Finite Element Analysis on Torsion Behaviour for Tapered Steel Section with Perforation

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Abstract A study of finite element analysis (FEA) on torsion behaviour for tapered steel section with perforation is presented in this paper. The attention was paid mainly to firstly determine the effect of the perforation on the torsion behaviour of tapered steel section and to know an optimal section of tapered steel section with perforation under torsion loading based on the results obtained from FEA of LUSAS software. Five (5) variables such as opening shape, web thickness and flange thickness were identified and analysed to know the effect on torsional rotation of tapered steel section. A total of one hundred and twenty (120) of finite element (FE) models were than employed in this analysis including tapered steel section without perforation. The results were expressed in terms of displacement and torsional resistance (TR). Based on the analysis result, it was clearly showed that there was no improvement on the engineering properties and performance of tapered steel section with perforation in term of TR. The presence of web opening will result in reduction of TR. It is concluded that all of the variables will affect the TR. In addition, weight was reduced as the material volume was reduce with the present of perforation.

Keywords Tapered steel section · Perforated steel beams · Torsion · Volume reduction · Finite element analysis · LUSAS 14.0

1 Introduction

Normally for a structural element, I-beam steel section was used. This was because I-beam section consists of strong axis and had the capability to carry both bending and shear loads in the web plane. However, in practical applications, I-beam section will experience torsional and bending when load was applied.

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Besides I-beams, tapered steel section was commonly used in steel construction industry. This was because the unique ability of structural efficiency which can save the material used and the cost [1, 2]. At the same time, it truly fulfils the architectural and functional requirements. These beams were used as it has the aesthetic value and less weight. In addition, it was also structurally efficient as the beam has tapered web which almost match the beam's bending moment variation [3]. For a wide flange beam (width/depth = 0.96), the web tapering increased the critical load buckling by 2%. Whereas for a narrow flange beam (width/depth = 0.19), the web tapering reduced the buckling load up to 10 and 6% for the tip point loading and the uniformly distributed load respectively. However, when the lateral torsional buckling occurs, the increasing of beam length will decrease the critical bending moment at the fixed support.

Previous researches have been carried out to study the lateral torsional buckling of web tapered tee-section [3], lateral torsional buckling of web tapered I-beam [1, 4–6] and shear buckling stress of tapered bridge girders with steel corrugated webs [7]. Besides that, a beam with equal and unequal flange, the lateral torsional buckling loads was higher for the small tapering ratio, $\alpha = h_{min}/h_{max}$ than greater α except for a short beam with equal flange.

In real life, there was not so many steel design standards give the guideline to design the steel to against torsion. Usually, torsion behaviour was ignored because it was thought to occur rarely and when it occurs, it was considered as unimportant problem [8]. The behaviour of steel section with perforation has been studied recently by few researchers. Various shape of perforation affected the local buckling [9] and Vierendeel capacity [9, 10]. Besides that, the increase of opening size is decreased the shear strength [11].

The validity of the finite element method was assessed by comparing the results with experimental results. A comparison between the results of finite element method with experimental results by previous researchers and the overall mean for M_{FE} and M_{test} ratios was 1.01 [12]. ABAQUS software was used in order to study the nonlinear behaviour of thin web panels by comparing the result with the available experimental results from other researcher [13]. Another researcher [14] also had compared the finite element method with theory and experimental for the study on torsional behaviour of rectangular hollow section. Others study for validity of finite element method also done by another researcher [11, 15, 16]. As two hexagon openings near to the end support was replaced with circular holes had decreased the buckling capacity and give a lower buckling factor. Besides that, elongated opening will decrease the critical buckling load especially near to the support as it was a high shear zone. Modification of a regular rectangular opening by removing the middle post between to web holes to create an elongated opening and had causes a concentration of stress at the corners of the opening [17]. Nowadays, for steel skeleton structures tapered steel sections as shown in Fig. 1 were more preferable.

According to the basic theory, the derivation of torque formula begins by considering the simple case of normal flat web beam [18].

Fig. 1 Tapered steel section with 3D view [2]
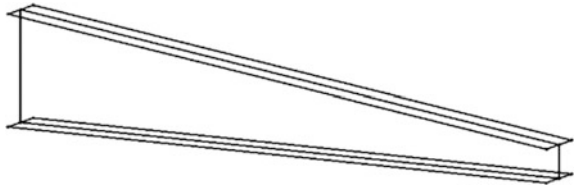
$$\theta = \frac{TL}{JG} \tag{1}$$

In which L was the length of the section, T was applied torque, J was torsion constant for the section, and G was shear modulus of the material. However, for a web tapered I beam the angle of twist was already derived [7].

2 Methodology

2.1 Finite Element Analysis on Torsion Behaviour with LUSAS

In this paper, all the models were developed by using LUSAS version 14.7 software. Throughout this research, the torsion behaviour of tapered steel section with or without perforation as found in Figs. 2 and 3 was resembled by applying a point
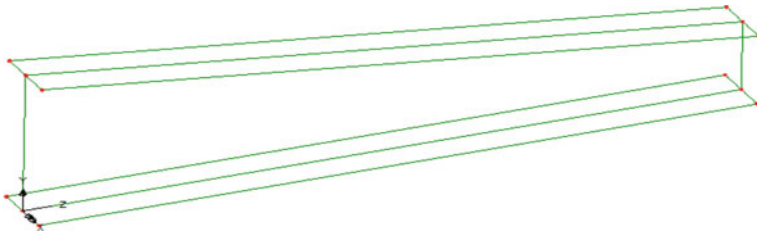
Fig. 2 3D view of tapered steel section
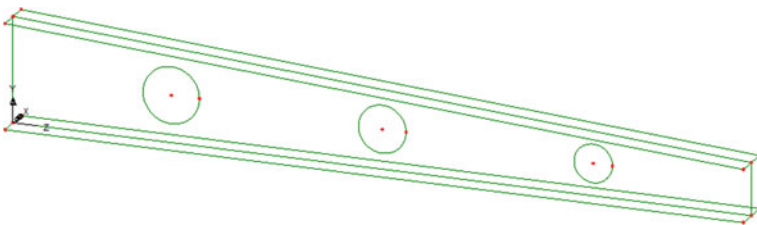
Fig. 3 3D view of tapered steel section with web opening

load at four different points at one end of the model in x and y direction. Another end of the model was restrained in x, y and z direction so that it will be fixed end support. To obtain the torsional rotation (θ), linear analysis was carried out for the both models. The finite element analysis will give the displacement value. From the value the torsion rotation of each model will be calculated. Quadrilateral thin shell element (QSL8) and interpolation order in quadratic were chosen. For this analysis, the material used was mild steel and the properties which were kept constant which were Young Modulus, $E = 209,000$ N/mm^2, shear Modulus, $G = 80,385$ N/mm^2 and Poisson ratio, $v = 0.3$.

A few variables as found in Figs. 4, 5 and 6 were investigated to identify the effect toward the angle of twist of the tapered steel section with opening. The variables involved were:

(a) Shape of opening
(b) Thickness of the web
(c) Thickness of the flange.

2.2 Convergence Study

Convergence criteria were defined to determine the suitable mesh for the model. The convergence of the mesh was established by independently increasing the mesh density in each part of the beam model section. The model was given increased mesh density in all part of the section simultaneously and with the higher-order elements (QSL8). From the result of the mesh ratio investigation as found in Fig. 7, element size 15 was selected.

3 Results and Discussions

A total of 120 non-linear finite element analysis were performed, covering different thickness of web and flange, different span length and different tapering ratio. For ease of comparison and discussion, the results presented in this dissertation were related to a cantilever steel beam of fixed depth (D) 500 mm and width (B) 200 mm for the $h_{\max}$ and for the $h_{\min}$ will be depends on the tapering ratio. The beams were applied with concentrated load at four different points at the end of the beam. While the web openings of various sizes 0.2D, 0.3D, 0.4D, 0.5D, 0.6D and 0.7D were located at the centre of web along the beam length.

(a) Shape of opening

(a)

(b)

(c)

(d)
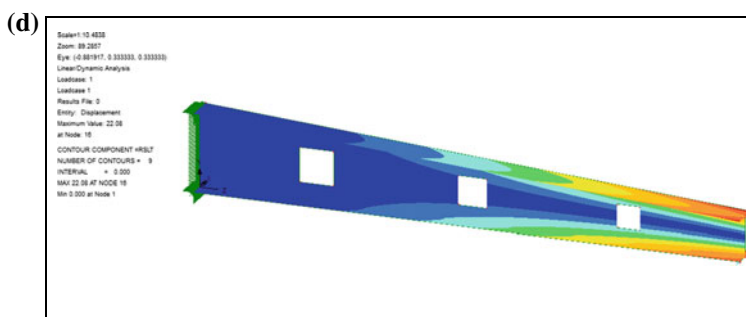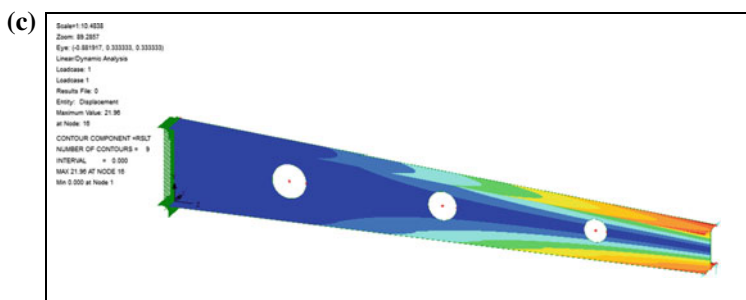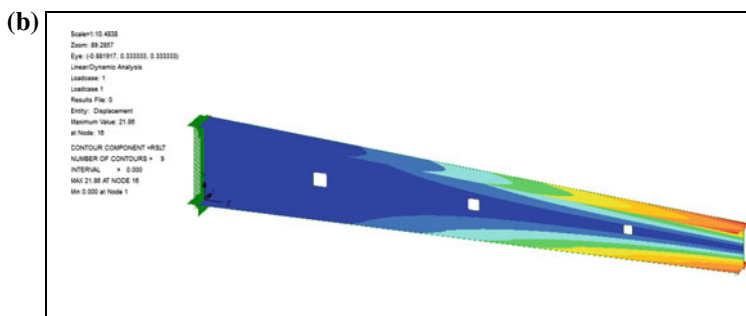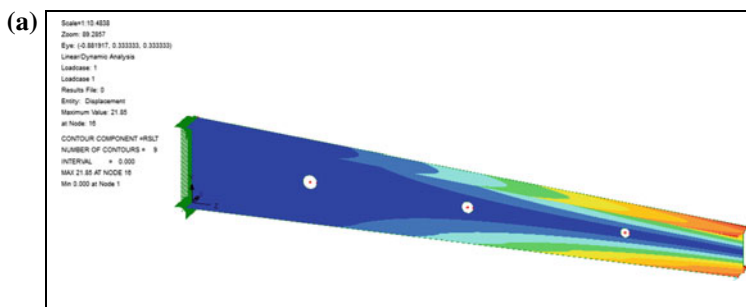
Fig. 4 **a** 0.2*D* circle shaped opening model, 1000 mm c/c, 500 × 200 × 13 × 9 section with 3.5 m length and 0.5 tapering ratio. **b** 0.2*D* square shaped opening model, 1000 mm c/c, 500 × 200 × 13 × 9 section with 3.5 m length and 0.5 tapering ratio. **c** 0.5*D* circle shaped opening model, 1000 mm c/c, 500 × 200 × 13 × 9 section with 3.5 m length and 0.5 tapering ratio. **d** 0.5*D* square shaped opening model, 1000 mm c/c, 500 × 200 × 13 × 9 section with 3.5 m length and 0.5 tapering ratio

3.1 Effect of Different Opening Shape

The effect of opening shape on torsional rotation was shown in Fig. 8. Circular shape clearly performs better than square shape as it retains its torsional rotation better than its counterpart. Circular shape opening possess lower torsional rotation at all opening sizes than square shape. For instance, circular shape opening and square shape opening at 0.2*D* has angle of rotation of 9.91° and 9.92° respectively. Meanwhile, the respective values at 0.7*D* were 10.08° and 10.14°. For comparison, the torsional rotation of control section was 9.90°.

From Fig. 8, it shows that square shape opening performs better than circular shape in terms of volume reduction. The volume reduction in web for both circular shape and square shape at 0.2*D* opening size were 1.10 and 1.41% respectively. The values increase to 13.61 and 17.33% respectively at any opening size of 0.7*D*.

## 3.2 Effect of Different Thickness of Web

For this case, the depth, width and thickness of flange are fixed while the thickness of web varies from 6 to 12 mm. The models have two different length with two different tapering ratios for each length was applied. All models were applied with 0.5*D* circular shape opening and the distance between the openings was fixed as 1000 mm c/c.

The result of displacement and angle of rotation were shown in Figs. 9 and 10. Tapered steel section with opening for 6 mm web thickness gave the lowest increase of torsional rotation in range of 0.15–0.27% when compared to tapered steel section without opening. It was observed that when the thickness of web increase, the torsional rotation will decrease.

3.3 Effect of Different Thickness of Flange

For this case, the depth, width and thickness of web were fixed while the thickness of flanges varies from 10 to 16 mm. The models have two different lengths with two

(b) Thickness of the web

(a)

(b)

(c)

(d)
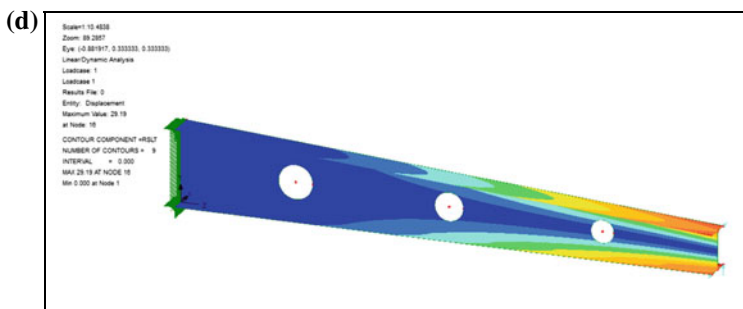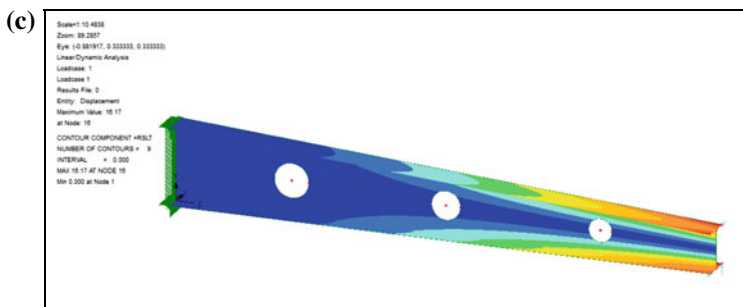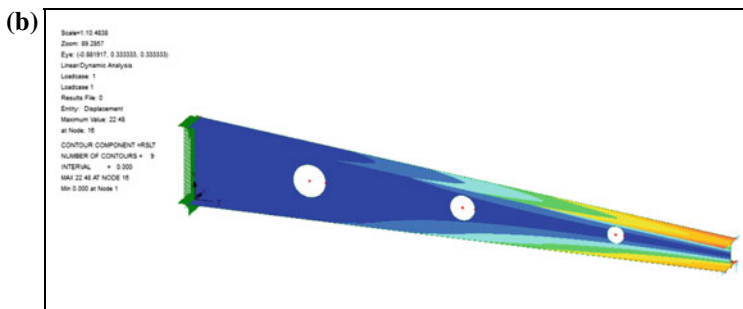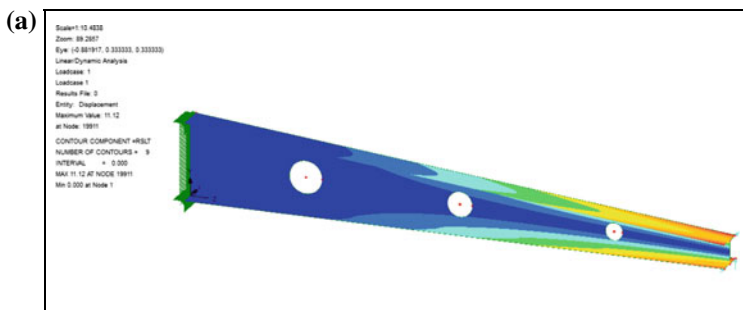
Fig. 5 a 0.5*D* circle shaped opening model, 1000 mm c/c, 500 × 200 × 13 × 12 section with 3.5 m length and 0.3 tapering ratio. **b** 0.5*D* circle shaped opening model, 1000 mm c/c, 500 × 200 × 13 × 6 section with 3.5 m length and 0.3 tapering ratio. **c** 0.5*D* circle shaped opening model, 1000 mm c/c, 500 × 200 × 13 × 12 section with 3.5 m length and 0.5 tapering ratio. **d** 0.5*D* circle shaped opening model, 1000 mm c/c, 500 × 200 × 13 × 6 section with 3.5 m length and 0.5 tapering ratio

different tapering ratios for each length was applied. All models were applied with 0.5*D* circular shape opening and the distance between the openings was fixed as 1000 mm c/c.

From the finite element analysis, the variation results of displacement and angle of rotation created by concentrated load, *P* were shown in Figs. 11 and 12. Torsional rotation increases from 0.23 to 0.56% for Fig. 11a, 0.56–0.80% for Fig. 11b, 0.46–0.89% for Fig. 12a and 0.79–1.42% for Fig. 12b respectively. It shows that tapered steel section with opening will increase the torsional rotation about 0.23–1.42%. It shows that the torsional rotation decreases as the thickness of flange increase.

From the graph, it was observed that when the thickness of web and flange increase, the angle of rotation for both models was decrease. This was because in the theory of torsion, the thickness of flange and web were inversely proportional with the angle of rotation. In the theory of torsion, the thickness of the section has been applied in calculating the value of torsional constant, (*J*). The tapered steel section with opening section gave the bigger value angle of rotation compared to tapered steel section without opening for all models which has different lengths with two different tapering ratios for each length. Due to high rotation value, geometry effect in nonlinear condition give important effects to describe the non-linear reaction in combined torsion and bending.

This was affected by the bending action about secondary minor axis due to the interaction between torsion and bending which caused by twist rotations ϕ. The first-order elastic central twist rotation $\phi_{L/2}$ due to pure torsion of the beams section was obtained by the approached addressed by Trahair and Bradford [19], Nethercot et al. [20] and Heins and Seaberg [21] as below where T = internal torque in middle part and $a^2 = EI_w/GJ$.

The effect of reduction in torsional stiffness was generated through effect of flexural-torsional buckling [20]. Despite of prevented section by continuous bracing torsional behaviour may occur due to the flexural-torsional buckling. However, an interaction between torsion and in-plane bending was affected an increment of torsional buckling behaviour and decreased the section strength, though section was prevented by flexural-torsional buckling. When the section fully yielded, the middle twist rotation in elastic condition was truly observed.

(c) Thickness of the flange

(a)

(b)

(c)

(d)
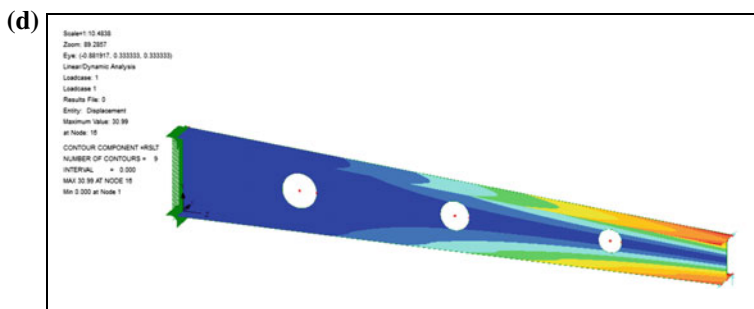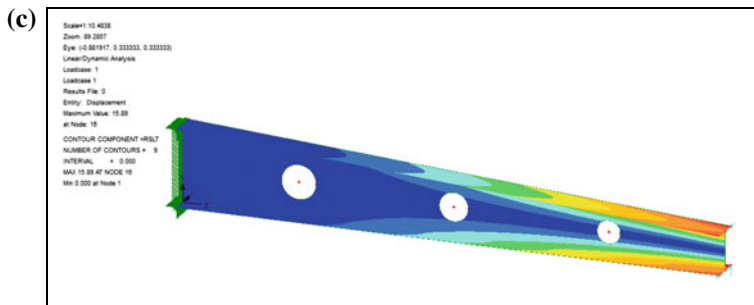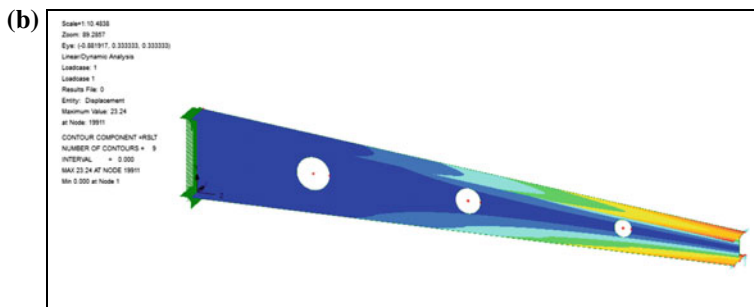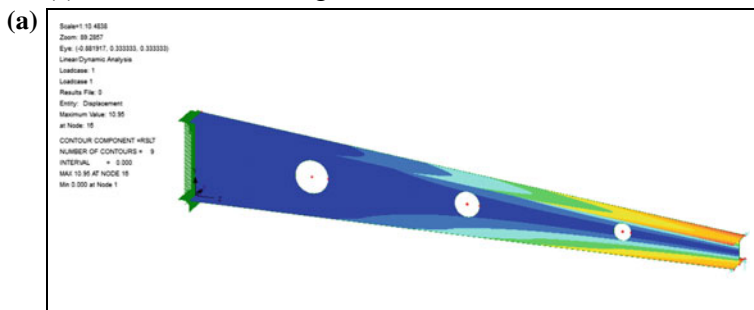
Fig. 6 **a** 0.5*D* circle shaped opening model, 1000 mm c/c, 500 × 200 × 16 × 9 section with 3.5 m length and 0.3 tapering ratio. **b** 0.5*D* circle shaped opening model, 1000 mm c/c, 500 × 200 × 10 × 9 section with 3.5 m length and 0.3 tapering ratio. **c** 0.5*D* circle shaped opening model, 1000 mm c/c, 500 × 200 × 16 × 9 section with 3.5 m length and 0.5 tapering ratio. **d** 0.5*D* circle shaped opening model, 1000 mm c/c, 500 × 200 × 10 × 9 section with 3.5 m length and 0.5 tapering ratio

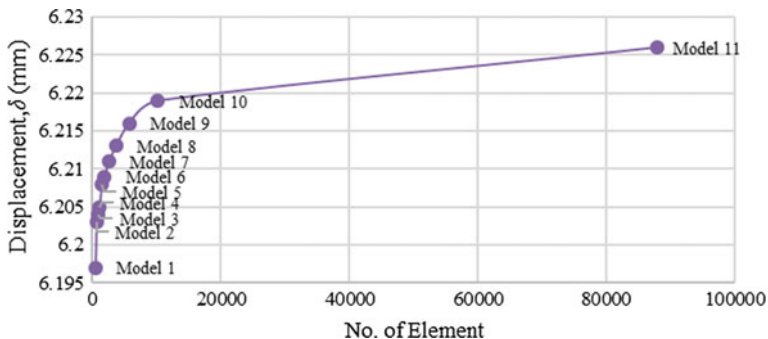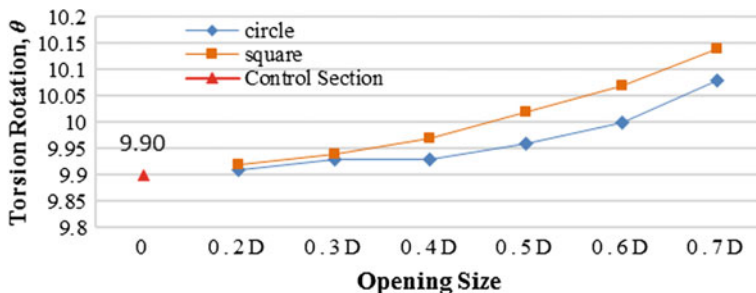**Fig. 7** Plot of maximum displacement against number of element

Fig. 8 Graph of torsion rotation, θ against opening size

3.4 Volume Reduction

Volume reduction was higher in square shape opening than circular shape opening. The results show that when all else being equal, square shape perform up to 17.33% better in volume reduction compared to its counterpart.

Volume reduction compared in web remains constant for each different thickness of web. From the results, it shows that the volume reduction compared in web does not change when all else being equal. The results also show that tapered steel section with perforation with 5.5 m length and 0.5 tapering ratio gave the highest volume reduction compared in web which was up to 7.4%.
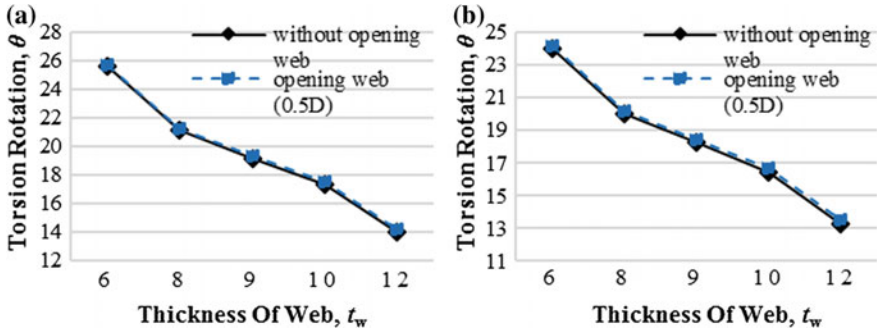
Fig. 9 Graph of torsion rotation, θ against thickness of web, t_w for model with 3.5 m length **a** Tapering ratio of 0.3 **b** Tapering ration of 0.5
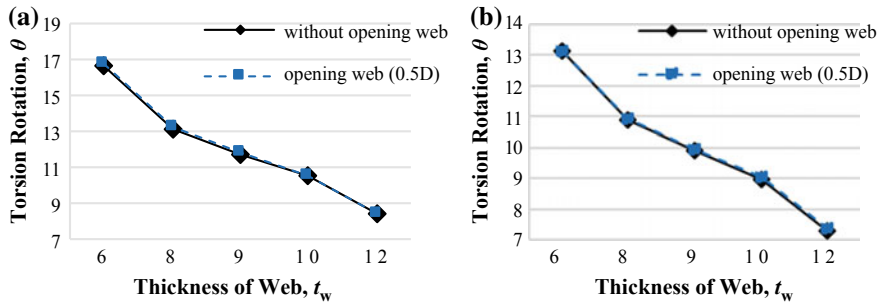
Fig. 10 Graph of torsion rotation, θ against thickness of web, t_w for model with 5.5 m length **a** Tapering ratio of 0.3 **b** Tapering ration of 0.5

Fig. 11 Graph of torsion rotation, θ against thickness of flange, t_f for model with 3.5 m length **a** Tapering ratio of 0.3 **b** Tapering ratio of 0.5
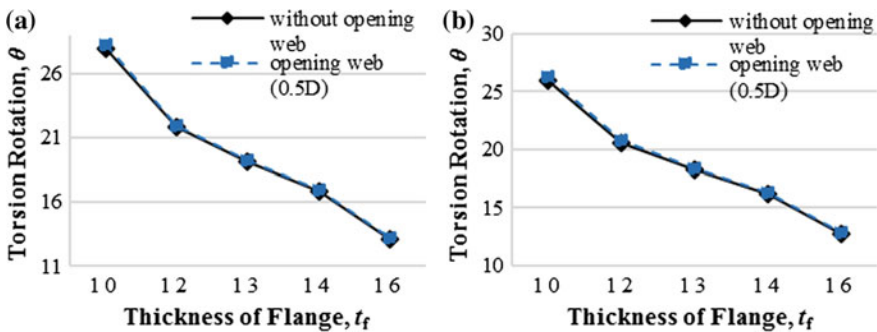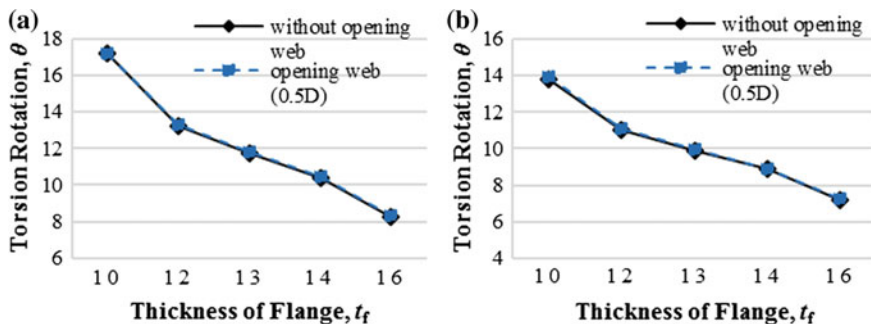
Fig. 12 Graph of torsion rotation, θ against thickness of flange, t_f for model with 5.5 m length **a** Tapering ratio of 0.3 **b** Tapering ratio of 0.5

Volume reduction compared to whole section decrease when the thickness of flange increase. The result shows that when else being equal, the volume reduction was 2.50–3.20% when the flange thickness increase to 16 mm. Volume reduction increase with the increase in opening size. The results show that when all else being equal, volume reduction increase by 2.62% in 0.2D opening size and 22.13% in 0.7D opening size.

Figures 13 and 14 shows the comparison mesh between tapered steel section with and without perforation. While Fig. 12 indicate the deformed shapes of tapered steel section with and without perforation.

Analysis result on opening shape indicate that circular shape opening was superior to square shape opening. When opening size exceed 0.3D, the torsional rotation difference about more than 0.40% was obtained. However, the torsional rotation between both shapes were only different 0.10% at 0.2D opening size and 0.70% at 0.7D opening size.

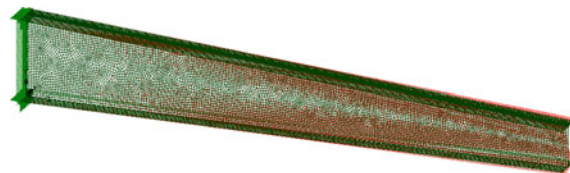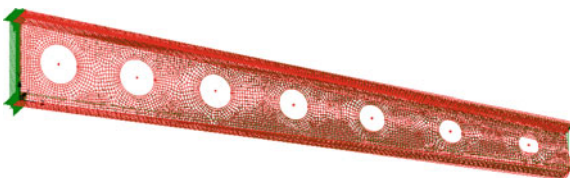**Fig. 13** Result of contour for tapered steel with perforation (0.5D)

Fig. 14 Result of contour for tapered steel on section without perforation

This analysis found that with the increment of web and flange thickness will decrease the torsional rotation. This was supported by the theory of torsion where the thickness of section will be applied in calculating the value of torsional constant. However, when compared the tapered steel section with and without perforation, it shows that 6 mm web thickness gave the lowest percent, 0.15–0.27% reduction of torsion resistance. For different flange thickness, the reduction of torsion resistance was from 0.23 to 1.42%. The optimal section for tapered steel section with perforation is tapered steel section with $0.4D$ to $0.6D$ circular shaped opening.

4   Conclusions

The engineering properties and performance of tapered steel section with perforation are investigated by finite element analysis. The analysis of results obtained from finite element method were carried out according to a few variables such as shape of opening and different thickness of web and flange. Furthermore, comparison between tapered steel section with perforation and without perforation has been done. The result indicates that the presence of perforation does not improve the engineering behaviour and performances were evaluated by torsional rotation and volume reduction respectively. From the results presented in this paper, the conclusions were:

- Circular shape opening perform better under torsion loading compared to square shape opening. The result show that when all else being equal, circular shape perform up to 0.70% better in torsional resistance compared to its counterpart.
- Torsional resistance increases as the web thickness increase. The results show that when all else being equal, 12 mm web thickness gave the lowest angle of rotation value. However, when all else being equal, the torsion resistance of tapered steel section with perforation only decrease in range 0.15–0.30% when compared to tapered steel section without perforation.
- Torsional resistance increases as the flange thickness increase. The result shows that when else being equal, 16 mm of flange thickness give the lowest angle of rotation. Besides that, the torsional resistance of 10 mm flange thickness of tapered steel section with perforation only decrease about 0.30–0.80% compared to tapered steel section without perforation.

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