THE BEHAVIOUR OF PORTAL FRAME EAVE HAUNCH CONNECTION WITH AND WITHOUT PERFORATED SECTION

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ABSTRACT

This study presented the result of analysis on portal frame eave haunch connection with and without perforated section. This connection was modelled as rigid connection. LUSAS 14.3 software has been used for modelling with nonlinear analysis. The purposes of this study were to determine the moment rotation, stress distribution, and failure pattern of the connection. The results were used to compare between two models which were eave haunch with and without perforated section. The results focus more on the difference of moment rotation, stress distribution and failure pattern between the two models. Based on the results, the moment resistance for the two models were almost the same but the rotation value for eave haunch that had perforated section was higher than eave haunch that without perforated section. The percentage difference of rotation between both models is 40%. From the contour stress diagram, the stress distribution and critical stress could be identified clearly. The results showed that the stress distribution at portal frame eave haunch connection without perforated section was more evenly than the connection with perforated section. Subsequently, the critical stress occurred at portal frame eave haunch connection without perforated section has also lower than the connection with perforated section. The percentage difference of the critical stress was calculated to be 3%. In other words, the portal frame eave haunch connection with perforated section is easier to rotate than without perforated section when the applied load is the same. The comparison of failure pattern had been identified and realized that the failure modes of the two modal were similar to each other which the column and rafter experienced bending when the loading applied to the top flange of the rafter.

Keywords: Portal frame, connection, moment rotation, stress distribution, failure pattern

Introduction

The basic structural form of portal frames was developed during Second World War, driven by the need to achieve the low-cost building envelope. Nowadays, it is commonly used structural forms for single-story industrial structures. They are mostly used in supporting the roofing and side cladding via cold-formed purlins and sheeting rails. Portal frame can be constructed by using cold and hot-rolled sections. In Malaysia, portal frame are mainly constructed using hot-rolled sections.

Due to transportation limitations, the joints are introduced at suitable position such as at eave and ridge part. High moment will be created at these connections such as at the interface of the column and rafter members (at the eaves). It is very difficult to develop sufficient moment capacity at these connections by providing 'tension' bolts located solely within the small depth of thereafter section. Therefore the lever arm of the bolt group is usually increased by hunching the rafter members at the joints. This addition increases the section strength (Rangachari Narayanan & Der-Avanessian, 1986).

Eave connections are usually designed as moment-fixed connection, which is a transfer of bending moment that takes place between the connecting members. However, tension bolts within the rafter height are inadequate for developing sufficient moment capacity at the connections (R Narayanan & Kalyanraman, 2003). Therefore, hunched elements using tapered I-sections are introduced at the bottom flange of the rafters (connection part) to increase the moment capacity of the element, instead of increasing the rafter size (Moore & Wald, 2003) and (R Narayanan & Kalyanraman, 2003).

Problem statement

The haunch is an effective method of locally increasing the capacity of the rafter at point of highest loading. It is cut from the rafter section and extends for 10% of the span at the eaves. Connection of the hunched rafter to the column is by an end plate.

Due to the high loading transferred to the column, a stiffener is often required in the web of the column opposite the flange of the haunch to prevent local buckling ("Tata Steel UK Limited to Sell Long Products ", 2016).

In term of connection design, a deeper and heavier haunch may be more suitable. This will reduce the tensile force in the bolts and the force in the compression zone at the bottom of the haunch and therefore reduce the shear force (caused by the tension in the bolts) in the top of the column.

The potentially weak areas may occur in the eave haunch with perforated section due to the presence of opening such as circular holes. The failure mode usually happened due to the reduction of the plastic strains in the link flanges and consequently increasing the plastic stress in the web around the edges of the penetration (Tsavdaridis, Faghih, & Nikitas, 2014). Therefore, the positions and sizes of openings along the eaves haunch are important especially when the web opening moves closer to column flange where web local buckling and fracture might obtain (Yang, Li, & Yang, 2009). The perforated part will decide the moment resistance at the eaves haunch connection. The moment resistance (M) and the rotation (θ) need to be determined if the haunch is perforated and compared with the haunch without perforation in a fixed type (welded) of connection.

Literature review

There are many types of steel portal frame with eaves haunch connection. Normally, the column base is designed as pinned support for the convenience of the foundation design and construction. It may not give the most economic cost but rather for the convenience of construction. The frame relied on the bending resistance of the connections, which are stiffened by a suitable haunch at the eaves part of the portal frame. The advantage of this frame structure is that it is stable in its plane and provides a clear span that is unobstructed by bracing. The portal frame (columns and rafters) normally used I sections rather than H sections. The external column sections are normally significantly heavier (in terms of mass/unit length) than the rafter sections, if the rafters are hunched at rafter or column connections. The rafter will normally be reinforced by a haunch at the connection to the columns.

In addition to increasing the moment resistance of the rafter, the presence of the haunch also increases the lever arms of the bolts in the tension zone, which is important if the connection carries a large bending moment. Generally the bolts in the tension zone (the upper bolts under conventional gravity loading) are nominally allocated to carry tension from the applied moment, whilst the lower bolts (adjacent to the compression stiffener) are nominally allocated to carry the vertical shear, which is generally modest.

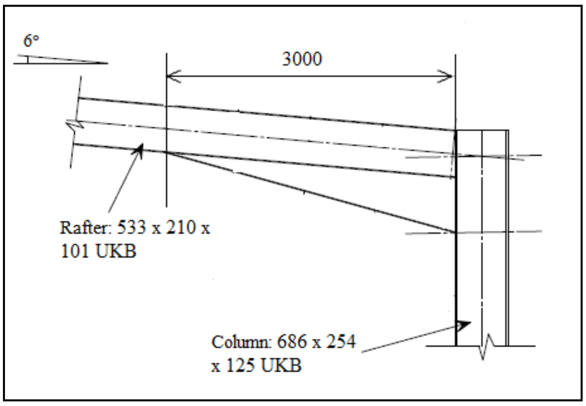
However, for rigid type of portal frame connection, the deformation gives no significant influence on the distribution of internal forces and moments in the structure. In other word, rigid connection is capable to transmit the forces and moments. The deformation of rigid portal frame does not reduce the resistance of the structure (Shin, 2011). Rigid connection has no relative rotations occur between the connected members, transfer not only substantial bending moments, but also shear and axial forces (J.G.S.daSilva, P.C.G.daS.Vellasco, S.A.L.deAndrade, M.I.R.deOliveira, & 胡大柱, 2005).

The haunch has a great effect on the economy of the structure by allowing smaller rafter sections to be selected. The proportions of the haunch depend on the characteristics of each individual building, especially on the size of the rafter (inclined horizontal beam). These characteristics determine the ability of the structure to carry the loading throughout the design life. If the environment is clean, dry and protected from the weather, details such as intermittent fillet welds or bolts at very large spacing are usually acceptable (Shin, 2011).

Díaz, Victoria, Martí, and Querin (2011) conducted a research related to the finite element model of beam to column extended end plate joints. The model was calibrated and validated with experimental results found in the literature and with the model proposed by Eurocode 3. The research concluded that finite element model was able to accurately predict the failure mode of the joint.

This dissertation research focuses on understanding of the behavior of welded connection for portal frame eave haunch with and without perforated section. Column size 686 x 254 x 125UKC are connected to 533 x 210 x 101 UKB or rafters as shown in Figure 1. The end plate bolted connection is made from 1204 x 250 mild steel plate with a thickness of 20 mm is chosen to connect rafters to columns. This study is to determine the moment rotation, failure pattern and stress distribution at the part of eaves haunch welded connection with and without perforated section. The analysis will be conducted using finite element method with the aid of computer software LUSAS 14.3.

Fig. 1: Portal frame eave haunch connection



In-plane rotation of the connection is the most prominent type of deformation in portal frames, and is caused by the bending moment acting at the connection. It can thus be stated that the rotation of a connection is a function of the moment applied to it. The rotation (θ) of a connection is defined as the change in angle of the structural components connected to it, that is, the change in angle between the center lines of the column and the beam due to the loading of the portal frame resulting in a moment being generated at the connection (Shi, Shi, & Wang, 2007).

A studied done by Verweij (2010) found that web-post buckling due to shear transfer is the controlling mechanism. From the horizontal shearing force, combined with the vertical shear forces that act on the tees, the diagonal tensile and compressive action was developed in the web-post and had caused local or lateral-torsional buckling.

Methodology

Connection Configuration

The portal frame eaves haunch connection was modelled based on the single span symmetrical portal frame to Eurocode 3. Advance Universal Beam sections were used for the rafters and columns. The geometry and properties of the model were made as similar as possible to that of the actual case in real life. The components of the connection modelled were rafter, column, endplate and bolts. The bottom of the column and the apex part of rafter was restrained in the x, y and z directions. Figure 2 shows the plan view of endplate and Figure 3 shows the portal frame eaves haunch connection model that will be analyzed by using LUSAS software.

Fig. 2: **Plan view of the endplate and dimension detail**

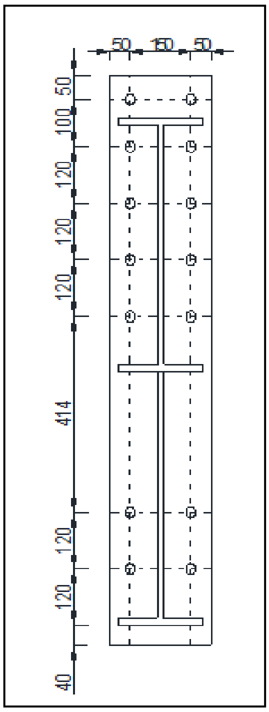
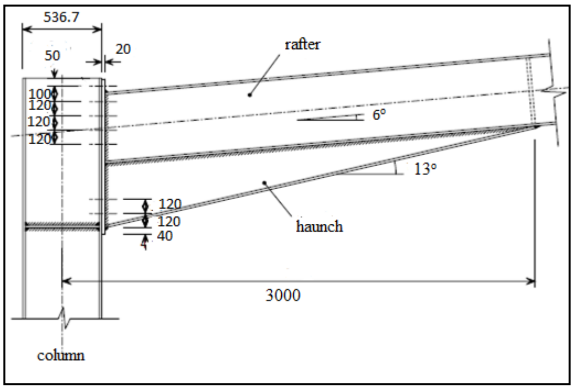


Fig. 3: Portal frame eaves haunch connection section and dimension



NONLINEAR MATERIAL PROPERTIES

In this study, all the components used are steel. Steel is a material that has nonlinear properties. Material non-linearity occurs when the stress-strain relationship ceases to be linear and the steel yields and becomes plastic.

For the elastic dataset, all elements were defined as elastic isotropic with a Young's Modulus of Elasticity of 2.09 x 10^5 N/mm^2 and Poisson's lateral to longitudinal strain ratio of 0.3. The mass density of steel is 7.85 x 10^{-5} N/mm^3. All data used in this study were the same data used in previous study by (Ahmad, 2005).

In the plastic section, Stress Potential model was selected and applied with nonlinear material properties. Von Mises yield criteria was used for all material models. Von Mises material models use a consistent formulation in the evaluation of the stiffness matrix, which provides quadratic convergence characteristic. This formulation can ensure a fast and efficient solution (Ahmad, 2005). Table 1 shows the elastic and plastic dataset that used in this study.

Table 1: Summary of Elastic and Plastic Dataset

Elastic dataset	
Young's Modulus of Elasticity	2.09 x 10^5 N/mm^2
Poisson's lateral to longitudinal strain ratio	0.3
Mass density of steel	7.85 x 10^{-5} N/mm^3
Plastic dataset	
Initial uniaxial yield stress	300 N/mm^2
Hardening gradient slope	10 000
Plastic strain	100

BOUNDARY CONDITION AND LOADING

Displacements in the X, Y and Z directions were set as free to rotate but fixed in translation (pinned support) at the bottom of the column. The loading in the model was derived from the manual calculation.

HAUNCH LENGTH SECTION

The haunch section was fabricated from the cutting of a 533 x 210 x 101 UKB, Grade S355 rafter. The portal frame eaves haunch connection without perforation section acted as a control specimen and the results were compared with the perforation section in terms of moment rotation, stress distribution and failure pattern.

The diameter of the opening in the haunch section was set at 0.8D (D = depth of the haunch). It is essential for the connection to distribute the stresses to the desired location to avoid the formation of plastic hinge. From the previous study by Tsavdaridis and Papadopoulos (2016), the beams to column connection behave in a satisfactory manner and provide an enhanced performance in terms of stress distribution when subjected to cyclic loading especially when the web openings were located at a particular distance from the face of the column. The ideal distance from the face of the column was identified as 350mm with 1.2do spacing between two circular holes (do is the depth of the rafter).

The position of the circular size 0.8D is shown in Figure 4 and circular diameter in its position and spacing between diameters of two circular holes are shown in Table 2 and Table 3. Due to the fact that eaves haunch section with perforation is a new topic and not much research related to it, the opening size 0.8D circular is selected based on the research of perforated beams with multiple closely spaced web openings by Tsavdaridis, Kingman, and Toropov (2015).

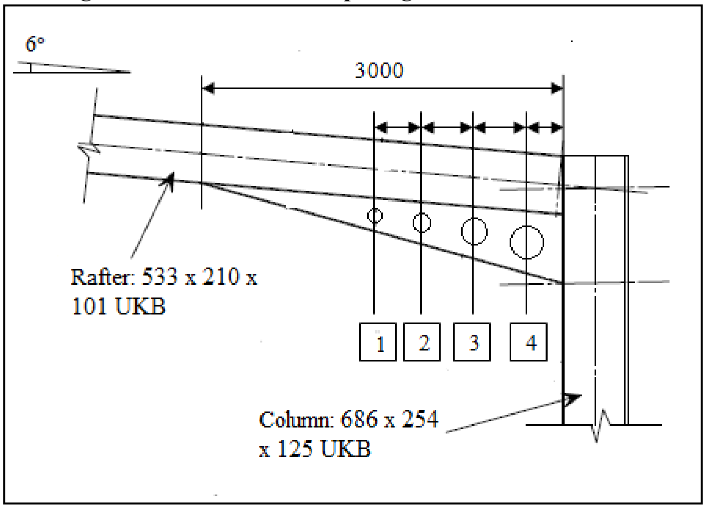
Table 2: Circular diameter in its position respectively

Position	Circular diameter (mm)
1	207.60
2	250.64
3	302.60
4	365.28

Table 3: Spacing between diameter of two circular holes

Position	Circular diameter (mm)
1-2	300.80
2-3	363.12
3-4	438.40
4-column face	350.00

Fig. 4: Position of circular opening in eave haunch section



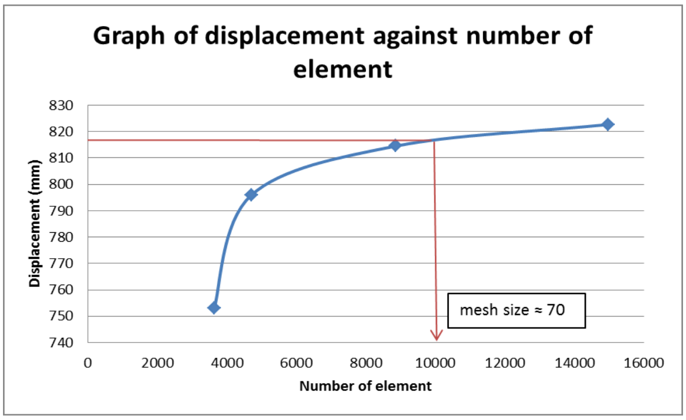
CONVERGENCE STUDY

In this study, the model of portal frame eave haunch connection without perforated section had being used to carry out the convergence study. Thus, after obtained the suitable mesh size, this mesh size was used to carry out the rest of the analysis by LUSAS 14.3. The results obtained will be more accurate and reliable. Table 4 below shows the different mesh size with different value of displacement. In this study, the mesh size of 70 was selected for the rest of the models using the graph of displacement against number of element as shown as in Figure 5.

Table 4: Displacement and Number of Element for the Different Mesh Size

Mesh size	Displacement (mm)	Number of element
90	753.093	3628
80	795.903	4696
70	814.525	8863
60	822.681	14973

Fig. 5: Identified the Mesh Size from the Graph of Displacement against Number of Element



MOMENT ROTATION
Unfortunately, we cannot obtain moment rotation curve directly from the LUSAS software. However, we can get the moment data from each load factor that we assigned. To plot the graph of moment-rotation (M-Φ) curve, manual calculation is needed. The rotation data is obtained from the displacement at certain node. The rotation is the change in angle between the centre lines of the column and the rafter due to the loading on the portal frame resulting in a moment being generated at the connection.

The vertical displacement at free end of rafter due to maximum load case is the important part need to be addressed. The free end of rafter is the place where the maximum bending moment occurred. The maximum deflection, δ for elastic condition of a cantilever beam can be calculated by this equation:

$$\delta_{max} = \frac{wl^4}{8EI}$$

Fig. 6: Deflection of a cantilever beam

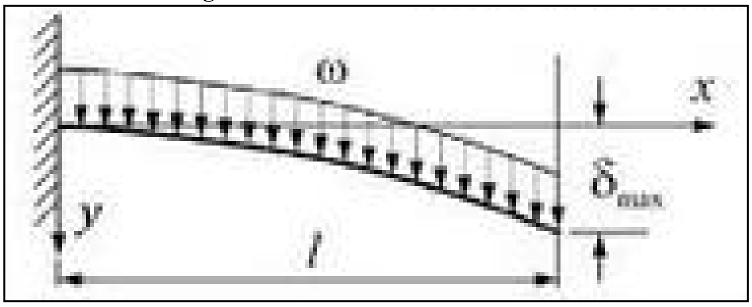
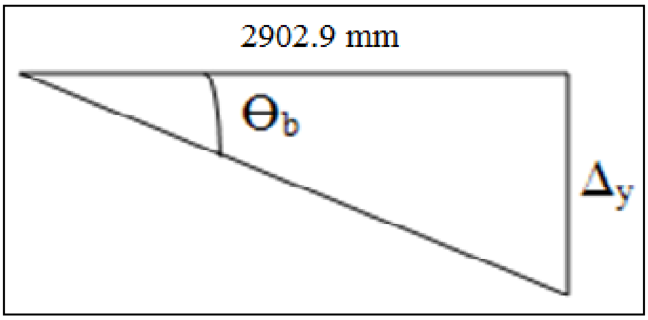
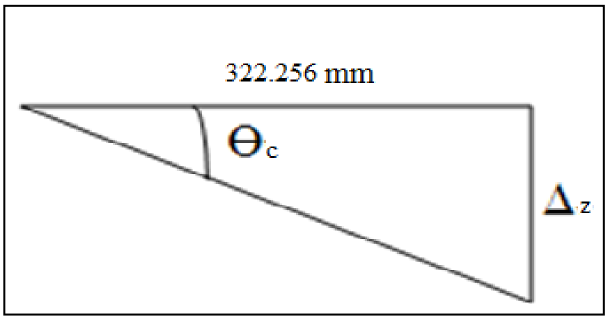


Fig. 7: Obtained the rotation values by using Pythagoras Theorem





The rotation of the connection was calculated based on the displacement of rafter in Y direction and displacement of the column in Z direction. From the displacement of Y, Δ_y and Z, Δ_z direction, using Pythagoras Theorem in Figure 7 to calculate the rotation of the two nodes (Θ_b and Θ_c).
The calculation procedures for the connection rotation (Φ_j) are as following:

$$|\Phi_j| = \Theta_b - \Theta_c \quad (1.1)$$
$$\Theta_b = \tan^{-1}(\Delta_y/2902.9) \quad (1.2)$$
$$\Theta_c = \tan^{-1}(\Delta_z/322.256) \quad (1.3)$$

where Θ_b = beam rotation
Θ_c = column rotation
Φ_j = connection rotation
Δ_y = vertical displacement
Δ_z = horizontal displacement

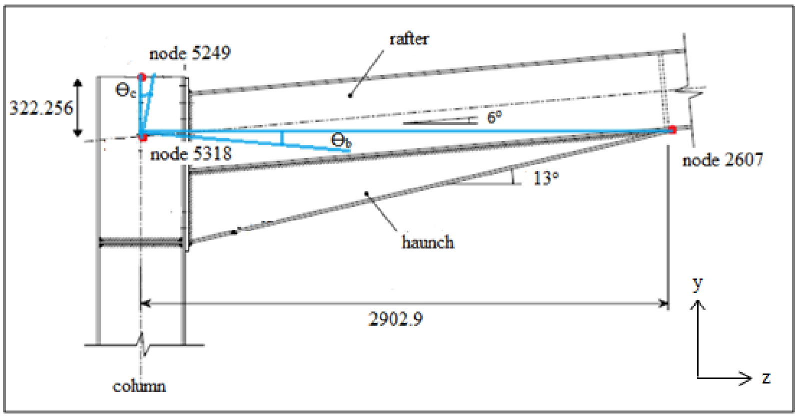
The unit of Θ is in radian whereas the linear measurements, Δ are in millimetre.
The applied moment is calculated by using the formula below:
$M = wL^2/2$ x load factor
$= 11.3 \times 10^3 \times 15^2 / 2$ x load factor
= 1.27 kNm x load factor (1.4)
where M is applied moment in kNm and W is applied uniform distributed load in kN/m^2 acting along the rafter top flange surface.

ASSUMPTION OF MODELLING
In this study, there were several assumptions to be made in this model. These assumptions were very important in order to create a model that can be as similar as possible to the actual connection. The assumptions were:
- The column end was set as pinned support.
- The welds between the rafter to the endplate and endplate to column flange were rigid therefore these components were modelled as a unit.

Results And Discussion

MOMENT-ROTATION CURVE (M-Φ)
In order to plot a moment-rotation curve, values of displacements and loading were used to calculate the values of moment and rotation. The location of nodes used to determine the value of rotation is shown in Figure 8. Node 5249 is located at the center of column web where the vertical height from node 5318 to node 5249 is 322.256 mm, while node 2607 is located at the end of the eave haunch part where the horizontal distance from node 5318 to node 2607 is 2902.9 mm.

Fig. 8: Position of nodes (red dots) in the models that used to determine the rotation



The values of vertical displacement at node 2607 and horizontal displacement at node 5249 for portal frame eave haunch connection without perforation and with perforation is shown in Table 5 and Table 6, respectively. These data were obtained from the Load Factor at each increment. The values of the rotation were obtained from Equation 1.1, Equation 1.2 and Equation 1.3 in order to obtain the value of Θb, Θc and Φj, respectively. On the other hand, the moment, M at the connection is obtained from the Equation 1.4.

The load factor was obtained from the convergence study by uniform increment. For each increment, the current load factor was multiplied by the specified load components to generate the applied load. Thus, where the number of iterations taken was less than the desired value, the incremented load factor will subsequently be increased.

Table 5: The displacement at Node 5249 and Node 2607 for portal frame eave haunch connection without perforation with different load factor respectively

Load Factor	Horizontal displacement of Node 5249 (Δ_z) mm	Vertical displacement of Node 2607 (Δ_y) mm
0	0	0
0.10	6.880	73.214
0.24	19.124	202.560
0.38	158.300	1628.800
0.46	396.500	1396.000
0.54	266.000	231.770

Table 6: The displacement at Node 5249 and Node 2607 for portal frame eave haunch connection with perforation with different load factor respectively

Load Factor	Horizontal displacement of Node 5249 (Δ_z) mm	Vertical displacement of Node 2607 (Δ_y) mm
0	0	0
0.10	6.890	73.245
0.24	19.140	202.590
0.38	17.650	231.770
0.46	160.000	1618.800
0.54	120.000	1396.000

Table 7: The tabulation of computation moment and rotation for portal frame eave haunch connection without perforation with different load factor respectively (refer to Table 5)

Moment (kNm)	Δ_z (mm)	Θ_c (rad)	Δ_y (mm)	Θ_b (rad)	$\lvert\Phi_j\rvert=\Theta_b-\Theta_c$ (rad)
0	0	0	0	0	0
0.127	6.880	0.021	73.214	0.025	0.004

0.310	19.124	0.059	202.560	0.069	0.010
0.480	158.300	0.457	1628.800	0.510	0.053
0.580	396.500	0.890	1396.000	0.450	0.440
0.690	266.000	0.690	231.770	0.08	0.610

Table 8: The tabulation of computation moment and rotation for portal frame eave haunch connection with perforation with different load factor respectively (refer to Table 6)

Moment (kNm)	Δ_z (mm)	Θ_c (rad)	Δ_y (mm)	Θ_b (rad)	$\lvert\Phi_j\rvert=\Theta_b-\Theta_c$ (rad)
0	0	0	0	0	0
0.127	6.890	0.021	73.245	0.025	0.004
0.310	19.140	0.059	202.590	0.069	0.010
0.480	17.650	0.055	231.770	0.080	0.025
0.580	160.000	0.460	1618.800	0.510	0.050
0.690	120.000	0.360	1396.000	0.450	0.090

Table 9: Summary of computation moment and rotation for portal frame eave haunch connection with and without perforation with different load factor respectively

Without perforation		With perforation	
Moment (kNm)	$\Phi_j=\Theta_b-\Theta_c$ (rad)	Moment (kNm)	$\Phi_j=\Theta_b-\Theta_c$ (rad)
0	0	0	0
0.127	0.004	0.127	0.004
0.310	0.010	0.310	0.010
0.480	0.053	0.480	0.025
0.580	0.440	0.580	0.050
0.690	0.610	0.690	0.090

COMPARISON OF MOMENT-ROTATION CURVE (M-Φ) BETWEEN PORTAL FRAME EAVE HAUNCH CONNECTION WITH AND WITHOUT PERFORATED SECTION

Fig. 9: Moment Capacity, M_R of the connection without perforated section

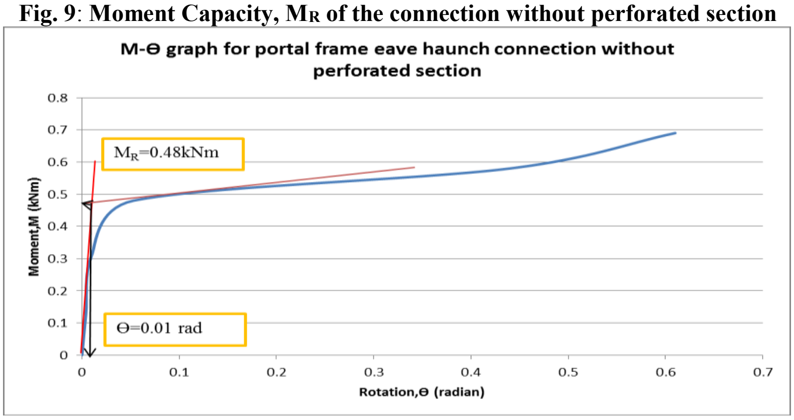
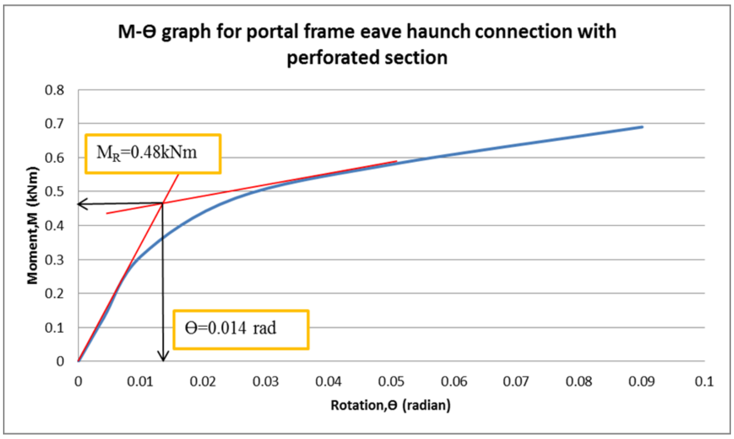


Fig. 10: Moment Capacity, M_R of the connection with perforated section



From the Figure 9 and Figure 10 above, the moment capacity, M_R of the connection for both models are 0.48 kNm. However, the rotation for eave haunch with perforated section which is 0.014 rad is slightly higher compared to eave haunch without perforated section which is 0.010 rad. The percentage difference of rotation between both models is 40%. From the finite element analysis, the ultimate moment for both of the models is about the same which is 0.69 kNm.

The results showed that the portal frame eave haunch connection without perforated section is stronger than the eave haunch connection with perforated section. As the applied uniform distribution load is constant for both models, the percentage difference of rotation between both models is also found to be 40%. In other words, the portal frame eave haunch connection with perforated section is easier to rotate than without perforated section when the applied load is the same. Based on the results, the best portal frame eave haunch connection to be used is without the perforated section.

COMPARISON OF FAILURE PATTERN FOR PORTAL FRAME EAVE HAUNCH CONNECTION WITH AND WITHOUT PERFORATED SECTION

From the analysis of LUSAS 14.3, the failure pattern in terms of the deflection of the column for portal frame eave haunch connection with and without perforated section was found to be same. As both of the models' connection were welded or fixed, and the column end was pinned support, the maximum deformation occurred at support. However, the eave haunch connection remained rigid due to the welded connection. The column and rafter were bent due to loading. The failure pattern of the LUSAS model is shown in Figure 11 and Figure 12.

Fig. 11: The failure pattern for portal frame eave haunch connection without perforated section

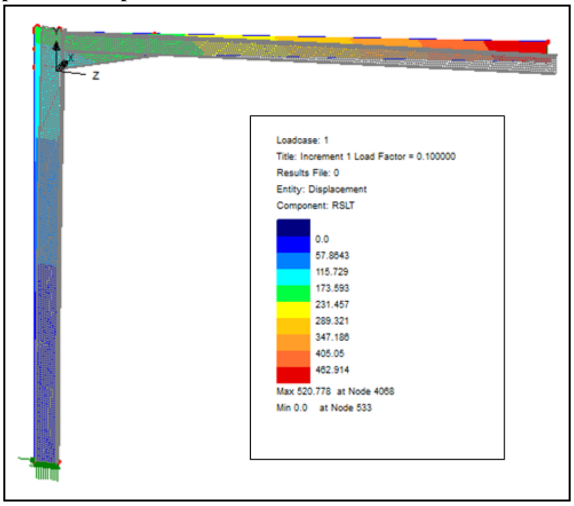
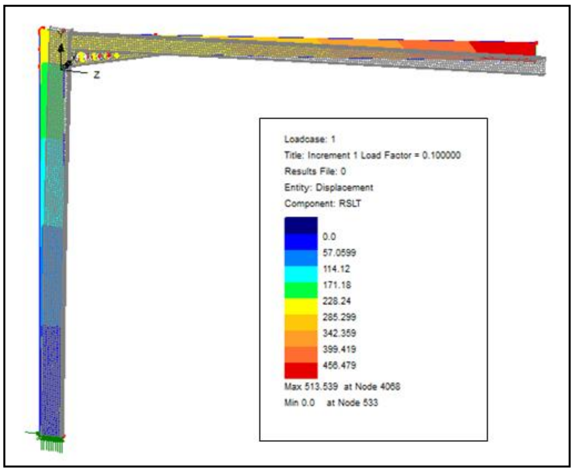


Fig. 12: The failure pattern for portal frame eave haunch connection with perforated section



From the comparison of failure pattern between portal frame eave haunch connection with and without perforated section models, the results showed that both models' failure pattern were the same. The rafter and column deflected from the original position due to the applied load. This type of failure confirms that the portal frame eave haunch connection is welded as a unit.

COMPARISON OF STRESS DISTRIBUTION FOR PORTAL FRAME EAVE HAUNCH CONNECTION WITH AND WITHOUT PERFORATED SECTION

Figure 13 and Figure 14 show the stress contour for the portal frame eave haunch connection without perforated section and with perforated section, respectively. It can be seen that the maximum stress for the eave haunch connection without perforated section and with perforated section is 7.413 x 10^3 N/mm^2 and 7.63 x 10^3 N/mm^2, respectively. The percentage difference is calculated to be only 3%. The red circle and arrow in both figures indicate the position of critical stress and the critical stress value respectively. The results also showed that, at the eave haunch part, the perforated section affected the stress distribution where higher critical stress occurred for the eave haunch connection with perforated section.

Fig. 13: Stress contour for portal frame eave haunch connection without perforated section

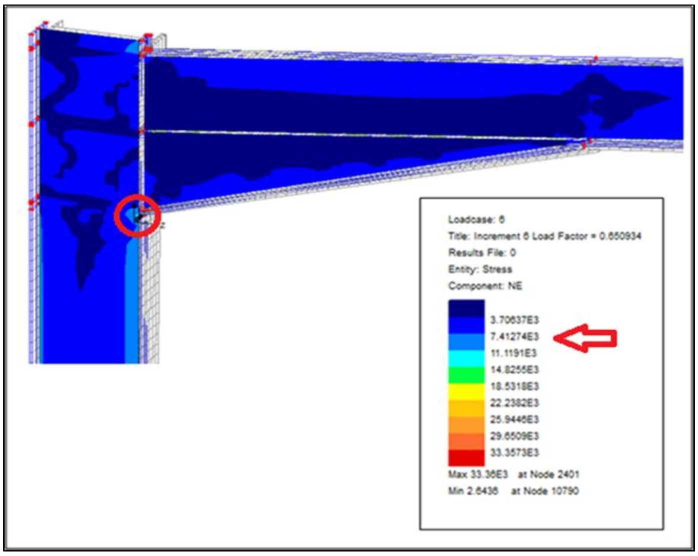
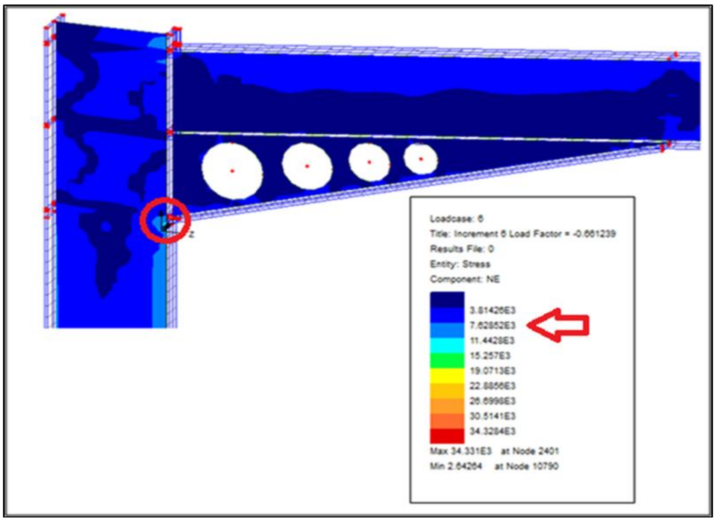


Fig. 14: Stress contour for portal frame eave haunch connection with perforated section



Conclusions

In this study, the connection was set as rigid or welded and the column support was set to be pinned. The effect of opening holes or perforated at the eave haunch section showed similar moment resistance, M_R but larger rotation, Ɵ compared to eave haunch section that is without perforation. The following are the conclusions that could be drawn.

1. The eave haunch section with the perforated section was not showing significant effect on the moment resistance, M_R value if compared to eave haunch section without perforated section. The percentage of difference was insignificant. The rotation value for eave haunch section with the perforated section was higher than eave haunch section without the perforated section. The percentage difference of rotation showed to be 40%. Based on the comparison of these two finite element models, the portal frame eave haunch connection without perforated section sustained higher load with lesser rotation compared to eave haunch section with perforated section. Moreover, the moment-rotation curve was almost linear at the beginning under an elastic condition occurred for both of the models. Thus, the moment-rotation curve can be used to represent the connection's stiffness, strength and ductility.
2. The failure pattern of the two models showed that the connection behaved as fully rigid or welded. The column and rafter experienced bending mode due to loading but the connection remained as rigid.
3. The eave haunch without perforated section resisted slightly higher stress than the eave haunch with perforated section. The critical stress occurred at the eave haunch connection with perforated section was higher than without perforated section. The specific strength of portal frame eave haunch connection with and without perforated section was found to be almost the same. The percentage in terms of difference the specific strength for the 2 models was recorded to be only 2.91%.

Finite element analysis is one of the ways in analyzing connection and it has been widely used in the research. There are still have some improvement and recommendations for future studies on the portal frame eave haunch connection especially the eave haunch part that have perforated section. The recommendations are as follows:

1. Experimental work should also be carried out to analyses the connections by undergoing several testing at lab. By doing so, the output data from the laboratory work and LUSAS 14.3 can be validated.
2. A proper steel characterization testing should be carried out in order to determine the hardening gradient and plastic strain for the column and rafter. Thus, a more accurate input data can be incorporated into software in order to obtain reliable results.
3. Other parameters such as the number of holes opening, distance between two holes and shape of the holes opening can be taken into consideration for future investigation.

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