load is 14%. This higher reduction may be due to its largest opening length. So the diamond-shaped perforation is selected as optimum perforation for C section which is having comparatively higher buckling load and volume reduction. A similar trend is observed for opening size 0.5D.The study on the effect of corner rounding of perforation showed that corner rounding increases the buckling load slightly. For diamond-shaped perforation, the effect is more, as shown in figure 9, and this may be due to a decrease in the stress concentration. For diamond-shaped perforation corner rounding of perforation increases the buckling load up to 3%.

In the case of Z section, which is considered as purlin, from Table 2, for both the opening sizes octagon shape shows less reduction in buckling load and for type (2) it is 12%. In the case of Z section also elongated circle type perforation showed a higher reduction in buckling load (20%). Here the octagon shape is considering optimum shape. Here also analysis of section having perforations with rounded corner is done and as in the case of C section here also found a small increase in buckling load due to the reduction in the stress concentration.For octagon shape, the increase in buckling load is around 3%.

Analysis of sections with perforations having equal area showed that for C section as the column, the section with elongated circle perforation is having higher buckling load and for Z section square shape is having higher buckling load compared to other shapes. The shape of the perforation is one of the main factors which affects the buckling load. Even though the area reduction is constant if the shape of the perforation is different buckling load also will be different. The stress pattern study showed that maximum stress is concentrated at the sides which are parallel to the loading. When the width of that side decreases stress concentration increases. The maximum stress concentration is observed for the diamond shape.
The analysis of frame with and without perforations showed that with the introduction of perforations there is a reduction in buckling load. When type (1) optimum perforation is applied to the frame percentage reduction in buckling load is 9% and the corresponding volume reduction is 5%. For type (2) perforation buckling load and volume reduction is 20% and 10% respectively.
From the analysis of building with and without perforation it is observed that when perforations are introduced, for type (1) perforated building reduction in buckling load is 18% and the corresponding volume reduction is 12% and for type (2) perforated building the reduction in buckling load and volume are 35% and 21% respectively.

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