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Finite Element Analysis on Triangular Web Profile Steel Section with Opening: Effects of Torsion Behaviour

Fatimah De'nan[1*], Nor Salwani Hashim [1], Lye Chu Wei [1]

[1]School of Civil Engineering, Universiti Sains Malaysia,
14300 Nibong Tebal, Penang, MALAYSIA

*Corresponding Author

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Abstract: In recent decades, there is a massive demand for steel sections that normally used in the construction of roads, railways, other infrastructures, appliances and buildings. This paper summarizes the torsion behaviour analysis for triangular web profile steel section with opening. Comparison on parametrical study is made using LUSAS software between triangular web profiles steel sections without opening and triangular web profile steel section with opening. A total of eighty finite elements analyses involve the changes of web thickness, flange thickness, span length, incremental loading, and size of circular opening were run to investigate the torsion behaviour effect on web opening shapes. The value of displacement and torsional rotation are the outcome of the final results. It was observed that triangular web profile steel section without web opening are able to maintain the static equilibrium by having higher torsional resistance compared to that of section with web opening.

Keywords: Web profile steel section, size of circular web openings, torsional rotation, finite element analysis, LUSAS

1. Introduction

1.1 Corrugated Steel Web

For civil engineering structures such as bridges, a lot of efforts have been carried out on the development of longer-span horizontal members. There is same case for large building; there is an increasing demand for horizontal members that realize not only longer span, but also reduction in height of story. Although steel structures can provide higher strength, but if large members used in the construction of steel structures, it will cause buckling instability, excessive deflection, vibration, deterioration of fatigue strength and the need for excessive stiffeners due to the high width-to-thickness ratio [1,6,10].

Conventionally, I-shaped with flat beam is commonly used in construction field. But, due to the imperfection of the section, the design has been improved by designing steel beam with web opening of various shape and sizes. Castellated beams with circular web openings are commonly used where large web openings are provided along the beam at regular intervals for flexible routing and re-routing of building services. In addition, in modern buildings, openings are frequently required to be provided in structural members so that the building services may be incorporated into structural zones for simplified layout and installation.

Nomenclature is included if necessary
TriWP   triangular web profile

A triangular web profile (TriWP) steel section with opening is a built-up steel section made up of two flanges connected to a web plate of triangular profile which has a hollow circle cut-out along the length of its web. The

**Corresponding author: cefatimah@usm.my*

proposed triangular web profile steel section with opening definitely will reduce the weight of the steel section and may achieve better or similar resistance to torsion compared to without opening. Due to the more application of corrugated section in steel design, a three-dimensional finite element model using LUSAS 14.3 is developed to study and investigate the behavior of torsion for triangular web profile steel section with opening. Thin shell element is chosen to represent the element type of the model.

Beams with corrugated webs (Fig. 1) have been manufactured in Sweden, Germany and Japan and have been widely used in United States, Europe and Japan, and bridges in France. Researches on the behaviour of corrugated web beams have been extensively carried out by researchers in order to find the best way to utilize the sections with corrugated webs. The early works are carried out by Elgaaly, 1998 [8] and has been further developed to the practical stage. Corrugated steel beam is built up beam using two plates of flanges and corrugated steel webs. The corrugated web is introduced in order to allow the use of thin plates without stiffeners for use in buildings and bridges because it can eliminate the usage of larger thickness and stiffeners, result in reduction in beam weight and cost. Besides that, Chan et al. [3] also prove that the use of vertical corrugated web in the I-girder able to reduce up to 10.6% of weight compared to the original I-girder with same static capacity. Hence, this has contributed to reduction of cost of beam fabrication. Moreover, the uses of corrugated steel web can significantly increase the buckling resistance and reduce the thickness of web by replacing the stiffened steel plate of plate girder [13].

Fig. 1 - Corrugated web beam

Sayed-Ahmed [14] has studied the lateral-torsional buckling of I-girders with corrugated webs and has performed a series of finite element analysis and concludes that the I-girder with corrugated webs has higher resistances to lateral-torsional buckling compared to I-girder with flat webs.

Chan et al. [3] has investigated beams with plane web, vertically and horizontally corrugated webs and the results show that beams with vertically corrugated web able to stand 38.8% to 54.4% higher moments than the horizontal corrugated web. On the other hand, it is also found that the vertically corrugated web provides stronger support against the flange buckling compared to plane and horizontal corrugated web types. This can prove that the vertical corrugation produces higher strength than the horizontal corrugation and the plane web.

In order to use corrugated web in the I-girder, it is crucial to thoroughly understand the flexural and torsional behaviour of the I-girder with corrugated webs. However, studies on these behaviours are uncommon [12]. The results of previous studies on the flexural and torsional behaviour of I-girder with corrugated webs are summarized as follow: Seshadri [15] has investigated the bending strength of steel beam with corrugated web and the result indicates that the contribution of web to the ultimate moment capacity of a beam with corrugated web is negligible and this capacity will be based on the yield stress of flange. Abbas et al. [1] has studied the behaviour of corrugated web I-girder under in-plane load. The research discovers that the corrugated web I-girder under primary moment and shear cannot be analyzed using conventional beam theory alone because a torsion moment component is produced in them and this result in an out-of-plane twist simultaneously as it deflects in-plane under the in-plane loading.Files must be in MS Word only and should be formatted for direct printing, using the CRC MS Word provided. Figures and tables should be embedded and not supplied separately.

1.2 Behaviour of Steel Web Elements with Opening

Castellated steel beam which is fabricated from standard hot-rolled I-section has a lot of advantages such as aesthetic architectural appearance, ease of services through the web openings, optimum self-weight-depth ratio, economic construction, larger section modulus, and greater bending rigidity. However, the castellation of the beam will result in distinctive failure modes. These failure modes are depending on geometry of the beam, size of web opening, web slenderness, type of loading, quality of welding and lateral restraint condition [7]. The potential failure modes are associated with castellated beams are shear buckling of a web post, formation of flexure mechanism, lateral torsion buckling, formation of Vierendeel mechanism, rupture of welded joints in a web post and compression buckling of a web post [9].

In the last decade researchers have tried to examine the web opening shapes of perforated steel sections so that can provide better understanding of stress distribution in the vicinity of web openings and to identify those that have the best structural behavior under certain type of loading [4,5]. The objective is to provide the maximum possible web opening area for the integration of services while keeping the minimum possible self-weight for different type of loading.

Liu and Chung [11] has stated that in all opening shapes, increase in the opening depth will reduce the shear and moment resistance of perforated sections, this indicates that both shear and flexural failure of perforated section are primarily controlled by opening depth. Basher et al. [2] has stated that the presence of web opening will result in reduction of ultimate shear strength and when the opening size is small, the reduction is small, around 2% to 3% and can be neglected. However, for large size of opening with depth exceeding 0.2 times girder depth, the reduction of ultimate shear strength cannot be neglected.

Tsavdaridis and D'Mello [16] has carried out an experimental work and finite element study in order to investigate and compare the behavior of perforated steel beams with various standard and non-standard web opening shape configuration. Since the depth of web openings has to be as low as possible in order to prevent Vierendeel effects prior to web-post buckling failure in perforated sections with relatively thin webs, a diameter, d_o equal to 0.7h is adopted. From the result obtained, it shows that the failure of perforated section occurs under combined action of shear and moment with high deformation is observed as the web-posts are subjected to high shear, followed by heavy distortion of web opening. Besides that, it is also proven that when the web-post width increased, the vertical shear capacities also will increase and when they are subjected to high Vierendeel bending forces, it will slightly decrease. However, when the narrow elliptical web openings are considered, the capacity only gradually increase as Vierendeel bending is not critical. Besides that, the lateral torsional buckling affected by the distance between the shear center of the beam and location at an application of load [17]. However, the lesser angle of web corrugation may increase the load carrying capacity [18].

Numerical study on torsion behaviour of triangular web profile steel section with and without opening is presented in this paper. The objective of the study is to investigate the effect of web opening on the torsion behaviour of triangular web profile steel section. Fig. 2 shows the different views of triangular web profile steel section with opening.

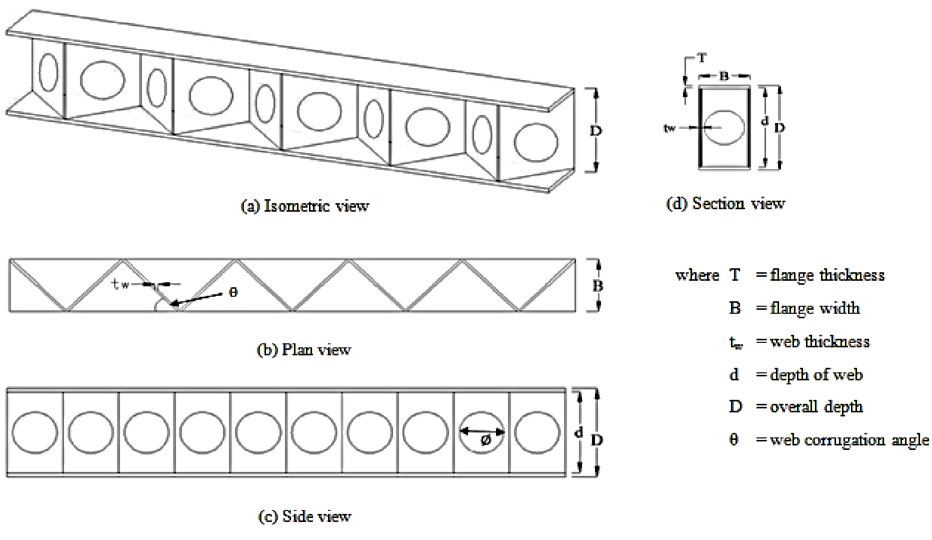


Fig. 2 - Different views of triangular web profile steel section with opening

2. Methods

In this paper, all the models are developed by using LUSAS version 14.7 software. LUSAS Analyst is rich in powerful and advanced features to meet analysis need and extend the design capacities which contain a comprehensive range of unrivalled engineering analysis facilities to cater for all types of engineering design. LUSAS model are defined in term of geometric features and must be subdivided into finite elements for solution. This process of sub division is called meshing. Mesh datasets contain information about element types, element discretisation and mesh type. All the models were assigned ungraded mild steel for material property with Young's Modulus, E, of 209×103 N/mm2, shear modules, G of 79×103 N/mm2 and Poisson ratio of 0.3. The beams are simply supported and constrained in x, y and z directions. Quadrilateral thin shell element (QSL8) and interpolation order in quadratic are chosen. The modeling procedures to create a triangular web profile steel section with opening using LUSAS are shown in Fig. 3.

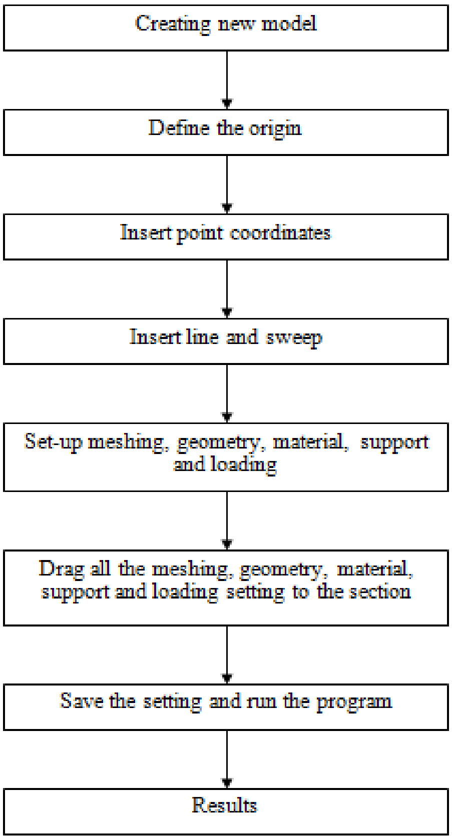


Fig. 3 - Flow chart of general modeling procedure using LUSAS software

2.1 Convergence Analysis

Convergence criteria are defined to determine the suitable mesh for the model. The convergence of the mesh is established by independently increasing the mesh density in each part of the beam model section. The model is 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, element size 20 is selected for both type of steel section and this meshing is adapted to all the models of triangular web profile steel section with and without opening throughout this study.

3. Results

A total of 80 non-linear finite element analyses were performed, covering different thickness of web and flange, different span length, different applied load, and different size of opening. For ease of comparison and discussion, the results presented in this paper are related to a cantilever steel beam of fixed depth (D) 200mm and width (B) 100mm with a span of 1m under concentrated load at the end the beam. While the web openings of various sizes 0.1D, 0.2D, 0.3D, 0.4D, and 0.5D is located at the centre of web along the beam length.

The behaviour and performance of triangular web profile steel beam with circular opening subjected to pure torsion based on the result of finite element analysis is discussed. Besides that, comparison between torsion behaviour of triangular web profile steel beam with and without opening is discussed in this study. Moreover, deformation shape of both models after applied loading is shown in order to investigate the effect of web opening to the torsion behaviour.

3.1 Effect of Different Thickness of Web and Flanges

In term of the effects of thickness of web and flanges, the results show that web without opening have higher resistance to torsion compared to that of web with opening. For both models, it is shown that, as expected, as the thickness of web and flange increase, the torsional rotation decreases. The results can be summarized in Fig. 4 and Fig. 5.

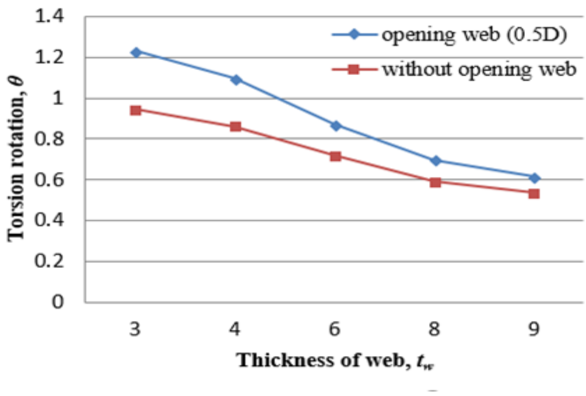


Fig. 4 - Graph of torsion rotation, θ against thickness of web, t_w

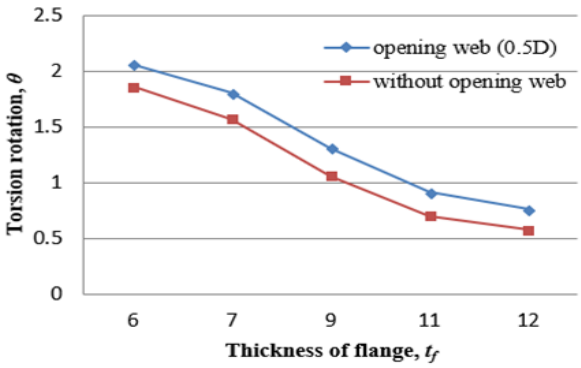


Fig. 5 - Graph of torsion rotation, θ against thickness of flange, t_f

3.2 Effect of Different Span Length and Different Applied Loading

For the case of different span length (Fig. 6), the dimension of model is fixed to 200× 100×6×3 mm while the length of beam varies from 1.0m to 5.0m. Meanwhile, for incremental loading, the dimension of model is also set to 200×100×6×3 mm while torsion loads of 20 kN, 40 kN, 60 kN, 80 kN, and 100 kN is applied, respectively.

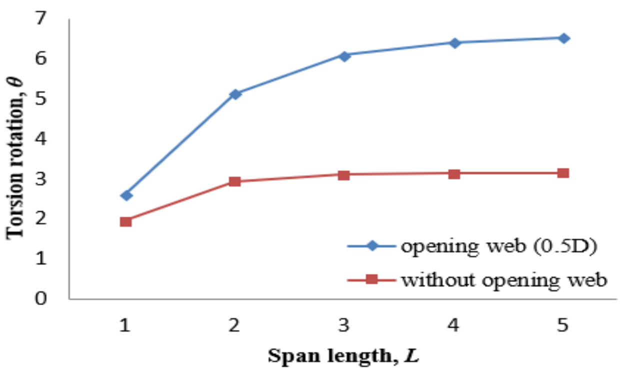


Fig. 6 - Graph of torsion rotation, θ against span length, l

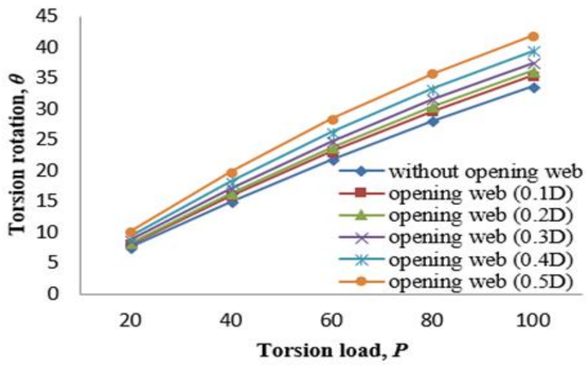


Fig. 7 - Graph of torsion rotation, θ against torsion load, P

3.3 Effect of Different Sizes of Opening

In term of the effects of different size of opening which is varies from 0.1D to 0.5D, the results show that increasing the size of web opening tends to increase the torsional rotation. The results can be summarized in Table 1 and Fig. 8. By referring to Fig. 8, the analysis result shows that the presence of web opening will result in reduction of resistance of torsion and when the opening size is small, which is 0.1D and 0.2D, the difference of torsion rotation value between triangular web with and without opening is small, around 1% to 4%. However, for large size of opening with depth exceeding 0.2D, the reduction of torsion resistance is significant, around 10%. This statement is strongly proven by Basher et al. [2].

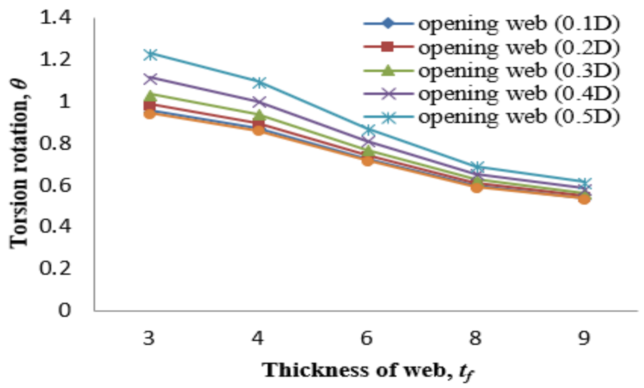


Fig. 8 - Graph of torsion rotation, θ against thickness of web, t_f (effect of size of opening)

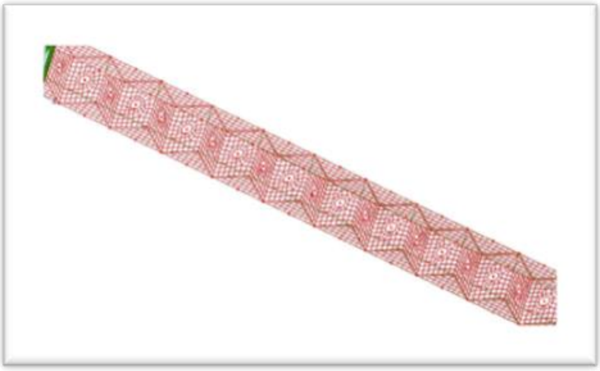
Table 1 - Result of torsional rotation due to different size of opening

Model Dimension (D x B x t_f x t_w)	Size of opening 0.1D θ (degre)	0.2D θ (degre)	0.3D θ (degre)	0.4D θ (degre)	0.5D θ (degree)
200 x 100 x 10 x 3	0.9556	0.9858	1.0363	1.1147	1.2300
200 x 100 x 10 x 4	0.8730	0.8981	0.9398	1.0036	1.0955
200 x 100 x 10 x 6	0.7251	0.7423	0.7703	0.8123	0.8711
200 x 100 x 10 x 8	0.5962	0.6077	0.6262	0.6536	0.6909
200 x 100 x 10 x 9	0.5385	0.5479	0.5629	0.5849	0.6146

3.4 Deformation Mesh

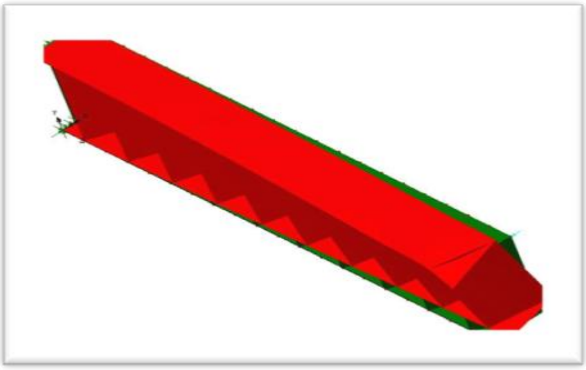
Deformed shapes of triangular web steel section with opening size of 0.1D, 0.2D, 0.3D, 0.4D, and 0.5D is shown in Fig. 9(a) and Fig. 9(b) in order to compare with triangular web steel section without opening. Fig. 10(a) and Fig. 10(b) show that the deformation shapes of steel section of triangular web without opening and with opening respectively. Fig. 11 show the comparison between 2-D view of deformation of triangular web without opening and triangular web with opening size 0.1D, 0.2D, 0.3D, 0.4D, and 0.5D.

(a) Without opening

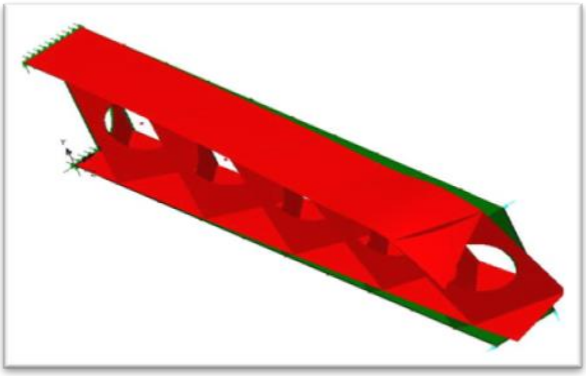


(b) With opening

Fig. 9 - Deformed mesh of triangular web profile steel section



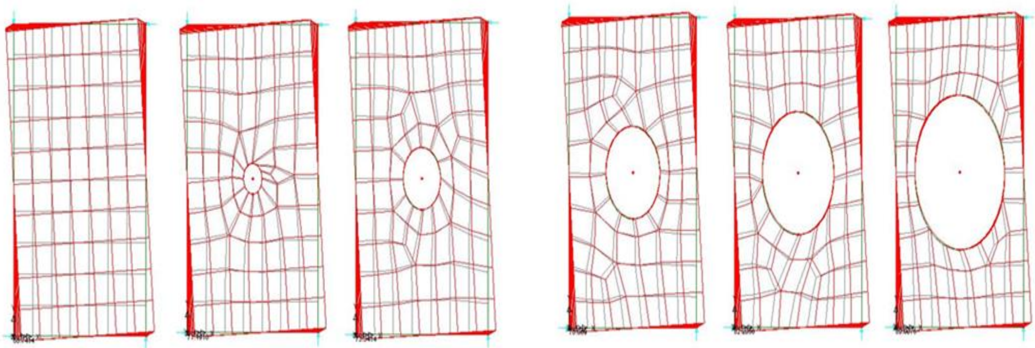
(a) Without opening



(b) With opening

Fig. 10 - Deformation shapes of steel section of triangular web profile steel section

3.5 2-D View of Deformation Shapes



(a) without opening (b) 0.1D (c) 0.2D (d) 0.3D (e) 0.4D (f) 0.5D

Fig. 11 - Comparison between 2-D view of deformation of triangular web without opening and triangular web with opening size 0.1D, 0.2D, 0.3D, 0.4D, and 0.5D

4. Conclusion

In this paper, a new section, known as triangular web profile steel section with opening is developed in order to compare the torsion resistance with the previous triangular web profile steel section without opening. A total of 80 non-linear finite elements runs were performed and five variables such as thickness of web and flange, span length, incremental loading and size of opening were tested to determine their influence to the torsional rotation of the model. LUSAS software was fully used throughout this study because it provided good prediction and it is more economical for designing a structural member as it can be done without carry out actual experiment. From the results presented in this paper, the conclusions are:

a) The torsional rotation value for both triangular web profile steel section with and without opening decreases when the thickness of flange and web increases. This is because thickness of plate is inversely proportional to the torsional rotation. However, triangular web with opening has higher torsional rotation value compared to triangular web without opening.

b) The torsional rotation value for both triangular web profile steel section with and without opening increases when the span length and torsion loading is increases. This is because span length and loading are directly proportional to the torsional rotation. However, triangular web with opening has higher torsional rotation value compared to triangular web without opening.

c) The presence of web opening has contributed to reduction of torsion resistance of triangular web. When the size of opening is small, which is 0.1D and 0.2D, the reduction of strength is small, around 1% to 4% and can be neglected. However, for large size of web opening with depth exceeding 0.2 times the beam depth, the reduction of torsion resistance of triangular web cannot be ignored.

d) For all the circular openings, the deformation patterns are similar and the depth of web openings has to be as low as possible.

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