Finite element modelling of reinforced large-opening on the web of steel beam considering axial forces

by Made Sukrawa

Submission date: 20-Feb-2019 09:18AM (UTC+0700)
Submission ID: 1080603959
File name: ge-opening_on_the_web_of_steel_beam_considering_axial_forces.pdf (574.19K)
Word count: 3676
Character count: 17632

Finite Element Modelling of Reinforced Large-Opening on the Web of Steel Beam Considering Axial Forces

Made Sukrawa

Civil Egr.Udayana University.

Corresponding author: msukrawa@unud.ac.id

Abstract. Experimental and analytical researches on the effect of web opening in steel beams have been repeatedly reported in literature because of the advantages gain from the many function of the opening. Most of the research on this area, however, did not consider deformation and stress in the beam due to axial force. In seismic design of steel structure, the axial force in the beam could be significantly high and therefore worth considering. In this study a beam extracted from a braced frame structure was analyzed using finite element models to investigate the effect of combined bending and axial forces on the deformation and stresses in the vicinity of the opening. Large size of square, rectangular, and circular openings of the same depth were reinforced and placed in pair, symmetrical to the concentrated load at mid span of the beam. Four types of reinforcement were used, all around (AA), short horizontal (SH), long horizontal (LH), and doubler plate (DP). The effect of axial load was also investigated using rigid frame model loaded vertically and laterally. Validation of the modelling technique was done prior to the parametric study. It was revealed that the axial force significantly contributes to the stress concentration near the hole. Stiffener of circular shape was effective to improve the stress distribution around the circular opening. For square and rectangular openings, however, the horizontal stiffener, extended beyond the edge of opening, performed better than the other type of stiffeners.

INTRODUCTION

Opening on the web of steel beam of multi-story building are very useful to allow crossing of utilities such as cables and pipes. The open web construction could be intentionally designed to increase the bending capacity of the beam using the same amount of materials, as in the cases of cellular and castellated beams. With the opening, vertical spaces are used more efficiently and the overall cost reduction of the building is possible. The hole that was cut from the web of an I-beam, however, is critical for many reasons. It reduces the bending and shear capacities of the beam and introduces stress concentration around the hole.

Many researches on steel beam with web opening have been done and reported in the literature. Most of them onlyconsidered vertical loading to evaluate the stiffness and strength of the beam with opening, with or without reinforcement around the opening. Moment-shear interaction was used to evaluate the capacity of the beam with web opening. Axial force was not considered when evaluating the deformation and stress associated with the web opening. In seismic design of steel structures, however, the beam of a moment frame or braced frame will undergo axial forces in addition to bending moment and shear forces. The axial forces could be significantly high depending on the magnitude of earthquake. Accordingly, this force should be included in analyzing the effect of opening on the deformation and stresses around the beam opening.

The effect of axial force on the behaviour of composite beams was reported by Kirkland et al. [1] using moment-shear-axial force interaction. The developed finite element model showed anexcellent agreement with the experimental results. The concept could be extended for the analysis of beam with web opening.

In this analytical study, steel beam with large openings of different shapes were analyzed using finite element software, together with the effectiveness of different configuration of stiffener around the opening, including the use of doubler plate, a method used to strengthen the beam-column joint for seismic design. SAP2000, common

Proceedings of the 3rd International Conference on Construction and Building Engineering (ICONBUILD) 2017
AIP Conf. Proc. 1903, 020018-1–020018-9; https://doi.org/10.1063/1.5011498
Published by AIP Publishing. 978-0-7354-1591-1/$30.00

software for analysis and design of structures, was used for the FE modelling. The effect of concentrated load nearby the opening was also investigated to obtain the best shape of opening, stiffener type, and location of the opening along the beam.

The current study focused on the effect of axial force on the stress developed in large opening, cut from rolled I-shape, with reinforcement around the opening. The stress was evaluated using the yield stress as a bench mark. The failure load and mode of the models are not considered in this study due to lack of experimental data and limitation of the software. For the purpose of beam design, the stress in the beam prior to yielding is important information to evaluate rather than its failure mechanism.

MODEL VALIDATION

To validate the modelling technique used in the analysis, a model with known exact solution is made prior to development of models with opening of varying shapes and stiffener. In addition, a tested cellular beam reported in literature was also used for validation.

Referring to the theory of elasticity [2], when a thin plate with a hole is subjected to normal forces, there will be stress concentration at the edges of the hole. To the extreme, when a very large plate with a very small hole is subjected to normal force of S, the maximum stress near the hole will be close to 3S. This phenomenon is used to validate the model together with experimental results reported in the literature.

The first validation model (M1) was an 11 mm thick steel plate of 1 m x 1 m contains circular hole of diameter 100 mm (Fig. 1). The left edge of the plate was subjected to forces that correspond to normal stress of 72.7 MPa. The right edge is simply supported. Shell element of thick formulation was used to model the plate to include transverse shear deformation. The shell element will also cover full shell behaviour, a combination of membrane and plate behaviour. Though the plate thickness, t is less the 1/10 of the plate size, the transverse shear deformation could be important. In the vicinity of bending stress concentration, such as sudden change of thickness, and near a hole or re-entrant corner the transverse shear deformation should be considered [3]. As far as stress before yielding is of concern, linear analysis of homogeneous material was assumed for the steel using elastic modulus of 210000MPa.

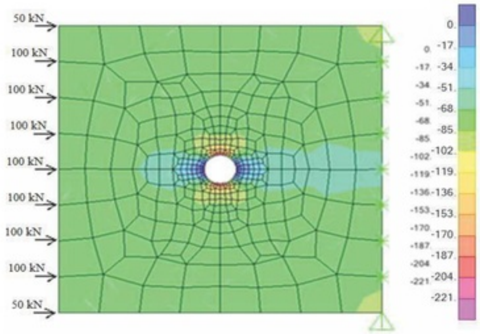

FIGURE 1. FEM and stress contour of the plate M1

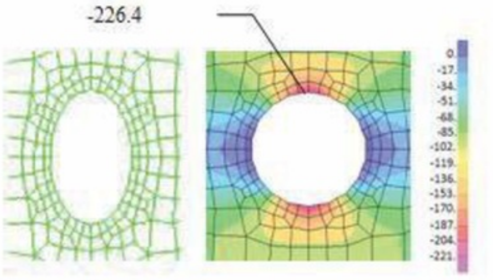

FIGURE 2. Deformed shape and max.stress of M1

The deformed shape of the plate is shown in Fig. 2 together with the stress value around the hole. It was found that the maximum tensile stress occurred on top and bottom of the hole was 226.4 MPa and the stresses on the left and right edge of the hole was 48.3 MPa in compression.

Under compression the circular hole deforms in an oval shape with high compression on top and bottom of the hole. The ratio of maximum stress and the applied load was 3.1, compared to 3 for very large plate. These results can be regarded as that the model represents the behaviour of the actual specimen. Mesh convergence study was done by trying smaller sizes of meshes but the stress value did not change significantly. Therefore the model can be considered adequate.

The second problem (M2) used to validate the SAP2000 model was a cellular beam tested by Morkhade and Gupta [4]. The 100 mm deep beam was perforated with 11 circular opening of diameter 50 mm with spacing of 3 times the hole diameter. The geometry of tested beams is shown in Fig. 3. The 2-meter beam span was centrally loaded at the mid span until failure, and the load-deformation curve at mid span was plotted together with analysis result using ANSYS software. The ANSYS model was stiffer than the actual test data at early loading stage. The resulting curve was almost perfectly bilinear. The beam yield at a load of 16.5 kN at deformation of about 9 mm. Beyond those numbers the curve was flat until deformation value of about 16 mm.

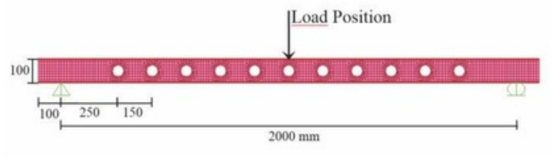

FIGURE 3. Cellular beam loaded at mid span.

The tested beam was modelled in SAP2000 using mesh configuration (near the hole) similar to M1. Non linear static push over (SPO) analysis was performed to obtain the load-deformation curve of the model up to failure. The SPO curve was plotted together with test result [4] in Fig. 4. It is obvious from the **Fig.** that the SAP2000 model is stiffer than the reported experimental data. This result however, is similar to the result reported by Morkhade and Gupta [4] in which the ANSYS model was stiffer than the tested model. From the **Fig.** can also be seen that the SAP2000 model is stronger than the tested model. The small difference could be due to error in the test data or other limitations in the SPO analysis, or its combination. Never the less, the SPO curve can still mimics the load-deformation behaviour of cellular beam before yielding.

In the design practice of steel structures linear model and analysis together with load factors are commonly used. In this study, the focus is given to the effect of axial force on the stress distribution nearby the opening. Therefore, analysis is limited to the linear stress using the simplest technique to be applied for the modelling of beams with reinforcement around the large-opening.

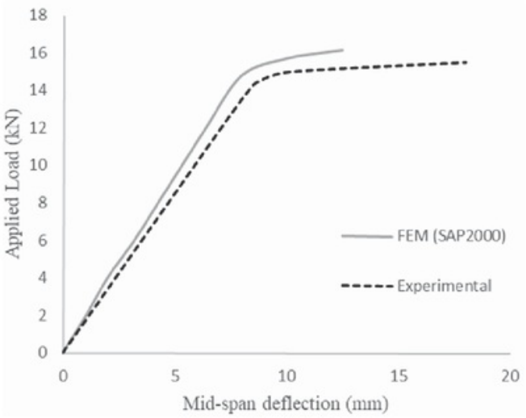

FIGURE 4. Load-deformation curve

PARAMETRIC STUDY

The parameter evaluated in this study were the effect of axial forces, the effect of stiffener types for 3 different shapes of opening, and the effect of concentrated load on the deformation and stresses on the beam with stiffened opening. Un-stiffened opening was also included as comparison. The parameters were evaluated on a simply supported beam, extracted from a 3 story braced frame as shown in Fig. 5. The axial load was that the axial force in the beam obtained from seismic load combination. The geometry of the model is shown in Fig. 6. The steel material used is grade 409 with yield stress, f_y of 320 MPa and ultimate stress, f_u of 500 MPa. The openings were placed in the beam in pair at a distance 550 mm from the point load at mid span so that the spacing of opening is much more than that specified by AISC steel design guide, which is equal to the depth of the opening for square and 1.5 the diameter of opening for circular opening [5].

Three different opening shapes were chosen, circular, square, and rectangular of depth D greater than half the beam depth. The type of stiffener used around the opening were all around (AA), short horizontal (SH), long horizontal (LH), and doubler plate (DP) of twice the size of the opening as detailed in Fig. 7. For the circular hole, the stiffener was 216 mm pipe. The horizontal stiffener was evaluated because it was strongly suggested by Rodrigues et al. [6] for opening height greater than half the total height of the beam. The thickness was 8 mm, the minimum thickness suggested for horizontal stiffener to increase local resistance to Vierendeel bending and to prevent local buckling of the web of the tee [5]. The same thickness of plate was used for square and rectangular holes in accordance to detailing limit in high shear zone.

The effect of axial load was observed by comparing two models of beam, one model was loaded vertically using dead and live (DL) and the other was loaded using combination of vertical and axial load, (DL+A).

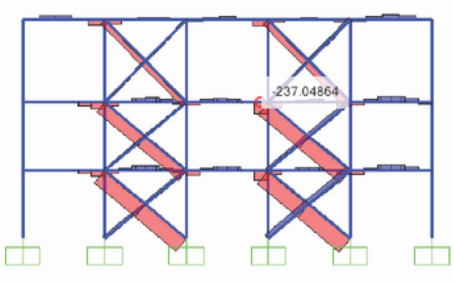

FIGURE 5. Braced frame with axial load diagram

The idea of using doubler plate as stiffener came from the concept applied for beam-column joint in seismic design as suggested by FEMA P-1051 [7]. Other configuration of stiffener was also considered during the course of this study including short and long vertical models. However, these two models did not significantly improve the stress distribution around the opening.

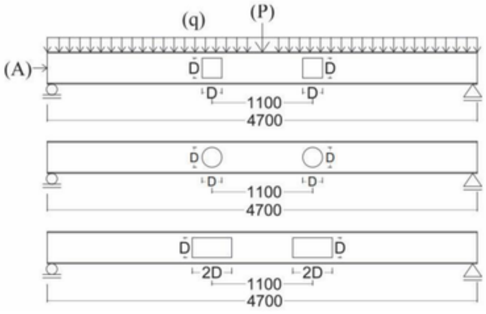

FIGURE 6. Geometry of beams with large openings

(D = 0.62 H)

The beam extracted from Fig. 5 was loaded with distributed vertical load of 5 kN/m for dead and 6 kN/m for live loads and the point load of 50 kN for dead and 37 kN for live loads. The axial load was 237 kN as obtained from the seismic analysis of the braced frame. Table 1 shows the deformation and stresses near the hole of the beam of varying hole shape and stiffener types subjected to vertical load (DL) and axial load (A). The effect of stiffener and axial load on the stress distribution for the circular, square and rectangular hole is shown in Fig. 8.

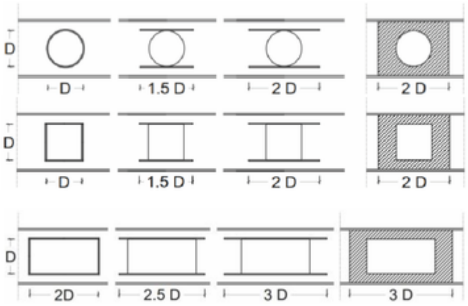

FIGURE 7. Detail of stiffener (all around, AA; short horizontal, SH; long horizontal, LH; doubler plate, DP)

TABLE 1. Effect of axial force on max.stress and disp.

Type of Stiffener	**S-max (MPa)**		**d-max**	
	DL	**DL+A**	**DL**	**DL+A**
Square				
None	313.65	391.04	8.71	9.06
AA	221.10	291.97	8.56	8.59
LH	173.35	210.15	8.49	8.55
DP	198.59	257.85	8.42	8.54
Rectangular				
None	583.13	650.43	10.16	10.34
AA	363.81	440.23	9,72	9.75
SH	271.64	311.14	9.14	9.50
LH	226.41	254.97	9.41	9.43
DP	342.89	395.97	10.00	9.70
Circular				
None	186.18	279.72	8.54	8.58
AA	111.44	168.98	8.49	8.51
SH	127.34	186.69	8.04	8.05
LH	128.12	186.83	8.08	8.12
DP	132.14	201.26	8.20	8.23

Note: steel grade 409, fy = 320 MPa, fu = 500 MPa

Fig. 9 shows the effect of opening shape and the axial load (dash line) on the stress concentration near the opening. It is obvious from the graph that circular shape is the best and the rectangular shape is the weakest.

The effect of axial load on the stress in the opening was also evaluated in a frame structure modelled using shell element as shown in Fig. 10. The beam of the frame is rigidly connected to the columns and loaded vertically due to dead and live load (DL) as in the beam model. The frame was also loaded laterally to simulate seismic load of 10% times the total vertical load. The stress contour near the openings was plotted for load case of DL and DL+A in Fig. 11.

In construction practice secondary beam was normally used to stiffen the floor slab. In such cases, the opening should be placed away from the secondary beam. For the purpose of evaluating the effect of concentrated load on the deformation and stress distribution, a pair of stiffened circular openings was placed at varying distance from the point load at mid span. Vertical and axial loads were applied to the beam and the results are given in Table 2.

To study the effect of opening size, additional models were made using opening depth of h/3 and h/2 of circular shape. The maximum stress was compared to those of the large opening of depth 0.62 h. The results are shown in Fig. 13.

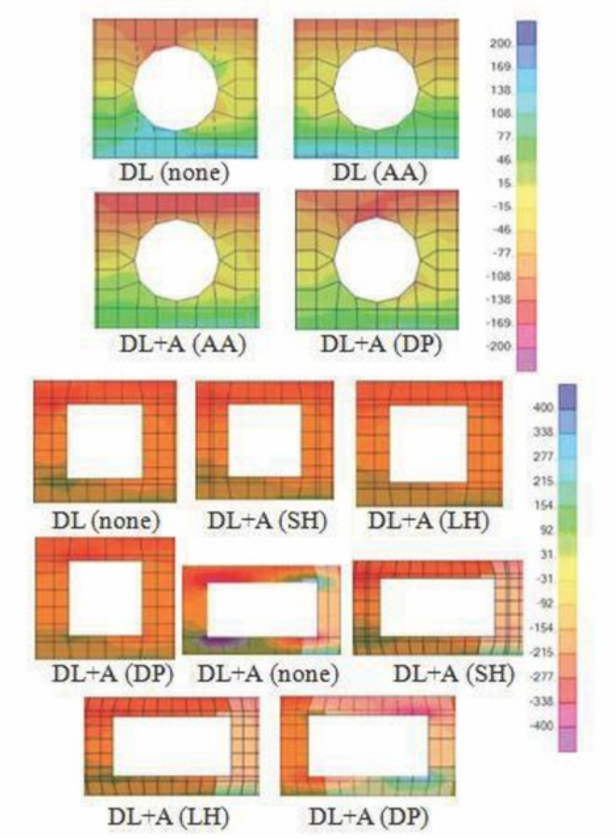

FIGURE 8. Stress near the opening (effect of stiffener and axial load)

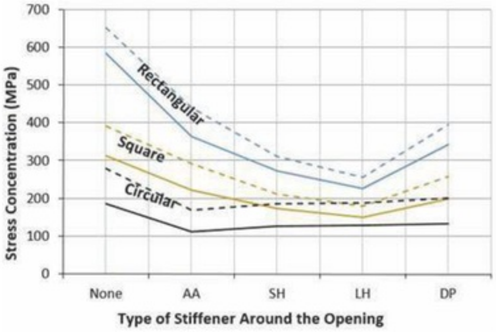

FIGURE 9. Effect of opening shapes on stress concentration (dash line shows the effect of axial force)

From Table 1 can be seen that the maximum stress near the hole increased significantly when the axial load is combined with vertical load (DL+A). In average, the increases are 25%, 15%, and 51% for square, rectangular and circular opening, respectively. The axial load also increases deformation under the hole at a lesser degree. Using steel of 320 MPa, the beam with circular opening is safe against yielding as the maximum stress due to combined DL+A was 279.72 MPa. For the square opening, however, the stress in the un-reinforced opening exceeded the yield stress. The rectangular opening was the weakest in that only opening with horizontal stiffener were safe against yielding.

From Fig. 11 can also be seen that when the frame was subjected to lateral load of 42.8 kN the maximum stress near the web opening increased by 14.5 %. Compared to the simple beam model, the stress increase in frame model is 3.5 times smaller because the axial load on the simple beam model was 5.5 times higher.

TABLE 2. Effect of point load on max.stress and disp.

X	S-max (MPa)		d-max (mm)	
	DL	**DL+A**	**DL**	**DL+A**
200	200.25	291.08	9.27	9.17
400	192.54	285.97	8.93	8.87
550	186.18	279.72	8.54	8.58
800	176.03	268.76	7.72	7.79
1000	167.57	259.80	7.02	7.04
1200	158.83	250.44	6.25	6.19
1400	150.23	240.83	5.17	5.23
1600	140.99	240.83	4.24	4.19
1800	136.99	234.42	3.05	3.09
2000	140.22	300.32	1.09	3.09

Note: X is distance of opening from the point load

Effect of axial forces

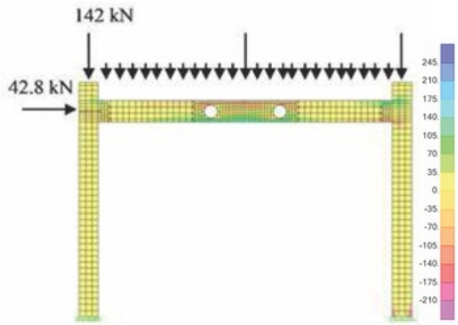

FIGURE 10. Frame model with circular web opening

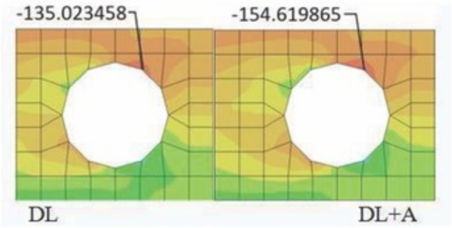

FIGURE 11. Stress contour around the opening

Effect of Stiffener Type

The effect of stiffener in reducing the stress in the vicinity of opening can be seen by comparing the maximum stress of specimens with and without stiffener. Stress contour in Fig. 8 shows the change in stress distribution with the introduction of stiffener. For the configuration of opening and stiffeners used, it is obvious that rectangular opening is the weakest and the circular opening is the strongest. In all stiffened specimens of various type of stiffener, the average stress reduction observed were 33%, 41%, and 48% for circular, square, and rectangular openings, respectively. For the circular hole, the round stiffener was the most effective followed by the doubler plate, long and short horizontal. The stress reduction varies from 29% for short horizontal to 40% for all around stiffeners. For the square hole, the long horizontal was the best followed by the short horizontal, doubler plate and all around stiffeners.

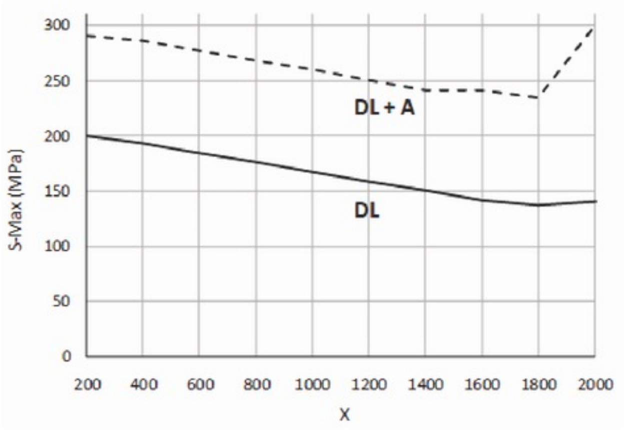

FIGURE 12. Effect of distance of opening (x) from point load at mid span

Fig. 12 shows that the maximum stress in the opening varies linearly with the distance from the concentrated load. The farther it is from the concentrated load the smaller the stress. Therefore, the hole should be placed away from the concentrated load.

The size of opening was another important parameter that affects the stress distribution on the opening. Fig. 13 shows that the smaller the opening the lower the maximum stress near the opening.

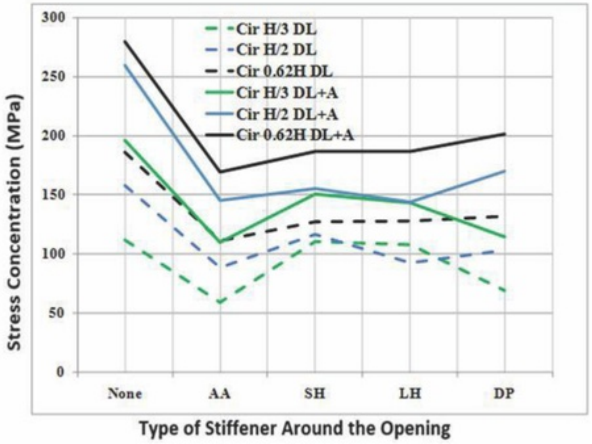

FIGURE 13. Effect of concentrated load on various size of circular opening

DISCUSSION OF RESULTS

The effect of axial force on the stress concentration in the stiffened opening is so high that it should be considered in the analysis and design of beam with web opening. The long horizontal stiffeners behave better than the short one because of the longer tee-section. This is in agreement with the result from previous study that the most important parameter is the length of the tee-sections above and below the web opening which controls the magnitude of local Vierendeel moments acting on the tee-sections [8, 9].

The effect of concentrated load on stress was not very critical but the trend is that, the closer the hole to the concentrated load, the higher the stress near the hole. Model on the varying size of opening confirm that large opening is critical for stress concentration.

CONCLUSION

Finite element modelling of large-opening on the web of steel beams was done by varying the shape and reinforcement of the beam opening considering vertical and axial loads. The results from finite element modelling showed that the presence of axial load was very influential to contribute to the stress concentration nearby the opening. It increases the maximum stress by 15%, 25%, and 51% for the square, rectangular, and circular opening, respectively. Circular hole is the strongest type of opening followed by square and rectangular opening. Reinforcement of large circular hole using circular pipe is better than those using other types of stiffener. Vertical stiffener was not as effective as the horizontal one. Rectangular opening is the one that need the most attention. Long horizontal reinforcement should be used in large opening of this shape. For the square and rectangular opening, doubler plate and all around stiffener were not as effective as horizontal stiffener extended beyond the edge of the opening. The result of this study also confirm that the larger the size of an opening, the bigger the stress concentration nearby the opening.

It is worth noted that the important effect of axial load on the stress concentration on the opening should be considered in the design guide. Further investigation is necessary to study the actual behaviour of the beam with web opening subjected to combined vertical and lateral forces.

REFERENCES

1. B. Kirkland, P. Kim, B. Uy, G. Vasdravellis, Journal of Constructional Steel Research, **114**, pp. 66–76, (2015).
2. S. P. Timoshenko and J. N. Goodier., *Theory of Elasticity, Third Edition*, (Mc Graw Hill, Inc., 1987), p. 90.
3. CSI, Reference manuals, Computer and Structures Inc., (2015)
4. S.G. Morkhade and L.M. Gupta, An experimental and parametric study on steel beams with web openings, Int. J. Adv. Struct. (2015), Eng, 7, pp. 249-260.
5. D. Darwin, *Design of Steel and Composite Beams with Web Openings* (AISC, 1990).
6. F. Rodrigues, P. C.G. da S. Vellasco, L.R.O de Lima, S.A.L de Andrade, Finite element Modelling of Steel Beams with Web Openings. Engineering, **6**, 886-813. (2014)
7. Federal Emergency Management Agency, NEHRP Recommended Seismic Provisions: Design Examples (FEMA, July 2016), P-1051.
8. T.C.H. Liu and K.F. Chung, Journal of Constructional Steel Research, **59**, 9, pp. 1159–1176, (2003).
9. R.M. Lawson and S.J. Hicks, Design of composite beam with large web opening (SCI Publication, 2011), P355.

Finite element modelling of reinforced large-opening on the web of steel beam considering axial forces

ORIGINALITY REPORT

4%	3%	2%	2%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	aip.scitation.org Internet Source	2%
2	ira.lib.polyu.edu.hk Internet Source	1%
3	Submitted to Nottingham Trent University Student Paper	1%
4	Pedro Colmar Gonçalves da Silva Vellasco, Luciano Rodrigues Ornelas de Lima, Sebastião Arthur Lopes de Andrade, Marley Maria Bernardes Rebuzzi Vellasco et al. "Finite Element Modelling", Elsevier BV, 2017 Publication	<1%
5	Dabaon, M.A.. "Experimental and numerical model for space steel and composite semi-rigid joints", Journal of Constructional Steel Research, 200908/09 Publication	<1%
6	Liu, T.C.H.. "Steel beams with large web openings of various shapes and sizes: finite	<1%

element investigation", Journal of Constructional Steel Research, 200309

Publication

Exclude quotes	On	Exclude matches	Off
Exclude bibliography	On		