Contents List available at RAZI Publishing

Engineering Heritage Journal / Galeri Warisan Kejuruteraan

Journal Homepage: <http://www.razipublishing.com/journals/galeri-warisan-kejuruteraan-gwk/>
<https://doi.org/10.26480/gwk.01.2017.11.20>

Behaviour of Flush End-Plate Connection for Perforated Section

Fatimah De'nan*, Nurfarhah Naaim and Lai Chun Leong

¹School of Civil Engineering, Universiti Sains Malaysia, 14300 Nibong Tebal, Penang, Malaysia*Email: cefatihmah@usm.my, farhah.naaim@yahoo.com, www.roxas92@gmail.com*This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited*

ARTICLE DETAILS

ABSTRACT

Article history:

Received 15 September 2016

Accepted 22 December 2016

Available online 10 January 2017

Keywords:

flush end plate; perforated section; beam-to-column connection; moment rotation; non-linear finite element method.

This paper presents the study on the behaviour of the beam to column connection by using flush end plate connection for I-beam steel section with perforation. Moment rotation and failure pattern of flush end plate connection for perforated section were studied. The model was modelled by using LUSAS software and then analysed with nonlinear finite element analysis. Nineteen models were generated for flush end plate connection with perforated beam section consisting of variable parameters such as opening size, distance between the first opening and column face, and spacing between the openings. The moment resistance and rotational stiffness of the connection are found to be reduced by the presence of the openings. The geometric parameter of the openings affected the behaviour of the connections. It is found that the larger the opening size, the lower the strength and rigidity of the connection. Furthermore, it is found that the presence of openings causes increment in the deflection of the beam. However, some perforated sections with optimum geometric parameters for openings have higher strength to weight and rigidity to weight ratio than normal section without perforation. In this study, the most effective geometric parameter for openings are found to be size of 0.65h, distance between the first opening and column face of 800mm and spacing between openings of 1.3h (h is the depth of the beam web).

1. Introduction

Connection is one of the most important elements in structural components for steelwork. This is because the internal forces and moments at the connection are transferred by the connection from the connected members to other supporting member. The mechanical properties of the connections will have effects on the strength, stiffness and stability of the whole structure. Hence, most of the recent research works were focussed on the behaviour of the connection. For multi-storey buildings, the type of connections between the main structural elements which are usually classified as beam-to-column connections, beam-to-beam connections, column splices, column bases and bracing connections. However, the most common type of connections used in the research is the beam-to-column connection.

According to Eurocode 3 part 8 [1], simple pinned joint is defined as joint that is capable of transmitting the internal forces without developing significant moments, and accepting the resulting rotations under applied loads. Rigid joint is defined as joint which has sufficient rotational stiffness to justify analysis based on full continuity. Semi-rigid joint is defined as joint which is not classified as normally pinned joint or rigid joint. In the study [2], the researcher mentioned that simple pinned connection is connection which is designed for shear only, and the moment develops by the simple pinned connection is a nominal moment. For semi-rigid connection (also known as partial strength connection), it is defined as a connection which possesses moment resistance more than 25% of that of the connected beam, but less than 100% of that of the connected beam. For rigid or full strength connection, the moment resistance of the connection is higher than that of the connected beam.

Flush end plate connection is one type of end plate connections which is commonly used in the construction industry nowadays. The early finite element analysis of moment and plate connections is conducted by Krishnamurthy [3]. However, due to the limited technology of that time, some assumptions had to be made. In 1994, Sherbourne [4] carried a study on evaluating the moment-rotation relationships for steel bolted end-plate connections based on finite-element modelling. The typical model configuration studied consisted of a rectangular plate welded to the beam cross section and bolted by two rows each of two bolts at the tension flange of the beam and one row of bolts above compression flange, and it is found that the prying forces in the projected portion of the end plate will increase with decrease of end-plate thickness. For the moment resistance, researchers mention that the difference in moment resistance is believed to be due to the strain hardening and the post yield strength of the connection components, which were not considered in this theoretical model [5]. Study on flush end plate connection was also done on its seismic performance. Goudarzi [6] found that by increasing compressive axial

force, initially the moment capacity increases but the moment capacity was then decreased due to occurrence of different failure mode in type of beam flange bulking.

In the past, it was common that web openings was provided in structural floor beams for passage of services in order to accommodate building services within the constructional depth of a floor. Depending on the configuration of the web opening, the presence of web openings may have effects on the load capacities of the structural members [7-8]. Any increase in sizes in web openings of given shapes will reduce not only both the global shear and the global moment resistances of the perforated sections, but also the local axial, shear and moment resistances of the tee-sections. Furthermore, the Vierendeel moment is also increased at the same time. Consequently, it is expected that for web openings of various shapes but of same opening depths and lengths, their structural performance should be similar [9]. Study by Tsavdaridis and D. Mello [10] on determining and comparing the behaviour of perforated steel beams with different shape configurations and sizes of web openings had been carried out. The study found out that the shape of the web opening also significantly affect the position of the plastic hinges. For perforated sections with polygonal web openings, the stress usually tends to concentrate at the sharp corners of the polygons. Furthermore, perforated sections with non-standard elliptical web openings behave similarly to the standard non-polygon web openings in terms of the sequence of the plastic hinges formation, independent of the web opening shape.

1.1 Problem Statement

Connections are important elements for all steel structures. The mechanical properties of the connections will tend to have effects on the strength, stiffness and stability of the whole structure. If the connections are not designed properly, it means that the whole structure will have weak links to connect the structural members. This will affect its serviceability resulting higher deflections of the structural member. Hence, detail design of connections is very important as the design of the members themselves.

In reality, all steel connections are not perfectly rigid or perfectly flexible. For flexible shear connections, it will transfer some moment [11]. The exact moment-rotation relationship for a semi rigid connection is highly dependent on connection details, material properties, applied forces, and deformations [12]. Moment rotation ($M-\theta$) characteristics of bolted or bolted/welded steel connections are indicative of the connection's stiffness, strength, and ductility. Experimentally obtained $M-\theta$ behaviour is entirely dependent upon and highly sensitive to the

connection's geometric variables (i.e., plate/angle thickness, bolt diameter, bolt pitch, bolt gauge, etc) [13].

Beam to column connections are identified as one of the critical components of steel frames which experience yielding, buckling and other inelastic or brittle phenomena during earthquakes [14]. In the past years, bolted connections, especially end-plated connections are very popular. This type of connection has benefit of requiring less supervision and a shorter assembly time than welded connection. It also has a geometry that is easy to comprehend and can accommodate minor discrepancies in the dimensions of beams and columns [15].

Researches on steel I-beam sections with perforated section in the web have also been increasing over the past few years. Perforated steel section is also known as castellated section (with hexagonal openings), and cellular beams (with circular section) under the “umbrella” of perforated beam [16]. The use of perforated steel section can significantly reduce the weight and cost compared to regular steel section without perforated section. Also, with greater automation, the cost of their fabrication has been reduced to the level where for certain applications they may be competitive with open-web steel joists [17]. Furthermore, the use of perforation can improve the behaviour of the connections by enhancing their ductility, rotational capacity and their energy dissipation capacity [18]. Therefore, detail study on the behaviour of flush end plate connection for section with perforated section is required. The focus of the study are moment rotation and failure pattern of the flush end plate connection.

1.2 Parametric Study

1.2.1 Aim and Model Configuration

The objectives of the work presented here is to compare the strength and rigidity of flush end plate connection for perforated section and normal section without perforation, to perform parametric study on the effect of geometric parameter of the openings for perforated section on the strength and rigidity of the connection and to determine the effect of openings on the failure pattern and deflection of the model. The finite element method is used to investigate the behaviour of full scale steel beams with openings in the beam web, symmetrical about the centre-line. The connection involved the connection of H-column of size $254 \times 254 \times 82$ UKC with an I-beam of size $457 \times 191 \times 73$ UKB. The size of end-plate chosen in this research is 280×200 with thickness of 10mm. The arrangement and dimension of the connection model is shown in Fig. 1.

Fig. 1 Arrangement and dimension of the connection model

1.3 Significance of research

Significance of research to be obtained from this study will be the results and analysis of the characteristic of beam to column connection, when flush end plate and beam with perforation is used. It is necessary to compare the moment-rotation relationship of the connections from finite element analysis of beam with perforation and normal beam without perforation and among perforated sections with different openings geometric. The aim was to compare the strength and rigidity of the connection for section with perforation and normal section without perforation, and to determine whether section with perforation can replace normal section without perforation or not without reducing its connection strength. Even if the strength of the connection for sections with perforation are lower than normal section, perforated sections can still replace normal section as the reduction in its weight may be an advantage in some application. Flush end plate connection with perforated section is already available in industry, but it is still not widely used in the industry. If more research on the behavior of flush end plate connection with perforated section can be implemented, it helps to increase the diversity of products in the steel industry.

2. Methodology

2.1 Connection Configuration

In this study, 19 finite element models of flush-end plate connections are modelled by using finite element software, LUSAS to study the behaviour of the connection. Fig. 2 shows the illustration of the flush end plate connection model. The grade of steel used in designing the beam-to-column connection is S275. The beam dimension adopted is $457 \times 191 \times 82$ UKB, with length of 8m. The column used for this study is $254 \times 254 \times 73$ UKC, with length of 5m below the connection and 4.5m above the connection. The behaviour of the connection is compared between beam web with perforation and beam web without perforation. Table 1 shows configuration of the beam, end plate, and column. Six M20 grade 8.8 hexagonal head bolts are used in this study.

Fig. 2 Arrangement and dimension for flush end plate connection

Member	Section	Web thickness (mm)	Flange thickness (mm)	Plate thickness (mm)
Column	$254 \times 254 \times 73$ UKC	8.6	14.2	-
Beam	$457 \times 191 \times 82$ UKB	9.9	16.0	-
End Plate	280×200	-	-	10

For beam section, the perforated beam has circular openings at the web of the beam as shown in Fig. 3. The parametric study focuses on the effects of the distance between the web opening's centre line and the end plate, S_1 , and the spacing between the web openings, S_2 . To compare the strength and rigidity of the various geometric of web openings, 19 models are analysed with 18 models of perforated sections and 1 model of normal section without perforation. 18 models of perforated sections consist of section with different opening size (d_0), distance between the first opening and column face (S_1), and spacing between the openings (S_2). The values of d_0 , S_1 , and S_2 parameters are shown in Table 2. Each model is represented with a specific three-field identifier, as demonstrated in Fig. 4. For example: A2-400 is the beam section with web opening depth, d_0 of $0.8h$ with spacing between openings, S_2 of $1.3h$ and located at 400 mm away from the column's face.

Fig. 3 Geometric parameter of d_0 , S_1 , and S_2

Fig. 4 Analysis model classification

Table 2 Values of d_0 , S_1 , and S_2 for the models

Specimen	Opening depth, d_0	Spacing between openings, S_2	Distance between the web opening and the column's face, S_1 (mm)
A1-400	0.8h	0.87h	400
A1-600	0.8h	0.87h	600
A1-800	0.8h	0.87h	800
A2-400	0.8h	1.3h	400
A2-600	0.8h	1.3h	600
A2-800	0.8h	1.3h	800
A3-400	0.8h	1.9h	400
A3-600	0.8h	1.9h	600
A3-800	0.8h	1.9h	800
B1-400	0.65h	0.87h	400
B1-600	0.65h	0.87h	600
B1-800	0.65h	0.87h	800
B2-400	0.65h	1.3h	400
B2-600	0.65h	1.3h	600
B2-800	0.65h	1.3h	800
B3-400	0.65h	1.9h	400
B3-600	0.65h	1.9h	600
B3-800	0.65h	1.9h	800
C	-	-	-

2.2 Defining Material Properties

Material nonlinearity occurs when the stress-strain relationship ceases to be linear by plastic yielding and strain hardening. For elastic dataset, all elements were defined as elastic isotropic with a Young's Modulus of Elasticity of 2.05×10^5 N/mm² and Poisson's lateral to longitudinal strain ratio of 0.3. All data used here are the same as data used in previous study by Omar [19] (2012). For the contact line between end plates, it is assigned with contact spring stiffness, K of 1,000 kNm/rad. While for the contact line between bolts and nuts, it is assigned with contact spring stiffness, K of 10,000 kNm/rad. The plastic dataset bolts and shank and other section are shown in Table 3.

Table 3 Plastic dataset

	Bolt and shank	Beam, column, end plate
Initial uniaxial yield stress (N/mm ²)	560	300
Hardening gradient slope	20,000	10,000
Plastic strain	200	100

2.3 Loading and Boundary Condition

Uniformly distributed load of 57.4 kN/m is defined on the upper surface of the upper flange of the beam of span of 8m. In order to achieve the necessary range of the connection bending moments in the nonlinear analysis, the total load factor is increased from 1.0 to 50.0 with maximum change of load factor in each iteration is set as 5.0. The boundary condition of the model is as shown in Fig. 5. In the model, the fixed support is applied at the top and bottom end of the column where fixed the translation and rotation in all directions. At the right end of the beam, pinned support is applied where the translational movement is fixed in all direction and the rotational movement is free in all direction.

Fig. 5 Boundary condition of the model.

2.4 Convergence Study

In this study, all the models are established and analysed by using finite element analysis software, LUSAS. For simulating the structural behaviour of the model, different element types are used to establish the model. The convergence study is carried by manipulating the mesh density on the model. The mesh density of the model is increased in every part of the model section by decreasing the mesh size of the model. Table 4 shows data of six models which created with different of mesh size and number of elements with respective results of maximum nodal displacement. From the Fig. 6, the increment in displacement has decreased as the number of elements increased from model 6 to model 1. The result indicates that the convergence solution had been obtained when reached model 3 with number of elements of 5490. Hence, the mesh size applied on the models is 60mm based on the convergence study done.

Table 4 Data of maximum nodal displacements with different mesh sizes

Model	Element Size	Number of Elements	Maximum Nodal Displacement (mm)
1	30	31006	3.35329
2	35	26786	3.34903
3	50	13518	3.33555
4	60	5490	3.33029
5	80	2627	3.31454
6	100	1790	3.30366

Fig. 6 Graph of the maximum nodal displacement against the number of elements

2.5 Moment-rotation Curve

In LUSAS, the values of moment and rotation for the model are not provided directly. LUSAS only provided raw data which are the values of displacements at certain nodes with the corresponding increment of loading. However, the raw data from LUSAS is then used to obtain the values moment and rotation for plotting the moment-rotation (M- Φ) curve.

Moment rotation (M- Φ) curve could not be produced directly from the results of LUSAS analysis. LUSAS provides only the raw data such as the values of displacements at certain nodes with the corresponding increment of loading. In order to plot a moment rotation curve, the rotation and moment were computed from the raw data. The location of nodes used to determine the value of rotation is shown in Fig. 7. Point A is located at the center of column web, while point B is located at the neutral axis of the beam with a horizontal distance of x from point A. From the displacement values, the rotation of node B were calculated by using the Pythagoras Theorem as shown in Fig. 8.

Fig. 7 Location of nodes

Fig. 8 Rotation by Using Pythagoras theorem

The calculation procedures for connection rotation (Φ) are as follows;

$$\Phi = \tan^{-1} \left(\frac{y_T}{x_T + x} \right) \quad (1.1)$$

$$y_T = |dY_B - dY_A| \quad (1.2)$$

$$x_T = |dX_B - dX_A| \quad (1.3)$$

Where:

Φ = Rotation

y_T = Total vertical displacement

x_T = Total horizontal displacement

dY_B = Vertical displacement of node B

dY_A = Vertical displacement of node A

dX_B = Horizontal displacement of node B

dX_A = Horizontal displacement of node A

x = Horizontal distance between node A and B

The applied moment is calculated by using the formula below;

$$M = \frac{1}{8} wL^2 \times \text{Total Load Factor} \quad (1.4)$$

Where:

M = Applied moment (in kNm)

w = Applied uniformly distributed load (in kN/m)

L = Length of the beam (in m)

The moment-rotation (M- Φ) curve was developed by using the values of moment and rotation calculated. Moment resistance (M_R) of the connection was determined from the M- Φ curve plotted by using an intersection method (also known as knee joint method). This method had been used by researchers [20-21] in determining the moment resistance of the connection from the M- Φ curve. In this method, a straight line was drawn from a linear behaviour of the connection and another straight line was drawn from a non-linear behaviour of the connection. The straight line of the non-linear region was drawn at the point where the curve started to form a plateau. The moment resistance, M_R was determined from the intersection of the two lines. Fig. 9 showed the determination of moment resistance by using "knee joint" method. From the moment rotation curve, the rotational stiffness of the connection is calculated. By using "knee joint" method, the rotation at the "knee", Φ is obtained. The rotational stiffness, K is calculated by using formula as shown below.

$$K = \frac{M_R}{\Phi}$$

Fig. 9 Determination of moment resistance

3. Results and Discussion

3.1 Moment-Rotation Curve

In this analysis, the opening sizes analysed were 0.65h and 0.8h. The two opening sizes were used for eighteen models, which nine models for each opening sizes. Fig. 10 shows the graph of moment rotation (M- Φ) for the two opening sizes and normal I-beam steel section without perforation. Table 5 shows the moment resistance, M_R and rotational stiffness, K of the models. Table 6 shows the percentage difference in moment resistance, M_R and rotational stiffness, K for perforated section with opening size of 0.8h (model A) compare to perforated section with opening size of 0.65h (model B). Perforated section with circular web openings behaved similarly to the normal section without perforation. However, normal section without perforation possessed higher moment resistance compared to perforated section with circular openings. For perforated section with openings, the one with smaller opening size, 0.65h has higher moment resistance than the one with larger opening size, 0.8h. The moment resistance of normal section without perforation are 4.71% to 11.76% and 8.24% to 20% higher than perforated section with opening size of 0.65h and 0.8h, respectively. Perforated section with opening size of 0.65h has M_R which are 3.7% to 10.53% higher than perforated section with opening size of 0.8h. In addition, perforated section with smaller opening size has higher rotational stiffness (rigidity) compared to the one with larger opening size. The rotational stiffness of perforated section with smaller opening size is up to 29.35% higher compare to perforated section with larger opening size). For normal section without perforation, the rigidity is higher than perforated section (1.18% to 12.16% higher than perforated section with opening size of 0.65h and 6.57% to 37.94% higher than perforated section with opening size of 0.8h).

Fig. 10 Moment-rotation curve for different opening size

Table 5 Moment resistance and rotation stiffness of the models

No	Specimen	Moment Resistance, M_R (kNm)	Rotation, Φ (rad)	Rotational Stiffness, K (kNm/rad)	Percentage difference in M_R from model C (%)	Percentage difference in K from model C (%)
1	A1-400	340	0.0131	25954.20	-20.00	-31.60
2	A1-600	360	0.0152	23684.21	-15.29	-37.59
3	A1-800	365	0.0155	23548.39	-14.12	-37.94
4	A2-400	350	0.0108	32407.41	-17.65	-14.60
5	A2-600	375	0.0113	33185.84	-11.76	-12.55
6	A2-800	385	0.0113	34070.80	-9.41	-10.21
7	A3-400	355	0.0113	31415.93	-16.47	-17.21
8	A3-600	390	0.0110	35454.55	-8.24	-6.57
9	A3-800	380	0.0117	32478.63	-10.59	-14.41
10	B1-400	380	0.0110	34545.45	-10.59	-8.96
11	B1-600	390	0.0117	33333.33	-8.24	-12.16
12	B1-800	390	0.0117	33333.33	-8.24	-12.16
13	B2-400	385	0.0106	36320.75	-9.41	-4.28
14	B2-600	400	0.0110	36363.64	-5.88	-4.17
15	B2-800	405	0.0108	37500.00	-4.71	-1.18
16	B3-400	375	0.0105	35714.29	-11.76	-5.88

17	B3-600	405	0.0108	37500.00	-4.71	-1.18
18	B3-800	380	0.0110	34545.45	-10.59	-8.96
19	C	425	0.0112	37946.43	-	-

Table 6 Percentage difference in moment resistance, M_R and rotational stiffness, K for model A ($d_0=0.8h$) compare to model B ($d_0=0.65h$)

No	M_R for model A (kNm)	M_R for model B (kNm)	Percentage difference in M_R for model A compared to model B	K for model A (kNm/rad)	K for model B (kNm/rad)	Percentage difference in K for model A compared to model B (%)
1	340	380	-10.53	25954.20	34545.45	-24.87
2	360	390	-7.69	23684.21	33333.33	-28.95
3	365	390	-6.41	23548.39	33333.33	-29.35
4	350	385	-9.09	32407.41	36320.75	-10.77
5	375	400	-6.25	33185.84	36363.64	-8.74
6	385	405	-4.94	34070.80	37500.00	-9.14
7	355	375	-5.33	31415.93	35714.29	-12.04
8	390	405	-3.70	35454.55	37500.00	-5.45
9	380	380	0.00	32478.63	34545.45	-5.98

In this case, the effects of the distance between the first opening and column face, S_1 to the beam-to-column connection are analysed. Three distance between the first opening and column face, S_1 are used which are 400mm, 600mm, 800mm. The effects of distance between the first opening and column face vary differently dependent to the opening size and spacing between openings, S_2 . From Fig. 11, the moment resistance, M_R for the model with spacing between the openings of $0.87h$ increases when the distance between the first opening and column face, S_1 is increased. However, the rotational stiffness, K of the model decreases when the distance between the first opening and column face, S_1 is increased. Fig. 12 shows the moment-rotation curve for perforated sections with opening size of $0.65h$ and spacing between openings of $0.87h$. For small opening size ($d_0=0.65h$), the effects of the distance between the first opening and column face, S_1 are viewed from the $M-\Phi$ curve with difference in moment resistance, M_R and rotational stiffness, K of 2.56% and 3.64% when distance between the first opening and column face increases. For opening size of $0.8h$, the difference in M_R and K are up to 6.85% and 10.22%, respectively, as the distance between the first opening and column face increases.

Fig. 11 Moment-Rotation curve for different spacing**Fig. 12** Moment-Rotation curve for different spacing between openings

between opening

(opening size of 0.8h and spacing between openings of 0.87h)

(opening size of 0.65h and spacing between openings of 0.87h)

Fig. 13 and Fig. 14 show moment rotation curve for perforated section with spacing between the openings of 1.3h. For the model with spacing between the openings of 1.3h, both the moment resistance and rotational stiffness of the connection increases when the distance between the first opening and column face, S_1 increased. However the increment in the moment resistance and rotation stiffness as distance between the first opening and column face increases for opening size of 0.8h are more significant than perforated section with opening size of 0.65h. The increment in moment resistance and rotational stiffness as distance between the first opening and column face increases for opening size of 0.65h are up to 3.75% and 3.14%, respectively, while the increment in moment resistance and rotational stiffness as distance between the first opening and column face increases for opening size of 0.8h are up to 9.09% and 4.88%, respectively.

Fig. 13 Moment-Rotation curve for different spacing**Fig. 14** Moment-Rotation curve for different spacing between openings

between openings

(opening size of 0.8h and spacing between openings of 1.3h)

(opening size of 0.65h and spacing between openings of 1.3h)

Fig. 15 and Fig. 16 show moment rotation curve for perforated section with spacing between the openings of 1.9h. For the model with spacing

between the openings of 1.9h, both the moment resistance and rotational stiffness of the connection increases when the distance between the first opening and column face, S_1 increased from 400mm to 600mm. However, both the moment resistance and rotational stiffness of the connection decreases when the distance between the first opening and column face, S_1 increased from 600mm to 800mm. For opening size of 0.65h, both the moment resistance and rotational stiffness are higher than that of opening size of 0.8h. For the case of distance between the first opening and column face $S_1 = 800$ mm, both opening size of 0.65h and 0.8h have the same moment resistance and rotational stiffness.

Fig. 15 Moment-Rotation curve for different spacing**Fig. 16** Moment-Rotation curve for different spa between openings

between openings

(opening size of 0.8h and spacing between openings of 1.9h)

(opening size of 0.65h and spacing between openings of 1.9h)

For this case, the effects of the spacing between the openings, S_2 to the beam-to-column connection are analysed. Three spacing between the openings, S_2 are used which 0.87h, 1.3h, and 1.9h. The effects of spacing between the openings, S_2 also vary differently dependent to the opening size and distance between the first opening and column face, S_1 . Fig. 17 and Fig. 18 show moment rotation curve for perforated section with distance between the first opening and column face of 400mm. For distance between the first opening and column face of 400mm, the effects of spacing between the openings on the moment resistance of the connection are slightly different for opening size of 0.65h and 0.8h. For opening size of 0.65h, the moment resistance increases when the spacing between openings is increased from 0.87h to 1.3h. The moment resistance then decreases when the spacing between the openings is further increased to 1.9h. However, for opening size of 0.8h, the moment resistance increased as the spacing between the openings increases. In term of rotational, both opening sizes have the highest rotational stiffness, K at spacing between openings of 1.3h. The differences in moment resistance and rotational stiffness of connection for model of opening size 0.65h with different spacing between openings are up to 2.60% and 4.89%, respectively. The difference in moment resistance and rotational stiffness of connection for model of opening size 0.8h with different spacing between openings are up to 4.23% and 19.91%, respectively.

Fig. 17 Moment-Rotation curve for different spacing

Fig. 18 Moment-Rotation curve for different spacing between openings (opening size of 0.8h and distance between openings (opening size of 0.65h and distance between first opening and column face of 400mm)

From Fig. 19 and Fig. 20, both the moment resistance and rotational stiffness for both opening sizes with distance between the first opening and column face of 600mm increases as the spacing between openings is increased. The increment rotational stiffness for the opening size of 0.8h is quite big when the spacing between openings increased from 0.87h to 1.3h (increment of rotational stiffness is 28.63%). The differences in moment resistance and rotational stiffness for opening size of 0.65h as the spacing between openings increased are up to 3.7% and 11.1%, respectively. As for opening size of 0.8h, the differences in moment resistance and rotational stiffness as the spacing between openings increased are up to 7.7% and 33.2%, respectively.

Fig. 19 Moment-Rotation curve for different spacing

Fig. 20 Moment-Rotation curve for different spacing between openings (opening size of 0.8h and distance between openings (opening size of 0.65h and distance between first opening and column face of 600mm)

From Fig. 21 and Fig. 22, both the moment resistance and rotational stiffness of the connections for both opening sizes with distance between the first opening and column face of 800mm are highest when the spacing between openings is 1.3h. The increment of rotational stiffness for

opening size of 0.8h when spacing between openings increased from 0.87h to 1.3h is much higher than perforated section with opening size of 0.65h (increment of 30.88% for opening size 0.8h and 11.11% for opening size of 0.65h). The differences in moment resistance and rotational stiffness for opening size of 0.65h as the spacing between openings increased are up to 6.17% and 11.11%, respectively. As for opening size of 0.8h, the differences in moment resistance and rotational stiffness as the spacing between openings increased are up to 5.19% and 30.88%, respectively.

Fig. 21 Moment-Rotation curve for different spacing

Fig. 22 Moment-Rotation curve for different spacing between openings (opening size of 0.8h and distance between openings (opening size of 0.65h and distance between first opening and column face of 800mm)

3.2 Strength to Weight Ratio and Rigidity to Weight Ratio

The moment resistance, M_R and rotational stiffness, K of the models are compared to their corresponding weight. In further analysis, the moment resistance and rotational stiffness are divided by the corresponding weight to obtain the strength to weight ratio and rigidity to weight ratio. Table 7 shows the values of strength to weight ratio and rigidity to weight ratio for each models. Table 8 shows the percentage difference in term of strength to weight ratio and rigidity to weight ratio compare to normal I-beam section without perforation (model C). For normal I-beam section without perforation, its moment resistance and rigidity are higher than that of perforated sections. However, the strength to weight ratio of the normal I-beam section without perforation lower than some of perforated sections (depending on the geometric parameter of the openings). Perforated section with smaller opening size mostly have higher strength to weight ratio and rigidity to weight ratio than perforated section with larger opening size. However, when the distance between the first opening and column face reaches 800mm, perforated section with smaller opening size tends to have lower strength to weight ratio and rigidity to weight ratio. The difference of strength to weight ratio for perforated section is not significant. The difference of strength to weight ratio for perforated section with opening size of 0.65h and 0.8h is only up to 4.17%. The difference of rigidity to weight ratio for perforated section is more significant than strength to weight ratio. The difference of rigidity to weight ratio for perforated section with opening size of 0.65h and 0.8h is up to 22.33%.

For perforated section with different geometric parameters such as distance between the first opening and column face, S_1 and spacing between openings, S_2 , the effects on the strength to weight ratio and rigidity to weight ratio for each models vary differently. The perforated section have the higher strength to weight ratio and rigidity to weight ratio at the effective distance between the first opening and column face, S_1 and spacing between openings, S_2 . For perforated section with opening size of 0.8h, model A1-800 has the highest strength to weight ratio, but model A3-600 has the highest rigidity to weight ratio. For perforated section with opening size of 0.65h, model B1-600 has the highest strength to weight ratio, but model B2-800 has the highest rigidity to weight ratio. However,

for perforated section with opening size of 0.8h, the model which has the highest value in term of both strength to weight ratio and rigidity to weight ratio is model A2-800. The strength to weight ratio and rigidity to weight ratio of model A2-800 is 2.91% and 2.00% higher than normal I-beam section without perforation. For perforated section with opening size of 0.65h, the model B2-800 has the highest value in term of both strength to weight ratio and rigidity to weight ratio. The strength to weight ratio and rigidity to weight ratio of model B2-800 is 2.17% and 5.96% higher than normal I-beam section without perforation. In addition, model B2-800 has also higher strength to weight ratio and rigidity to weight ratio than model A2-800. Model B2-800 is 0.72% stronger in term of strength to weight ratio and 3.74% higher in rigidity to weight ratio than model A2-800. Hence, the effective geometric parameters for the openings are opening size of 0.65h, distance between the first opening and column face of 800mm and spacing between openings of 1.3h.

Table 7 Strength to weight ratio and rigidity to weight ratio of the models

N o	Specimen	Moment Resistance, M _R (kNm)	Rotational Stiffness, K (kNm/rad)	Weight, kN	Strength to Weight Ratio (kNm/kN)	Rigidity to Weight Ratio (kNm/rad· 1/kN)
1	A1-400	340	25954.20	5.06	67.13	5124.63
2	A1-600	360	23684.21	5.13	70.12	4613.10
3	A1-800	365	23548.39	5.20	70.14	4525.36
4	A2-400	350	32407.41	5.48	63.85	5911.88
5	A2-600	375	33185.84	5.55	67.55	5978.07
6	A2-800	385	34070.80	5.62	68.50	6061.57
7	A3-400	355	31415.93	5.76	61.63	5454.31
8	A3-600	390	35454.55	5.76	67.71	6155.48
9	A3-800	380	32478.63	5.83	65.19	5571.56
10	B1-400	380	34545.45	5.64	67.35	6122.35
11	B1-600	390	33333.33	5.68	68.64	5866.87
12	B1-800	390	33333.33	5.72	68.17	5826.76
13	B2-400	385	36320.75	5.88	65.51	6179.99
14	B2-600	400	36363.64	5.92	67.61	6146.39
15	B2-800	405	37500.00	5.96	68.01	6296.84
16	B3-400	375	35714.29	6.03	62.15	5919.25
17	B3-600	405	37500.00	6.07	66.69	6175.19
18	B3-800	380	34545.45	6.07	62.58	5688.66

19	C	425	37946.43	6.39	66.56	5942.55
----	---	-----	----------	------	-------	---------

Table 8 Strength to weight ratio and rigidity to weight ratio of the models						
N o	Specimen	Moment Resistance, M _R (kNm)	Rotational Stiffness, K (kNm/rad)	Weight, kN	Strength to Weight Ratio (kNm/kN)	Rigidity to Weight Ratio (kNm/rad· 1/kN)
1	A1-400	340	25954.20	5.06	67.13	5124.63
2	A1-600	360	23684.21	5.13	70.12	4613.10
3	A1-800	365	23548.39	5.20	70.14	4525.36
4	A2-400	350	32407.41	5.48	63.85	5911.88
5	A2-600	375	33185.84	5.55	67.55	5978.07
6	A2-800	385	34070.80	5.62	68.50	6061.57
7	A3-400	355	31415.93	5.76	61.63	5454.31
8	A3-600	390	35454.55	5.76	67.71	6155.48
9	A3-800	380	32478.63	5.83	65.19	5571.56
10	B1-400	380	34545.45	5.64	67.35	6122.35
11	B1-600	390	33333.33	5.68	68.64	5866.87
12	B1-800	390	33333.33	5.72	68.17	5826.76
13	B2-400	385	36320.75	5.88	65.51	6179.99
14	B2-600	400	36363.64	5.92	67.61	6146.39
15	B2-800	405	37500.00	5.96	68.01	6296.84
16	B3-400	375	35714.29	6.03	62.15	5919.25
17	B3-600	405	37500.00	6.07	66.69	6175.19
18	B3-800	380	34545.45	6.07	62.58	5688.66
19	C	425	37946.43	6.39	66.56	5942.55

3.3 Deformed Shape and Maximum Deflection

The maximum nodal displacement for each of the models are shown in Table 9. Table 10 shows the percentage difference in term of deflection for model A compared to model B. The mode of failure for all the 19 models

are the same. For perforated sections with different opening size, the maximum displacement (deflection) of the beam is higher for section with larger opening size. The maximum displacement of section with opening size of 0.65h is 48.22% to 265.87% lower than perforated section with opening size of 0.8h. The sections with opening size of 0.8h tend to have much higher deflection than perforated section with opening size of 0.65h when the spacing between the openings is small ($S_2=0.87h$). From the deformed shape of the models, it can be observed that there are deformations at the openings for section with opening size of 0.8h and spacing between openings of 0.87h. Both the perforated section with different opening size have deflection higher than normal section without perforation. Perforated section with opening size of 0.65h have deflections which are 24.5% to 113.4% higher than normal section without perforation, whereas perforated section with opening size of 0.8h have deflections which are 97.28% to 680.76% higher than normal section without perforation. For most of the model, the deflection decreased when the spacing between openings increases. However, the deflections are the least when the spacing between openings are 1.3h for both models with different opening size and distance between the first opening and column face of 600mm. For models with different distance between the first opening and column face, the deflection decreased as the distance between the first opening and column face, S_1 increased. However, the deflections are the least when the distance between the first opening and column face, S_1 are 600 for both models with different opening size and spacing between openings of 1.9h.

Table 9 Maximum displacement for all models

No	Specimen	Max. Displacement (mm)	Percentage difference in max. displacement compared to model C
1	A1-400	554.046	680.76
2	A1-600	447.155	530.13
3	A1-800	397.395	460.01
4	A2-400	206.104	190.44
5	A2-600	166.265	134.30
6	A2-800	138.435	95.08
7	A3-400	177.269	149.81
8	A3-600	131.221	84.92
9	A3-800	139.996	97.28
10	B1-400	151.432	113.40
11	B1-600	135.149	90.45
12	B1-800	122.965	73.28
13	B2-400	118.41	66.86
14	B2-600	101.61	43.19
15	B2-800	92.2585	30.01
16	B3-400	109.854	54.81
17	B3-600	88.3758	24.54
18	B3-800	94.4522	33.10
19	C	70.9626	-

Table 10 Percentage difference in term of deflection for model A compared to model B

No	Deflection for model A (mm)	Deflection for model B (mm)	Percentage difference in term of deflection for model A compared to model B
1	554.05	151.43	265.87
2	447.16	135.15	230.86
3	397.40	122.97	223.18
4	206.10	118.41	74.06
5	166.27	101.61	63.63
6	138.44	92.26	50.05
7	177.27	109.85	61.37
8	131.22	88.38	48.48
9	140.00	94.45	48

4. Conclusion

The behaviour of beam to column connection using flush end plate for normal I-beam section without perforation and beam section with perforation at the beam web was successfully determined using finite element analysis. The capacities of the connection is found to be dependent on the geometrical aspects of the openings such as the opening size, distance between the first opening and column face, spacing between openings.

The presence of openings at the beam web have effects on the moment resistance (strength) and rotation stiffness (rigidity) of the connection. Normal I-beam section tends to have higher strength and rigidity than beam section with perforations. The strength of normal section without perforation is 4.71% to 20% higher than beam section with perforations. While its rigidity is 1.18% to 37.94% higher than beam section with perforations.

For beam with perforations, different openings size also have effects on the strength and rigidity of the connection. For beam section with small opening size, the strength and rigidity of the connections are higher than that of larger opening size. For this study, section with smaller opening size are 3.7% to 10.5% and up to 29.35% higher than section with larger opening size in term of strength and rigidity respectively. From the parametric study, the geometric parameter such as distance, S_1 and spacing, S_2 affected the connection's behaviour in different ways. For both perforated section with opening size of 0.65h and 0.8h, both the strength and rigidity are higher when the distance between the first opening and column face is 800mm and spacing between openings of 1.3h. However, their strength to weight ratio and rigidity to weight ratio are higher than the normal beam without perforation. Perforated section with opening size of 0.65h has 2.17% higher in term strength to weight ratio and 5.96% higher in term rigidity to weight ratio compared to normal section. While perforated section with opening size of 0.8h, the strength and rigidity to weight ratio are 2.91% and 2.00% higher than that of normal section.

In this study, it is found that the mode of failure for all the 19 models are the same which is the bending of the beam. The connection is undamaged when the beam deflected. The deflection of the normal solid beam model is lower than that of perforated section model with difference of 24.5% to 680.76%. Perforated section with smaller opening size has smaller deflection than that of larger opening size (48.22% to 265.87% lower in deflection). For both perforated section with different opening size, the deflection is lowest when the distance between the first opening and column face is 600mm and spacing between openings of 1.9h.

Acknowledgement

The authors would like to thank the School of Civil Engineering of Universiti Sains Malaysia under Research University Grant (RUI), (Account number: 1001/PAWAM/814222) for their financial support.

References

- [1] CEN, B. & EN, B. (2005). "Eurocode 3: Design of steel structures Part 1-8: Design of joints".
- [2] Anis. (2006). "Behaviour Of Composite Partial Strength Connections With Trapezoid Web Profiled Steel Section". Doctor of Philosophy, University Teknologi Malaysia.
- [3] Krishnamurthy, N. (1978). "A fresh look at bolted end-plate behaviour and design." *Engrg. J. Am. Inst. of Steel Constr.*, 15(2), 39-49.
- [4] Archibald N. Sherbourne, M. R. B. (1994). "3D Simulation of End-Plate Bolted Connections". *Journal of Structural Engineering*, 120, 3122-3136.
- [5] Shi, Y., Chan, S. & Wong, Y. (1996). "Modelling for moment-rotation characteristics for end-plate connections". *Journal of Structural Engineering*, 122, 1300-1306.
- [6] Goudarzi, A., Ghassemieh, M. & Baei, M. (2012). "The Effect of Axial Force on the Behavior of Flush End-plate moment connections". Paper Title Line.
- [7] Darwin, D. and W. K. Lucas (1990). "LRFD for steel and composite beams with web openings." *Journal of Structural Engineering* 116(6): 1579-1593.
- [8] Redwood, R. and S. H. Cho (1993). "Design of steel and composite beams with web openings." *Journal of Constructional Steel Research* 25(1): 23-41.
- [9] Liu, T. & Chung, K. (2003). "Steel beams with large web openings of various shapes and sizes: finite element investigation". *Journal of Constructional Steel Research*, 59, 1159-1176.
- [10] Tsavdaridis, K.D. & Mello, C. (2009). "Finite element investigation of perforated steel beams with different web opening configurations". *ICASS'09/IJSSD-Proceedings of Sixth International Conference on Advances in Steel Structures and Progress in Structural Stability and Dynamics*. ICASS'09 Press.
- [11] Kukreti, A., Murray, T. & Abolmaali, A. (1987). "End-plate connection moment-rotation relationship". *Journal of Constructional Steel Research*, 8, 137-157.
- [12] Shi, Y., Chan, S. & Wong, Y. (1996). "Modelling for moment-rotation characteristics for end-plate connections". *Journal of Structural Engineering*, 122, 1300-1306.
- [13] Abolmaali, A., Matthys, J. H., Farooqi, M. & Choi, Y. (2005). "Development of moment-rotation model equations for flush end-plate connections". *Journal of Constructional Steel Research*, 61, 1595-1612.
- [14] Lehman, D. E., Roeder, C. W., Herman, D., Johnson, S. & Kotulka, B. (2008). "Improved seismic performance of gusset plate connections". *Journal of Structural Engineering*, 134, 890-901.
- [15] Archibald N. Sherbourne, M. R. B. (1994). "3D Simulation of End-Plate Bolted Connections". *Journal of Structural Engineering*, 120, 3122-3136.
- [16] Tsavdaridis, K. D., Kingman, J. J. & Toropov, V. V. (2015). "Application of structural topology optimisation to perforated steel beams". *Computers & Structures*, 158, 108-123.
- [17] Zaarour, W. & Redwood, R. (1996). "Web buckling in thin webbed castellated beams". *Journal of Structural Engineering*, 122, 860-866.
- [18] Tsavdaridis, K. D., Faghih, F. & Nikitas, N. (2014). "Assessment of perforated steel beam-to-column connections subjected to cyclic loading". *Journal of Earthquake Engineering*, 18, 1302-1325.
- [19] Omar, N (2012), "Beam to Column Connections for Triangular Web Profiled Steel Section (TRIWP)", *Politeknik Merlimau*, in the proceeding of the PPM Research Colloquium 2012.
- [20] Tahir, M, M (1997), "Structural and economic aspects of the use of semi-rigid joints in steel frames", PhD Thesis, Department of Engineering University of Warwick, United Kingdom.
- [21] Saggaff, A. (2006), "Behaviour of composite partial strength connections with trapezoid web profiled steel section", PhD Thesis, Faculty of Civil Engineering, Universiti Teknologi Malaysia.