Development of efficiency analysis for I-beam steel section with web opening via numerical method

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Abstract

Purpose – Due to the enormous increase in economic development, structural steel material gives an advantage for the construction of stadiums, factories, bridges and cities building design. The purpose of this study is to investigate the behaviour of bending, buckling and torsion for I-beam steel section with and without web opening using non-linear finite element analysis.

Design/methodology/approach – The control model was simulated via LUSAS software with the four main parameters which included opening size, layout, shape and orientation. The analysis used a constant beam span which is 3.5 m while the edge distance from the centre of the opening to the edge of the beam is kept constant at 250 mm at each end.

Findings – The analysis results show that the optimum opening size obtained is 0.65 D while optimum layout of opening is Layout 1 with nine web openings. Under bending behaviour, steel section with octagon shapes of web opening shows the highest yield load, yield moment and thus highest structural efficiency as compared to other shapes of openings. Besides, square shape of web opening has the highest structural efficiency under buckling behaviour. The lower buckling load and buckling moment contribute to the higher structural efficiency.

Originality/value – Further, the square web opening with counter clockwise has the highest structural efficiency under torsion behaviour.

Keywords Finite element analysis, LUSAS, Bending behaviour, Buckling behaviour, Torsion behaviour, Structural efficiency

Paper type Research paper

1. Introduction

Steel is a highly durable and resistant material, and the high strength-to-weight ratio of steel enables it to result in a high load-carrying capacity. A lot of advantages are found such as the strength uniformity, specific sizes from the manufacturer so that the section can be easily fabricated and it has high yield strength for both compressive and tensile strength (Maulana *et al.*, 2019). Structural steel sections are more concerned due to its material that can be produced with various shapes and properties (McKee, 2021; AISC, 2018) and I-beam is the most commonly used steel section (Brakefield, 2020). Besides that, steel can be produced in mass, easily assembled, replace and modify the nature of structural designs (Weldarc, 2017).

The application of opening in steel beams gives an advantage for longer floors span. This prevalence has likewise improved due to an architectural consideration on uncovered structures, thus elongated and castellated opening being typically used in structural steel sections. Sections with firmly spaced opening over throughout the full span are frequently practiced. However, certain heavy-mass structures such as bridges have been using opening beams although the best practice of these beams is to be applied for long spans which transfer a light uniform load. Likewise, the fabrication cost has been reduced to a certain extent when the open-web steel joists are more reasonable for certain applications (Tsavdaridis and D’Mello, 2011).

Previously, the optimize web sizes, layout and shapes of opening have been found by other researchers to know the stress distribution pattern in the surrounding of the web opening (De’nan and Hashim, 2016). Besides that, the web opening can also be applied for the cross-passing of utility system in the floors (Siddh and Pachpor, 2011). Due to the architectural and aesthetic need in the design consideration of the cross-sectional shapes, the higher demand of opening steel beam is identified to reduce the cost of materials.

I-beam steel section with circular web shape opening has become an option for all this time. Thus, to make it more advanced, I-beam steel section with certain types of shape opening can be adapted in current market. This technology can be further studied to know its behaviour, especially the efficiency of the steel under three main behaviours which are bending, buckling and torsion behaviour. Therefore, finite element analysis (FEA) method is adopted through LUSAS (LUSAS, 2007) software to analyse the structural efficiency and the behaviours of steel section.

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World Journal of Engineering
© Emerald Publishing Limited [ISSN 1708-5284]
[DOI 10.1108/WJE-03-2022-0117]

The authors would like to thank Universiti Sains Malaysia for the financial support under Fundamental Research Grant Scheme (Account No. 203/PAWAM/6071239).

Received 17 March 2022
Revised 18 April 2022
Accepted 26 April 2022

2. Literature review

The innovation in construction technology for the steel beam with web opening from the conventional I-beam has alleviated the material and cost saving. Nevertheless, beams with web opening are liable to fail under combination of bending and shear force. Likewise, the most dominant failure of the beam with large web opening is Vierendeel mechanism (Ahyar *et al.*, 2022; Rusli *et al.*, 2018). There are two main elements contributing to Vierendeel bending which includes the movement of shear force across the web openings and the rate of change of the bending moment throughout the span (De'nan *et al.*, 2017). Besides that, to provide a better understanding of the stress distribution in the locality of the web openings, the researcher had examined the types of web opening shapes thus the best structural behaviour under certain types of loading is identified (Tsavdaridis and D'Mello, 2012). Therefore, the maximum web opening area for the services integration is known whilst minimum self-weight for different types of loading can be maintained. According to Tsavdaridis and D'Mello (2011) due to uneven stress distribution, the stress distribution of perforated I-sections with vertical and rotated elliptical web openings has a better performance compared to standard web openings. Lesser stress concentrations at the web opening corners are observed by using diagonal stiffener in the direction of diagonal tension and diagonal compression, thus reducing the prominence of failure at the corners (Deepha and Jayalekshmi, 2020).

Inadequate lateral support to the compression flange in non-composite castellated section caused the section more prone to undergo lateral torsional buckling compared to composite beams (Soltani *et al.*, 2012). This phenomenon is due to the deeper and slender section caused by the reduction of web torsional stiffness. Meanwhile, a reduction with a maximum value of 18% and 50% was observed in LB (Lateral buckling) capacity for the cases of ratio height of opening, *HO* and height of beam, *H; HO*/*H* $\leq$ 0.5 and *HO*/*H* $>$ 0.5, respectively (Serror, 2011). The failure of bearing capacity and loss of stability of cross-section before plastification normally related to lateral buckling behaviour. The stability of each castellated beam generally referred to the lateral buckling resistance (Radic and Markulak, 2007). Furthermore, inelastic behaviour was noticed at certain degrees for elastic brace castellated beams subjected to lateral buckling together with torsion as well as cross-section distortion (Showkati, 2008).

Besides that, improvising of the beams structural performance with respect to web-post buckling failure has been found by using these new novel web opening shapes. Apart from that, an improvement of the manufacturing method for the novel web openings is caused to the sustainable in-design analysis. The stability (slenderness) of the web-post subjected to vertical shear load is investigated based on the effects of the web opening depth/web thickness as well as opening spacing/web opening depth of web-posts (Tsavdaridis and D'Mello, 2011). Moreover, a good agreement with the finite element results is observed for the lateral torsional buckling strength of unsymmetrical plate girders with corrugated webs subjected to uniform moment (Ibrahim, 2014). Nevertheless, more than 11% of an elastic lateral torsional buckling capacity increased when using an un-symmetrical corrugated web girder compared to the corresponding plate girder with the conventional flat web. Furthermore, the elastic lateral torsional buckling strength of the I-girders with corrugated webs is increased up to 10% compared to that of I-girder with flat webs (Hassan *et al.*, 2016).

A researcher had discovered that the compression flange of an I-section steel beam tends to buckle sideways when the beam section is insufficient stiff condition and too slender (Narayanan, 1984). Furthermore, the web opening has the lower critical bending moment which is associated with buckling instability of steel beam (Hassan *et al.*, 2016). Hence, study of web opening is needed to be done in order to produce steel section with least material but results in highest efficiency without compromising the safety factor consideration. However, based on the static and dynamic analysis, the higher values of stresses are observed near the opening (El-Dehemy, 2017). Besides that, the best location of web opening is middle two-third of the span (Morkhade and Gupta, 2019). In addition, most optimum size is 0.5 D due to the high values of the buckling moment compared with 0.6 and 0.7 D (De'nan *et al.*, 2017). Subsequently, the researcher discovers that I-beam without web opening has the highest buckling moments resistance compared to C-hexagon.

Throughout the past studies, the researchers had discovered the FEA on certain behaviour of I-beam but none studied on the structural efficiency of normal I-beam. Thus, the behaviour of I-beam with different parameters is analysed by FEA and the structural efficiency is determined. The structural efficiency of a section is regarded as high if the ratio of load-carrying capacity to its self-weight is high. High structural efficiency indicates that the structural element is strong and relatively light in design. The findings of the structural efficiency of I-beam steel section with opening under bending, buckling and torsion behaviour are needed to facilitate the optimization in construction. The purpose of this work is to verify the theoretical result on the structural efficiency through LUSAS software.

3. Methodology

The method of this study is summarized in Figure 1. This work starts with convergence study followed by the behaviour analysis which includes bending, lateral torsional buckling and torsion behaviour analysis to determine the section properties effect on the structural efficiency and determination of the most efficient model. The model simulation works are analysed by using LUSAS software. The reliability of this software has been reported in the open literature (Chhapkhane and Kamble, 2012; Morkhade and Gupta, 2019; Panedpojaman *et al.*, 2015). Detail explanation on the selection of input data in LUSAS is presented accordingly.

The convergence study was carried out to obtain more accurate solution, besides, minimize the computational effort. From Figure 2, it is shown that the result converged when the number of elements was 3,875. Thus, the mesh size of 20 mm was chosen and used for all sections with and without opening throughout this work. The quadratic quadrilateral semi-loof thin shell element (QSL8) has been selected for this simulation. With varying thickness and anisotropic and composite material properties, the semi-loof thin shell elements may represent the curved geometry (LUSAS, 2007). Plastic and large displacement behaviours are taken into account and also

Figure 1 Flowchart of analysis

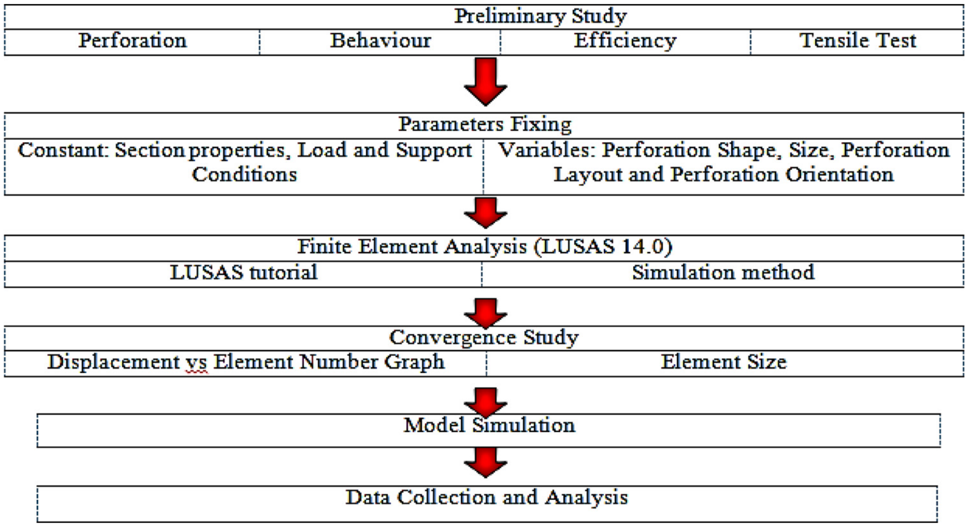
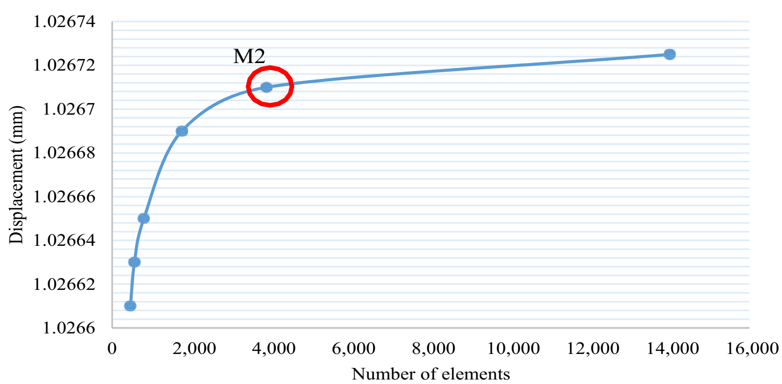


Figure 2 Convergence analysis



considered membrane and flexural deformations (Mimoune *et al.*, 2012) but transverse shear deformation is not included. Additionally, QSL8 elements provide correct eigenvalues for both consistent mass and lumped matrices which form the mass matrix using a function array shapes (LUSAS, 2007).

3.1 Section properties of model analysis

A total of 759 sections are modelled to determine the efficiency of the I-beam steel section with certain openings under bending, lateral–torsional and torsion behaviour. Figure 3 shows the front and isometric view of analysis model.

3.2 Support and loading condition

For this analysis, two types of support are proposed. The simply supported condition is used (x, y, and z translation direction is fixed and for every rotation direction are free) and applied on the bottom flange for both sides of the section. Concentrated load is applied on the middle part of the top flange. This support and loading condition is applied to model for bending and buckling analysis. Besides, 10 N concentrated loads are applied at top and bottom free end for torsion analysis (Nethercot *et al.*, 1997; Hughes *et al.*, 2011). A fixed support (fixed in each translation and rotation) is applied at one end and the other end is free. In this study, the section depth, D was maintained at 200 mm with flange width, B equal to 100 mm at the top and bottom, t_f is 8 mm and web thickness and t_w is 6 mm. The length of section involved is 3,500 mm.

3.3 Opening shapes and size

There are few shapes and sizes of opening were selected. The shapes included are ellipse, circular, square, diamond, hexagon, c-hexagonal and octagon. Meanwhile, the size of opening varies from 0.35 to 0.65 D, where D is total depth of web measured at vertical centre line of any opening shape. Figure 4 shows the detail of the dimensions of the shape of opening. Tsavdaridis and D'Mello (2012) reported that sections with small web openings (0.5 h) were considered, there was no significant reduction in the shear capacity with respect to any section. When the section with large web openings (0.75 h) is considered, the combination of the span and web opening position produced different results. Previous research revealed that the depth of web opening, d_o dominated the flexural and shear behaviour and also ordinary failures for perforated sections

Figure 3 Typical analysis mode: (a) the isometric view and (b) the front view

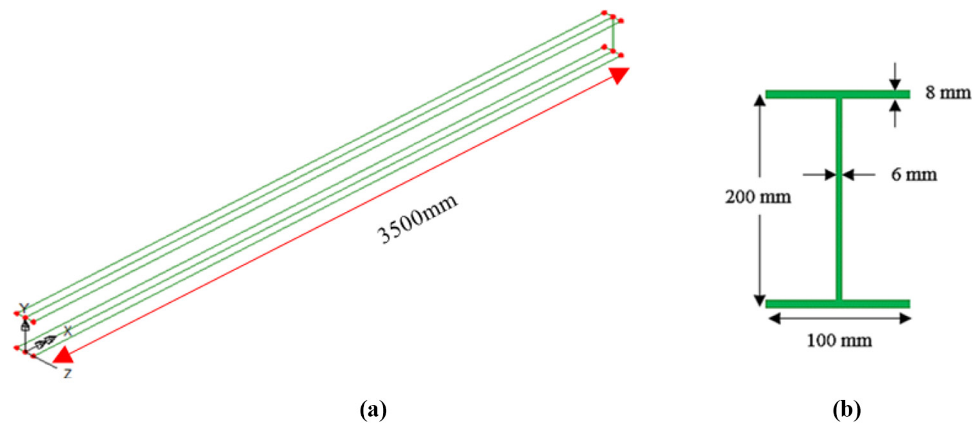
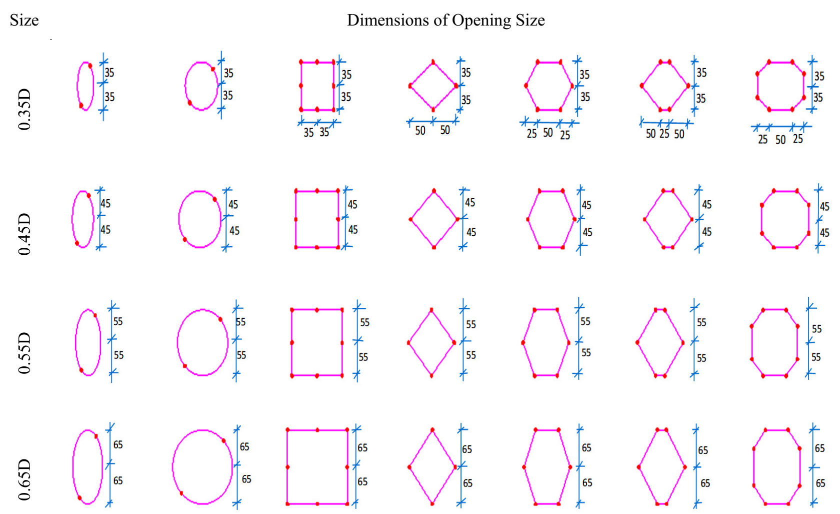


Figure 4 Details dimensions of opening size



(Tsavdaridis and D'Mello, 2012; Morkhade and Gupta, 2019). Circular openings were modelled with $S < 1.0\ d_o$. Meanwhile, regular hexagonal (60° edge angle) opening with $S = 0.423\ d_o$ and sharp corners was adopted as recommended by Tsavdaridis and D'Mello (2012). Besides that, square opening was designed and restricted about the circle where $S = 1.0\ d_o$.

3.4 Layout of opening

Three types of layout of opening are adopted in this work. The details and two-dimensional view of layout of opening are summarized and shown as in Figure 5. The edge of the analysis model is 250 mm at both sides for all the layouts. These shapes were used because the stress concentration around the corner regions of openings was critical (Morkhade and Gupta, 2019). The high stress zone around the corners indicates the formation of four plastic hinges in those regions, where one of the prime failure modes can occur. Therefore, this work focuses on the angle of the corner regions that contributes to the various shapes of web opening.

3.5 Orientation of opening

Three are three types of orientation of opening which is vertical perforation known as the non-rotated opening, while the same type of opening is rotated at 45° clockwise and anti-clockwise about the centre-point of any opening shape. The type of orientation opening is demonstrated as in Figure 6.

The most efficient model under bending loading condition is the I-beam steel section with vertical octagon web opening and opening size of 0.65 D, which is arranged in Layout 1 (L1) as shown in Figure 7(a). Furthermore, the most efficient model under buckling loading condition is the I-beam with steel section with vertical square shape and opening of 0.65 D in size, which is arranged in L1 as shown in Figure 7(b). On the other hand, Figure 7(c) shows that the most efficient models under torsion loading condition are found to be the I-beam steel section with opening size of 0.65 D, which is arranged in L1 with a square counter-clockwise shape obtained the same highest efficiency value.

Figure 5 The arrangement and number of web opening

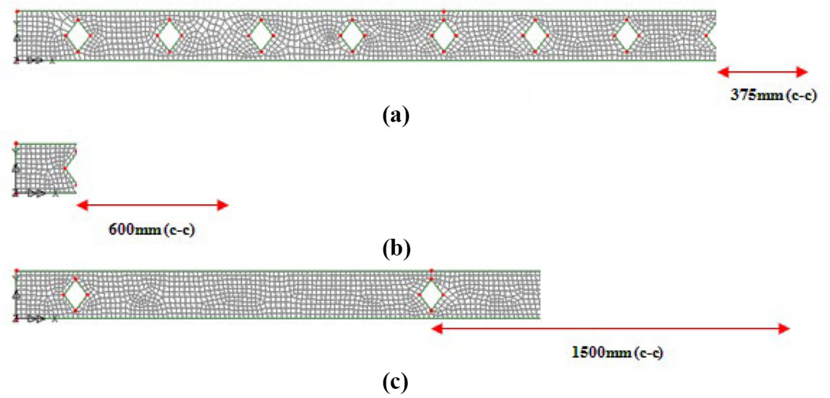


Figure 6 Types of orientation opening for analysis model: (a) normal opening; (b) clockwise orientation opening; and (c) anti-clockwise orientation

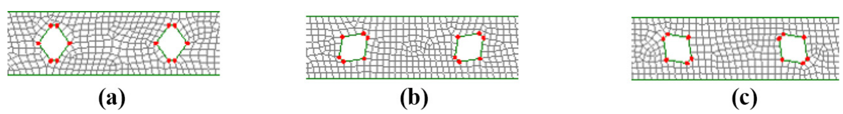
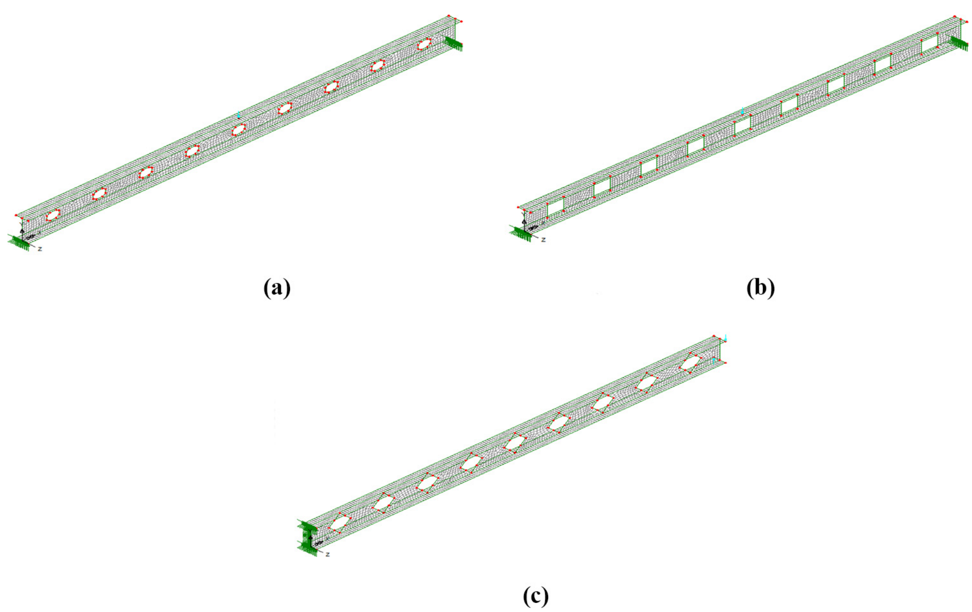


Figure 7 View of typical model in FEA: (a) bending behaviour (Morkhade and Gupta, 2019); (b) Buckling behaviour (Nseir *et al.*, 2012); (c) torsion behaviour (Nethercot *et al.*, 1997; Hughes *et al.*, 2011)



3.6 Analytical consideration

EN 1993 Eurocode 3 is significant to the design of steel buildings and other civil engineering works and conforms to the standards and requirements for the safety and serviceability of structures (ENV 1993-1-1, 1992). From the Eurocode 3 standard, EN1993-1–1 has been applied for the theoretical calculation for this analysis. The theoretical calculation using Eurocode standard was then compared with the finite element results. Before calculating the bending moment, buckling moment resistance and torsion, effective section properties were calculated.

3.6.1 Effective section properties calculation

As for section properties, the part of EN 1993 stated the steel structures design which is fabricated from steel material according to the steel grades as shown in Table 3.1 (EN1993-1–1, 2005) as shown in Table 1. In this table, the steel grade is based on the web thickness (t_w) and flange thickness (t_f) of the steel beam.

Then, based on Table 5 (EN1993-1–1, 2005), the classification of beam cross section is determined. The importance of cross-section classification is to determine the extent to which the resistance and rotation capacity of cross sections is restricted by its local buckling resistance. The classification of a cross section relies on the width-to-thickness ratio of the parts subjected to compression. Compression parts which incorporate all aspects of a cross section which is either totally or partially in compression under the load combination are considered. The various compression parts in a cross section (such as a web or flange), generally are classified in various classes. There are four classes of cross sections which include Class 1, Class 2, Class 3 and Class 4. Usually, Class 1 has been classified for normal I-beam which can form a plastic hinge with the rotation capacity that is required from plastic analysis without reduction of the resistance (ENV 1993-1-1, 1992).

3.6.2 Bending moment calculation

For simply-supported beam with concentrated load, the maximum bending moment at middle part is calculated using the following equation:

$$Moment, M_{Ed} = PL/4 \tag{1}$$

where:

P = applied load and L is length of the section.

In accordance with EN1993-1–1 (2005), section 6.2.5(1) (EN1993-1–1, 2005), the design value of the bending moment, M_{Ed} at each cross section shall satisfy:

$$\frac{M_{Ed}}{M_{c,Rd}} \leq 1.0 \tag{2}$$

where:

$M_{c,Rd}$ = the design resistance of building.

The design resistance for bending, $M_{c,Rd}$ about one principal axis of a cross section is determined as follows:

$$M_{c,Rd} = \frac{w_{eff} f_{yb}}{\gamma_{Mo}} \tag{3}$$

where:

W_{eff} = effective section modulus;
f_{yb} = basic yield strength; and
γ_{M0} = partial factor for resistance of cross sections.

Equation (4) derived the yield moment value. The calculated theoretical yield moment then is compared with the finite element results.

$$M_y = W_{el,y} f_f \tag{4}$$

where:

$W_{el,y}$ = elastic section modulus and f_y is yield strength.

3.6.3 Lateral torsional buckling moment calculation

The flexure load to I-beams possesses a high stiffness and strength about major axis compared to the minor axis. However, when the section is braced in a proper condition, which the section is avoided to twisting and lateral deflection, lateral torsional buckling occurred to prevent in-plane capacity direction. Besides that, the existence of opening in web section may also introduce lateral torsional buckling. As a result, the existence of openings in the web section may affect the load-carrying capacities of the I-beam steel section depending on the size, location, and shape of the web opening.

By using an evaluation of uniform moment illustration, the critical moment was calculated based on original case as a guide in numerical analysis. Therefore, the moment value by lateral torsional buckling moment assumption was depending on the moment between the two supports. Several evaluation results of flexural torsional buckling in terms of moment–gradient factor on elastic condition for original I-beam section were compiled (Suryoatmono and Ho, 2002). Nevertheless, the lateral torsional buckling effects of I-beam with different arrangement of web opening in inelastic condition were analysed by using LUSAS software with several range of slenderness.

Equations (5) and (6) show the calculation method to calculate the buckling load, P_b and buckling moment, M_b through the finite element results:

$$P_b = \lambda \times appliedload \tag{5}$$

$$M_b = \frac{P_b L}{4} \tag{6}$$

where:

λ = eigenvalue obtained from FEA and L is the whole length of the section.

Table 1 Nominal values of yield strength f_y and ultimate tensile strength f_u for hot rolled structural steel (EN1993–1-1, 2005)

	Nominal thickness of the element, t [mm]			
	$t \leq 40$ mm		$40\text{ mm} < t \leq 80$ mm	
Standard and steel grade	f_y [N/mm^2]	f_u [N/mm^2]	f_y [N/mm^2]	f_u [N/mm^2]
EN 10025–2				
S 235	235	360	215	360
S 275	275	430	255	410
S 355	355	490	335	470
S 450	440	550	410	550

In accordance with (EN1993-1–1, 2005), Section 6.3.2.1, a laterally unrestrained member subject to major axis bending should be verified against lateral torsional buckling as follows:

$$\frac{M_{Ed}}{M_{c,Rd}} \leq 1.0 \tag{7}$$

where:

M_{Ed} = the value of design moment and $M_{c,Rd}$ is the value of design buckling moment resistance.

The design buckling moment resistance of a laterally unrestrained beam should be taken as:

$$M_{b,Rd} = \chi_{LT} W_y \frac{f_y}{\gamma_{M1}} \tag{8}$$

where:

χ_{LT} = the reduction factor for lateral torsional buckling; and
W_y = the section modulus for Class 1 cross sections.

For bending members of constant cross section (Section 6.3.2.2) (EN1993-1–1, 2005), the value of χ_{LT} for the appropriate non-dimensional slenderness λ_{LT} should be calculated from:

$$\chi_{LT} = \frac{1}{\phi_{LT} + \sqrt{\phi_{LT}^2 + \lambda_{LT}^2}}$$

$$\phi_{LT} = 0.5\left[1 + \alpha_{LT}(\lambda_{LT} - 0.2) + \lambda_{LT}^2\right]$$

$$\lambda_{LT} = \sqrt{\frac{w_y f_y}{M_{cr}}} \tag{9}$$

where:

α_{LT} = an imperfection factor obtained from Table 6.3 (EN1993-1–1, 2005).
M_{cr} = the elastic critical moment for lateral torsional buckling:

$$M_{cr} = C_1 \pi^2 EI_z \left[\frac{I_w}{I_2} + \frac{L^2{}_{cr} GI_T}{\pi^2 EI_z}\right]^{0.5} \tag{10}$$

In the case of purely elastic beams, an existing design rule is given in equation (11) for certain failure mode (Mohebkhah, 2004; Mohebkhah and Showkati, 2005; Zirakian and Showkati, 2006):

$$M_{ocr} = \frac{\pi}{L_b}\sqrt{EI_y GJ}\sqrt{\left(1 + \frac{\pi}{L_b}\sqrt{\frac{EC_w}{GJ}}\right)^{2}} \tag{11}$$

where:

M_{ocr} = elastic buckling uniform moment;
E = Young's modulus of elasticity;
I_y = second moment of area about y-axis;
G = shear modulus of elasticity;
J = torsion section constant; and
L_b = the unbraced length which is the span length, L, in this case.

3.6.4 Torsional rotation calculation

Theoretically, the angle of twist, $\theta_{theoretical}$ for I-beam under non-uniform torsion is calculated:

$$\theta_{theoretical} = \frac{TL}{JG}\left(\frac{1 - \tanh(\mu L)}{\mu L}\right) \tag{12}$$

where:

T = applied torque;
L = length of section;
J = torsion constant; and
G = shear modulus

$$\mu = \sqrt{\frac{JG}{ET}} \tag{13}$$

3.6.5 Structural efficiency

Structural efficiency is defined as the weight of material that carries a given amount of load. The structural efficiency of an element is regarded as high if the ratio of its load-carrying capacity to its self-weight is high. High structural efficiency indicates that the structural element is strong and relatively light in analysis design. In the case of perforated steel section, the efficiency of the section and its percentage difference can be calculated by using equations (14) and (15) (De'nan *et al.*, 2017; Naaim *et al.*, 2016):

$$Efficiency = \frac{Load\ carrying\ capacity}{Self-weight\ of\ section} \tag{14}$$

$$\text{Percentage of structural efficiency} = \frac{c - a}{c} \tag{15}$$

where:

c = the efficiency of steel section without opening and d is the efficiency of steel section with opening.

3.6.6 Modelling of initial imperfections

Initial imperfections are normally considered in the FE modelling. Hence, superimposition of local and overall imperfections was used in FEA. Eigenvalue analyses are considered to determine the overall buckling mode of the structure. Eigenvalue buckling analysis predicts the theoretical buckling strength of a structure which was idealized as elastic section. Lowest eigenvalue from LUSAS is used as the shape of local and overall buckling mode (Aye *et al.*, 2018). Furthermore, local imperfections with magnitude 0.5% of the section thickness are included. Lowest positive eigenvalue from eigenvalue buckling analysis is computed from the constraints and loading condition for a basic structural configuration. Besides that, kinematic hardening rule is used in section modelling where the hardening gradient option is applied. The strain gradient (slope) and plastic strain are selected as 0.01 and 1.0 or 100%, respectively.

4. Results and discussions

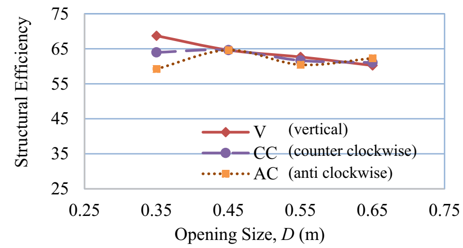
The I-beam steel section with web opening with the highest structural efficiency (in terms of bending, buckling and torsion resistance), respectively, was used to compare with the control sections (I-beam). The purpose of comparison is to prove the I-beam steel section with web opening in terms of structural feasibility. The structural behaviour and efficiency of I-beam steel section with web opening under bending, buckling and torsion loading conditions are investigated by using FEA. There were 759 models been analysed. As for the efficiency calculation, firstly, the self-weight for each model has been calculated. Then, the load-carrying capacity for each model is obtained to determine the structural efficiency of the steel sections. The structural efficiency is calculated from the ratio of load-carrying capacity to the self-weight.

The section may fail due to the vertical deformation on the top surface of the flange section where the load was applied. The upper surface of the web section buckled locally when the flange section deformed. However, for these sections, a slight lateral web distortion was observed at the middle span of the section. This finding indicates that the displacement governs the structure behaviour rather than buckling. Figure 8 shows the deformation patterns for analysed model. Each steel section with web opening failed due to the vertical loading affects. The compression flange buckled locally at the upper surface close to the middle span of the section. This may lead to the increase in the longitudinal stresses of the section.

The yield load obtained for this model is 58 kN while the yield moment is 50.75 kN m. The value of efficiency of the model is 68.71 (bending loading condition) as shown in Figure 9. The smaller yield load capacity and the lower efficiency of the steel section with opening are observed. Besides, the smaller opening size contributes to the larger load-carrying capacity for I-beam steel section with anti-clockwise diamond web opening. Thus, higher structural efficiency of the model was observed. The perforation layout with different perforation arrangement and number of perforations has affected the deformation of bending and efficiency of the I-beam steel section with anti-clockwise diamond perforation. In detail, when section with small web openings is considered (Tsavdaridis and D'Mello, 2009), some reduction in the load-carrying capacity was the result of the reduced moment capacity close to the mid span of the section. The area of this reduction was approximately one-third of the section span. However, the web opening position could yield completely different results when sections with large web openings are considered.

I-beam with various shapes of web opening is used in the numerical analysis. It is known that the initial geometric imperfection mainly affects inelastic and elastic behaviour of lateral torsional buckling of steel section (Trahair and Bradford, 1998). Load deflection analyses in linear condition are adopted to know the elastic lateral torsional buckling strength of I-beam with web opening. Finite element models are assigned in an ideal geometry to create an initial geometric imperfection. This is performed by the usage of section with various web opening shapes throughout the span length under the concentrate loading condition. Figure 10 illustrates three modes of elastic buckling for section with c-hexagon web opening where each model undergoes lateral torsional buckling modes.

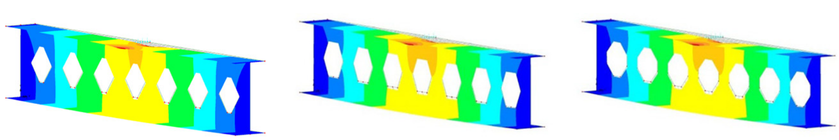
Figure 9 Structural efficiency–opening size graph



Throughout the analysis of section with c-hexagon web opening, the buckling mode shape was observed from the lowest eigenvalue due to the initial imperfection. Eigenvalue analyses were considered to determine the overall buckling mode. Lowest eigenmode from LUSAS is used as the shape of local and overall buckling mode. For this work, the eigenvalue is set to 3 and three different modes of failure were observed. Flange local buckling modes are dominant for the lowest buckling mode of the section with c-hexagon web opening and, a combination of lateral torsional buckling and the top flange local buckling is dominant for the eigenvalue 2. However, for the eigenvalue 3, the combination of top and bottom flange local buckling and also lateral torsional buckling of section are more susceptible. Nevertheless, for the lateral torsional buckling in nonlinear analysis, similar shape observed between the shapes of initial imperfection in lateral torsional buckling mode to ensure the failure occurred. However, the section acts similar to lateral torsional buckling mode as shown in Figure 10 for the lowest buckling mode of I-beam section.

The buckling load (Figure 11) and buckling moment (Figure 12) are 30.95 kN and 27.08 kNm, respectively. Whereas the efficiency of the model is 39.07 (Figure 13) which is highest among the other models which being tested under lateral torsional buckling load. The higher buckling loads contribute to the lower efficiency of the steel section with web opening. Besides, the smaller web opening size gives the larger load-carrying capacity of I-beam steel section with vertical square web opening. Thus, the structural efficiency of the model was higher. The opening layout with different opening arrangement and number of opening has affected the deformation of buckling and efficiency of the I-beam steel section vertical square web opening. Besides that, perforation

Figure 8 Deformation pattern: (a) C-hexagon; (b) hexagon; and (c) octagon



(a) (b) (c)

Figure 10 Deformation of I-beam with c-hexagon web opening based on eigenvalue number: (a) Eigenvalue 1; (b) Eigenvalue 2; and (c) Eigenvalue 3

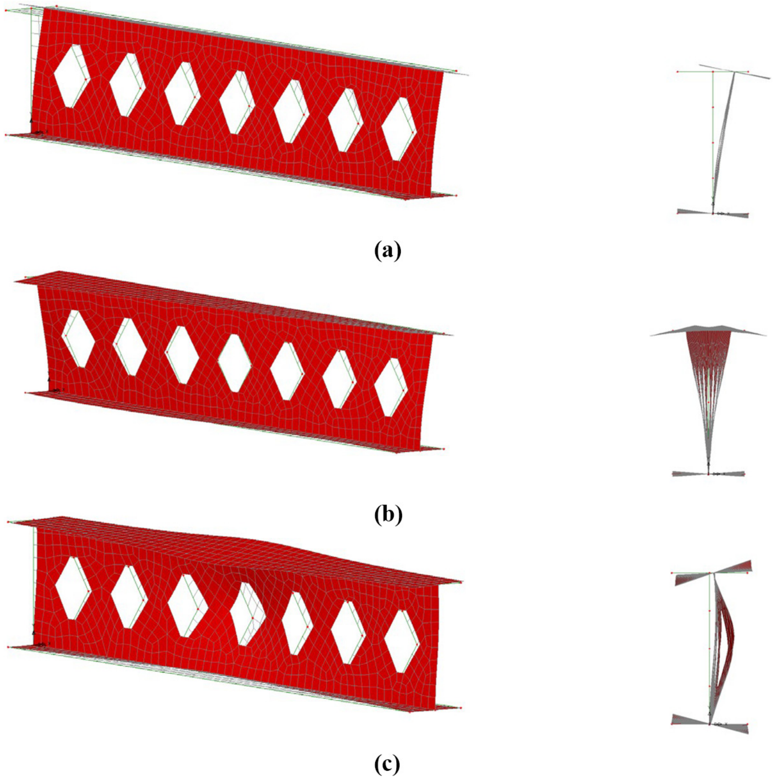


Figure 11 Load–opening size graph

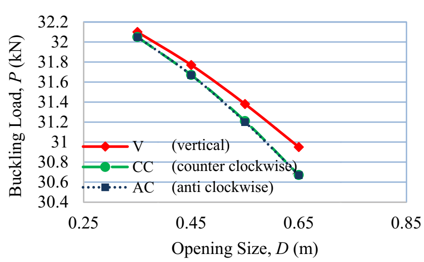
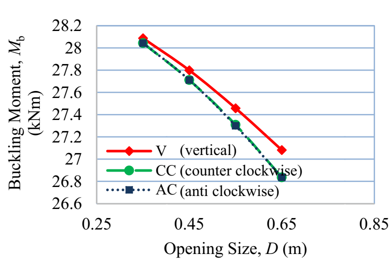
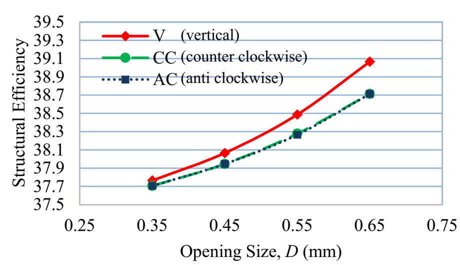


Figure 12 Moment–opening size graph



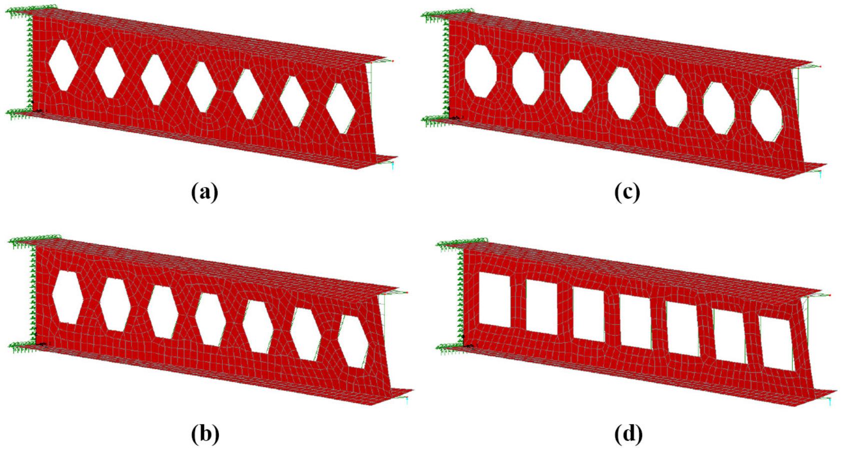
size of 0.75 D has the highest structural efficiency, although it can withstand a smaller buckling load (De'nan *et al.*, 2020). Nevertheless, the tapering ratio of 0.3 is the most efficient and an increment of percentage in structural efficiency is 114.36%.

Figure 13 Structural efficiency–opening size graph



Torsion behaviour mode for certain section using LUSAS through FEA is shown in Figure 14. A few findings are observed in particular figures as shown below. Coupled point load is applied at one side in opposite direction caused twisting section because it is free to warp. When a section is free to warp, the twisting moment does not affect the longitudinal stresses in the beam near the free end but merely produces stresses on the section. If a section is restrained from warping, as shown in Figure 14, the twisting moment is transmitted by lateral shearing forces which accompany the lateral bending of the flange but these stresses are not negligible near the restrained section. The square web opening section undergoes the torsional and lateral deformation at the middle part of section span. The free end sections undergo higher torsional deformation compared with other part of section. This lateral bending of each flange

Figure 14 Failure mode behaviour due to uniform torsion: (a) C-hexagon; (b) hexagon; (c) octagon; and (d) square



causes a longitudinal tensile stress along one edge and a compressive stress along the other edge.

Figure 15 shows the torsional rotation is 22.18° and the efficiency value is 10.53 (Figure 16). Based on the graph plotted as shown in Figure 15, torsional rotation increases as the opening size increases. Meanwhile, Figure 16 shows that the structural efficiency increases as the web opening size increases. Moreover, the same trend goes to the different opening size where the smaller opening size contributes to the smaller torsional rotation for I-beam steel section with counter-clockwise square opening thus obtaining a smaller efficiency. The opening layout with different opening arrangement and number of opening has affected the torsional rotation and efficiency of the I-beam steel section with counter-clockwise square web opening shapes. The square opening has the lowest self-weight (Hasan *et al.*, 2017). It was also reported that diamond perforation shape could resist the highest buckling load which was the same with the findings in this research. It was also found that a square perforation shape has the lowest self-weight among the three shapes of perforation steel section with perforated corrugated web profile. Beam with web perforation must be located at the centreline (Lagoros *et al.*, 2008). The maximum diameter of the perforation used should not exceed 0.75 D because an extremely large perforation causes reduced shear and moment capacities.

Figure 15 Torsional rotation–opening size graph

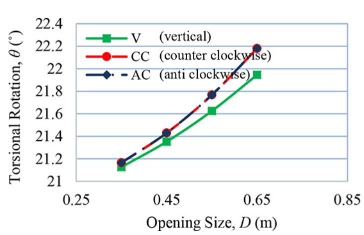
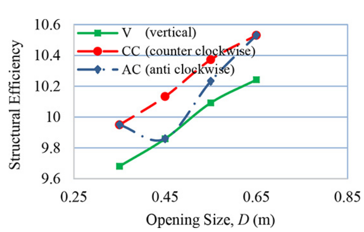


Figure 16 Structural efficiency–opening size graph



5. Conclusions

Based on FEA results, the following conclusions were observed;

The FEA is used to investigate the bending, buckling and torsion behaviour of I-beam with and without opening followed by the efficiency analysis model. Analysis results show that the size of opening has slightly effect under certain behaviours. Furthermore, three layouts and four opening sizes with 3.5 m section length were used to find the optimum size and layout of opening. Based on the result, both objectives have been achieved through the utilization of LUSAS software and the most efficient model is obtained. The most efficient model under bending loading conditions is the I-beam steel section with a vertical octagon web opening and perforation size of 0.65 D which is arranged in L1. Besides that, the most efficient model under buckling loading conditions is the I-beam steel section with a vertical square shape and perforation of 0.65 D in size which is arranged in L1. Further, the most efficient model under torsion loading conditions is the I-beam steel section with a perforation size of 0.65 D which is arranged in L1 with a square counter-clockwise shape obtaining the same highest efficiency value. Therefore, the optimum size in this study is 0.65 D due to the high values of the structural efficiency compared with 0.3, 0.45 and 0.55 D. Besides, the most optimum layout is L1 as compared to Layout 2 (L2) and Layout 3 (L3). This is because L1 has the highest web opening area as compared to the other layouts.

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