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BEHAVIOUR OF STRUCTURAL SUBASSEMBLIES OF STEEL BEAMS WITH OPENINGS

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ملخص

الكمرات المعدنية ذات الفتحات بالعصب كثيرة الإستخدام وخاصة في المباني متعددة الطوابق والتي من الشائع أن تكون ذات بحور واسعة. ويتم اللجوء إلي عمل الفتحات بعصب الكمرات المعدنية لتمرير وحمل مواسير الخدمات المختلفة والتي لو تم تعليقها بالكمرات تؤدي إلي تقليل الإرتفاع الحر المطلوب بدون عوائق. وبدراسة الأبحاث المنشورة التي تخص الكمرات المعدنية ذات الفتحات بالعصب تبين أن معظمها تتمحور حول سلوك الكمرات بسيطة الإرتكاز. ومنذ زمن طويل تستخدم التجارب المعملية لدراسة سلوك المنشاءات المعدنية ولكن إستخدامها يحتاج إلي تكلفة مادية عالية ووقت طويل لإجرائها. لذلك فإن الهدف من هذا البحث هو إستخدام طريقة العناصرالمحددة بواسطة برنامج ABAQUS لعمل نموذج ثلاثي الأبعاد ومعايرته .وذلك لدراسة سلوك الكمرات المعدنية ذات الفتحات بالعصب والمتصلة بواسطة وصلات ناقلة للعزوم بأعمدة مغلقة علي شكل علب مملوءة بالخرسانة. وبإستخدام هذا النموذج تم دراسة تأثير مقاس الفتحات علي سلوك الكمرات. حيث تم دراسة أربع مقاسات للفتحات تتراوح بين ٠,٥ الي ٠,٨ من عمق الكمرة. كما تم دراسة تأثير شكل الفتحات علي سلوك الكمرات بإستخدام ثمانية أشكال مختلفة للفتحات، وهي الشكل الدائري والقطع الناقص الأفقي والمائل والشكل السداسي والمربع والمستطيل والمتوازي الأضلاع وشبه المنحرف. وقد تبين من هذة الدراسة أن سلوك الكمرات المعدنية ذات الفتحات بالإطارات المعدنية يشابهه سلوك الكمرات المعدنية بسيطة الإرتكاز ذات الفتحات من حيث التشكلات والترخيم وشكل الإنهيار. كما تبين أيضا أن القدرة التحملية للكمرات المعدنية ذات الفتحات بالإطارات المعدنية تقل بوجود الفتحات بالعصب وتعتمد علي مقاس الفتحة وشكلها ومكانها. وتبين من الدراسة أن الفتحة الدائرية تعتبر من أفضل أشكال الفتحات والتي تؤدي إلي أقل نسبة نقصان للقدرة التحملية للكمرات لوجود فتحات بالعصب. وتقل القدرة التحملية للكمرات المعدنية ذات الفتحات بزيادة مقاس الفتحة، وتتأثر أكثر بطول الفتحة وخاصة في جهة الفلنجة المعرضة للضغط للكمرة المعدنية.

Abstract

Beams with web openings are an attractive system for multi-storey buildings where it is always desirable to have long spans. The openings in the web of steel beams enable building services to be integrated within the constructional depth of the floor, thus reducing the total floor depth. At the same time, the increased beam depth can give high bending moment capacity, thus achieving long spans. However, almost all of the research studies on web openings have been concentrated on simply supported beams. In this research, the commercial software package ABAQUS is used to conduct a comprehensive finite element (FE) study of the behaviour of structural subassemblies of steel beams with openings connected to CFT columns using reverse channel connection. Four sizes of perforated steel sections with eight different shapes were undertaken and studied in order to understand the significance of their effects and in turn advance the knowledge on the performance of perforated steel beams.

1 Introduction

The provision of beams with web openings has become an acceptable engineering practice. This form of construction maintains a smaller construction depth with placement of services within the girder depth, at the most appropriate locations.

The introduction of an opening in a web of the beam alters the stress distribution within the member and also influences its collapse behaviour. As reported by Lawson 1987; Darwin 1990; Redwood and Cho 1993; Oehlers and Bradford 1995 [1-4], the presence of web openings may have a severe penalty on the load carrying capacities of structural members, depending on the shapes of the web openings.

Key Words: Steel beam, Web opening, Opening size, Opening shape, Vierendeel mechanism, Flexural failure

Many researchers have experimentally studied perforated beams with various standard web opening shapes. However, due to the cost of conducting experimental tests, experimental research alone will not be able to provide sufficient information for thorough understanding of beam performance with different sizes and shapes of opening. Using numerical modelling provides an attractive alternative means provided the numerical model is adequately validated. Such an approach has been implemented by a number of researchers to study the behaviour of perforated beams with various standard web opening shapes and sizes. For example, Liu and Chang 2003 [5] developed a comprehensive finite element investigation on steel beams with web openings of various shapes and sizes. Wang and Chung 2008 [6] performed a numerical analysis and experimental investigations on the design recommendations for steel and composite beams with web openings. Chung et al. 2001 [7] and Chung and Lawson 2001 [8] studied steel beams and composite beams with openings using finite element models. The study led to that, services requires web openings up to 75% of the beam height are not uncommon. Based on finite elements models, Lakusic et al. 2008 [9] developed a study about the buckling curve for lateral-torsional buckling resistance of castellated beams considering an experimental and a numerical analysis. Radic et al. 2008 [10] performed a numerical analysis of castellated beams considering two different procedures for the calculation of the elastic critical moment for lateral torsional buckling. Other works can be cited concerning the web openings beams behaviour. Basher et al. 2009[11] investigated the effects of circular or square web openings on the ultimate strength of horizontally curved composite plate girders. Hagen et al. 2009 [12] and Hagen and Larsen 2009[13] performed some numerical simulations in order to provide data for the development of a design model for the shear capacity of steel girders with web openings, with and without transverse stiffeners and opening reinforcements. Lagaros et al. 2008 [14] studied an optimum design of 3D steel structures having perforated I-section beams. Lian and Shanmugan 2003[15] reported on plate girders curved in plan containing centrally placed circular web openings. Tsavdaridis and D'Mello 2012 [16] performed a comprehensive Finite Element (FE) study of four sizes of perforated steel sections with three different sizes of eleven standard and novel non-standard web opening shapes and their primary structural characteristics presented in detail in order to provide a simple design method for general practice. Panedpojaman and Rongram 2014 [17] validated design equations for Vierendeel bending of steel beams with circular web openings using ANSYS program. Rodrigues et al. 2014 [18] investigated the efficiency of longitudinal stiffeners welded at the opening region and the benefits of using an adequate edge concordance radius in beams with rectangular and square openings. Shaker and Shahat 2015 [19] utilized nonlinear finite element modelling techniques using ANSYS program, to study the effect of web openings on the capacity of beams having non-compact sections in order to determine the critical positions of web openings. However, so far, most of these existing numerical simulations have considered the behaviour of simply supported perforated beams with statically determinate structures in which the real behaviour of the joint is not modelled and in which the axial forces are not included. Therefore in this paper, a 3D finite element model is created using the commercial software package ABAQUS [20], to study the behaviour of structural subassemblies of steel beams with openings connected to CFT columns using reverse channel connection.

2 Description of the FE Model

Figure 1 shows the finite element model for the structural arrangement to be simulated in this research. The structural arrangement in Figure 2 represents a steel I-beam connected to two concrete filled tubular (CFT) columns. The top and bottom of the columns are rotationally unrestrained but are horizontally restrained to simulate the lateral stability system in a real structure. The simulation methodology to be summarised below:-

- Three-dimensional solid elements (C3D8) were used to model the main structural members (beam with opening, steel tube, concrete fill, connection components).
- Boundary conditions: half of the structure was modelled due to symmetry. The bottom of the columns was pinned in all three directions and the top of the columns was pinned in two directions but movement along the column axis was allowed; Half of the structure was modelled due to symmetry. All nodes at the beam mid-section were fixed in the axial direction, which effectively prevented rotation about the two principal axes of the beam cross-section, but allowed the beam to twist about its longitudinal axis. To represent the effect of the concrete slab, the beam was assumed to be fully restrained in the lateral direction.
- To reduce the number of elements and nodes in the FE model, the column was divided into three parts and only the central part connected by the joint (90 cm) was actually modelled using the solid elements. The other two parts away from the joint zone were modelled using general beam elements with "box" cross section for the steel tube and "rectangular" cross section for the concrete infill. The ABAQUS "Coupling" function was used to join the three column parts.
- The ABAQUS contact function was used to simulate interactions between many contact pairs, including the interface between the wall of the SHS and the concrete fill, between the bolt head and the web of the reverse channel, between the bolt nuts and endplate, between the bolt shanks and the web of the reverse channel, between the bolt shanks and the endplate, and between the web of the reverse channel and the endplate. In order to reduce computational cost, a contact was defined as surface to surface contact with a small sliding option. "Hard contact" was assumed for the normal contact behaviour and a friction coefficient of 0.3 was used in the tangential direction of the contact pairs.
- The welds were simulated using the "tie" type constraint in ABAQUS. It was assumed that the weld would not fail.
- The loads were applied to the beam at two point loads and are increased gradually until structural failure.
- The failure load was defined as the load at which the beam failed to support it.
- Most of the research work on perforated sections may be classified into the following two types of construction: 1. Hot-rolled steel beams with single web openings: 2. Fabricated beams with multiple web openings. This paper deals with perforated sections

with two web openings in each half of the beam. According to load pattern, one of the openings is subjected to global moment only and the other one is located in the region under global moment and global shear force.

- In the present investigation, the steel I-beams are hot rolled steel I-sections of class 1 or 2 (plastic or compact are treated). All web openings are concentric to the mid-height of the sections with size between 0.5h and 0.8 h, where h is the section web depth; no reinforcement is considered. For perforated sections with these geometrical dimensions, it is generally considered that local buckling in the tee-sections at the perforated sections is not critical.
- Opening shapes: A total of eight web openings of different shapes are considered, and the key dimensional parameter in all these opening shapes is the critical opening length, c, which is the length of the tee-sections above and below the openings. This critical opening length has major effect on the local applied moment on tee-sections. Details of the opening shapes together with the associated values of c are shown in Figure 3 and listed as follows:

Opening a: circular opening with c =1.0 d_o;
Opening b: horizontal ellipse opening with c □□2 d_o;
Opening c: inclined (rotated) ellipse rotated by angle (+30 ^{o}) and (-30 ^{o}) about the centroid of the web opening and with c □□2 d_o;
Opening d: regular hexagonal opening with c = 1.0 d_o and with sheared and rounded corners;
Opening e: square opening with c = 1.0 d_o and with sheared and rounded corners;
Opening f: rectangular opening with c = 2.0 d_o and with sheared and rounded corners;
Opening g: parallelogram opening with c = 2.0 d_o and with sheared and rounded corners;
Opening h: trapezoidal opening with unequal length of tee-section c_1 =1.0 d_o and c_2 = 2.0 d_o and with sheared and rounded corners.

Where (h) is the section height, (d_o) is critical opening depth, and (c) the length of the tee-sections above and below the openings.

- Failure Modes: Generally, there are three different modes of failure at the perforated beams with isolated web openings :

1. Flexural failure due to reduced moment capacity.
2. Shear failure due to reduced shear capacity.
3. Vierendeel mechanism at the Vierendeel action.

It is known that the shear and flexural failures of standard perforated sections are controlled mainly by the size (i.e. depth) of the web openings, whilst the Vierendeel mechanism is primarily controlled by the critical length of the web openings at the top and bottom tee-sections.

- In this investigation the FE results are presented in main two groups; the load against Mid-Span deflection curves obtained from the finite element modeling and the modes of failure.

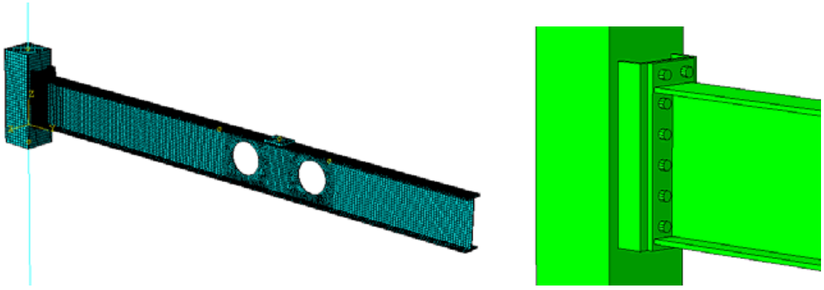


Figure 1: Finite element model for beam with circular web opening

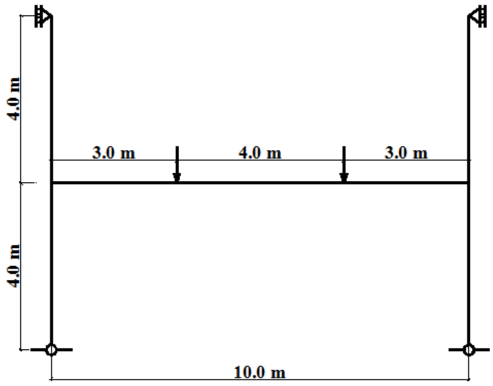
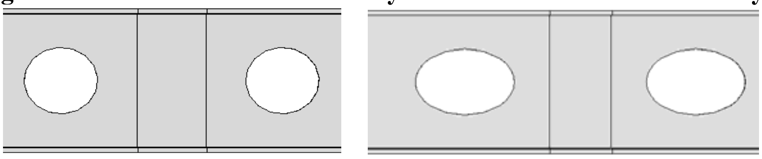
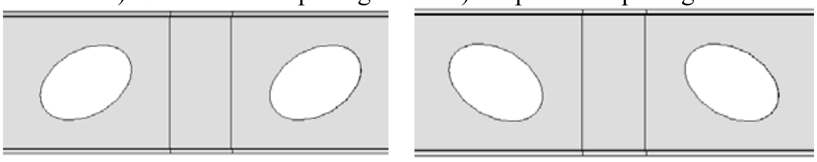


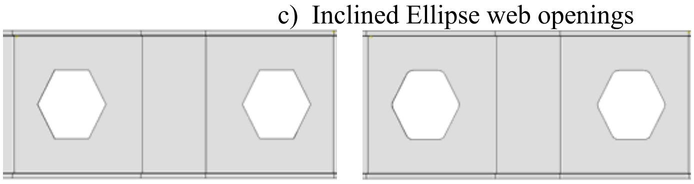
Figure 2: Dimensions and boundary condition of structure assembly



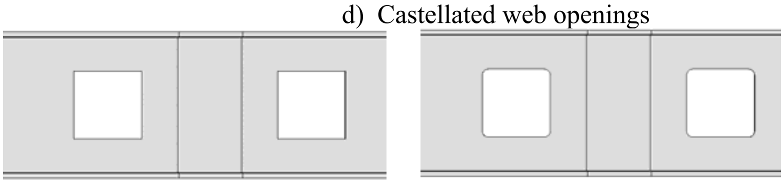
a) Circular web openings b) Ellipse web openings



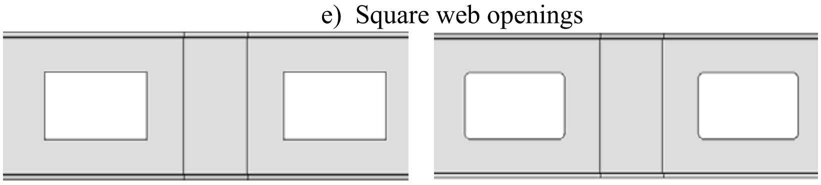
c) Inclined Ellipse web openings



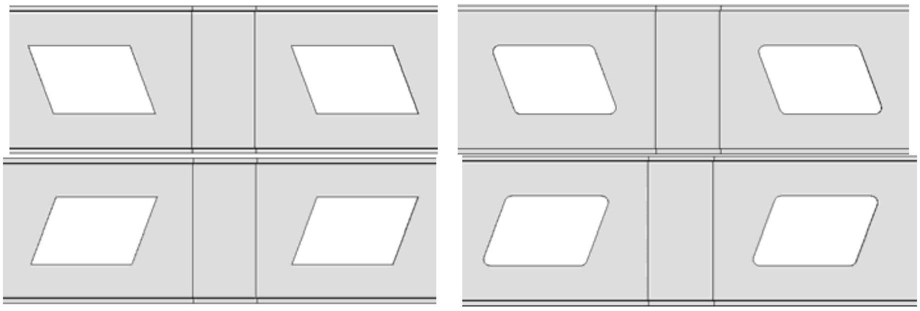
d) Castellated web openings



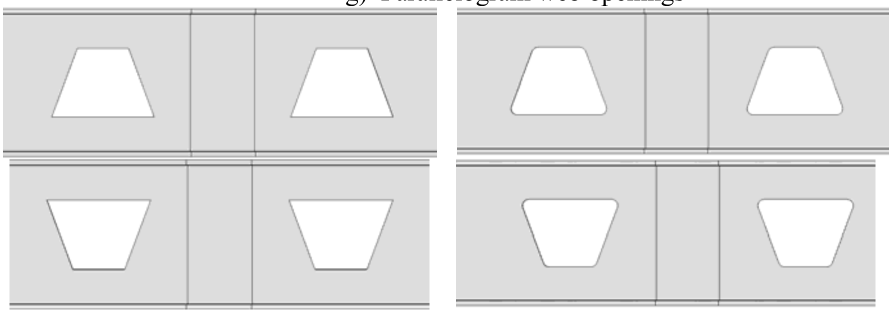
e) Square web openings



f) Rectangular web openings



g) Parallelogram web openings



h) Trapezoidal web openings

- Sheared Corners - Rounded corners

Figure 3: Geometric configurations of web openings

3 FE Results for Circular and Castellated Web Openings

Validation of the finite element model must be completed before being used in parametric study. The finite element model was validated against the test data of a steel I-section beam 2A with single circular web opening, as reported by Redwood and McCutcheon 1968 [21]. The test specimen with their geometrical details is represented in Figure 4.

In Figure 5, the deformed finite element model with the Vierendeel mechanism of the perforated section at failure is illustrated. The load–deflection curves obtained from the finite element modeling are plotted in Figure 6 together with the measured test data for direct comparison. It is shown that both the maximum moment capacities of the perforated sections and the deformation characteristics of the beam are modeled satisfactorily. This provides confidence in the use of the developed FE model.

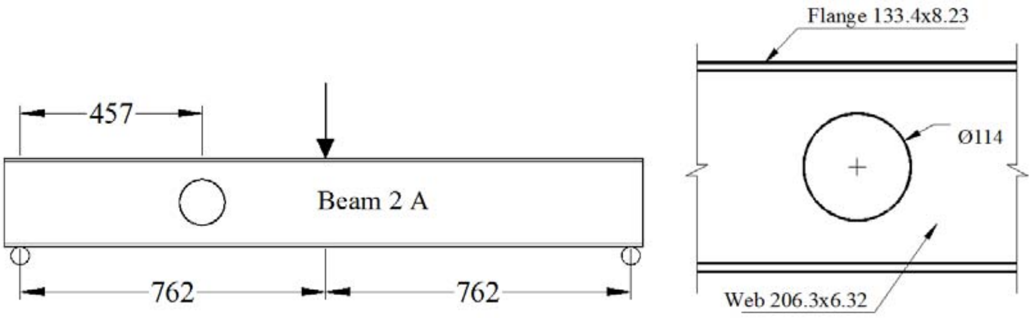


Figure 4: Finite element model and details of test specimens

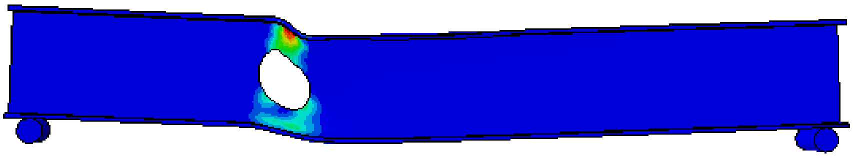


Figure 5: The deformed finite element model at failure.

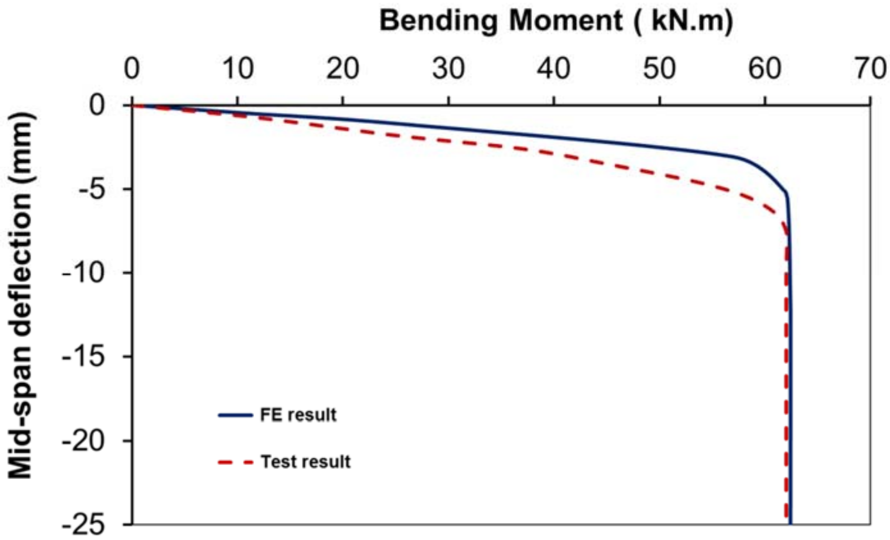


Figure 6: Comparison of load–mid-span deflection curves for test and finite element model

4 FE Results for Circular and Castellated Web Openings

The finite element model was built for different circular web openings sizes. The applied loads against Mid-Span deflection curves obtained from the finite element modeling are plotted in Figure 7. It is shown that the load carrying capacity of the beam decreases with the increase of the web opening size and the rate of reduction depends on the mode of failure. As shown in Figure 8, beams with circular openings sizes up to $d_o/h=0.7$ started to fail by formation of one plastic hinge in the lower tee sections. The beams were capable to carry additional load until other plastic hinges in the top tee sections were formed causing flexural failure due to reduced moment capacity. Beams with high openings sizes ($d_o/h=0.8$), due to the increase of the opening length c, failed by Vierendeel mechanism under the Vierendeel action at very low load carrying capacity. Vierendeel mechanism produced by formation of more than one plastic hinge (i.e. Four plastic hinges) at critical locations of the perforated sections under shear and moment, as shown in Figure 8. Overall deformed shapes for the two common failure modes, flexural failure and Vierendeel mechanism for beams with circular openings are shown in Figure 9.

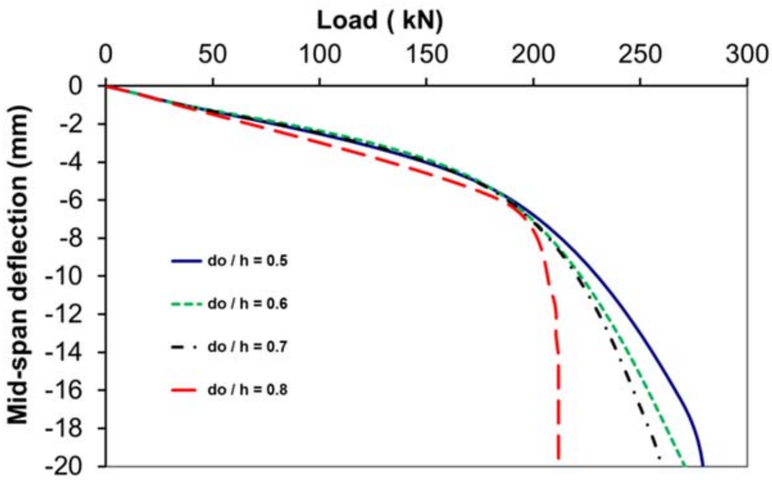
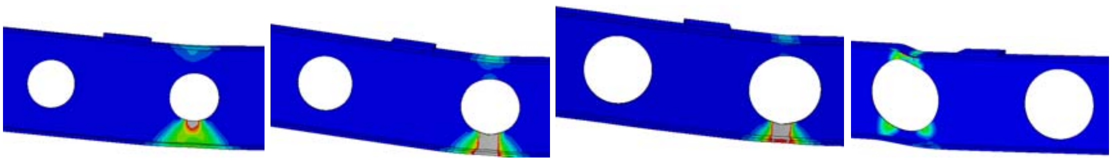


Figure 7: Load-=mid-span deflection curves for beams with different circular web opening sizes



d_0/h=0.5 d_0/h=0.6 d_0/h=0.7 d_0/h=0.8

Figure 8: Plastic strain at failure for beams with circular web openings

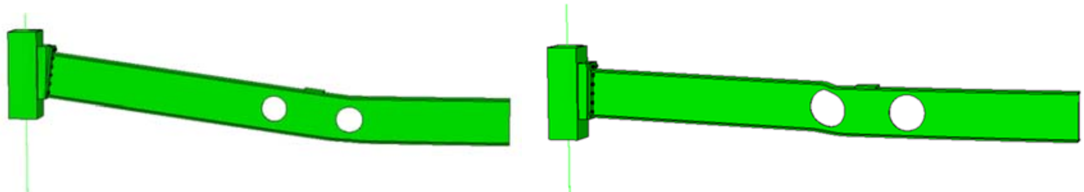


Figure 9: Overall deformed shapes at failure for beams with circular web openings

For the beams with castellated web openings, it is found that the steel beams behave similarly to the beams with circular web openings in terms of deformed shapes and - mid span deflection. As shown in Figures 10 and 11, beams with castellated openings sizes d_o/h=0.5 & 0.6 failed by flexural failure due to reduced moment capacity. Beams with high openings sizes d_o/h=0.7 & 0.8, failed by Vierendeel mechanism under the Vierendeel action at load carrying capacity lower than that for circular opening, due to stress concentration at the corners of the opening. Making corners at the openings rounded did not affect the performance of the beams, as shown in Figure 12, except for the case of high openings sizes d_o/h=0.8 where the load carrying capacity of the beam with sheared corner openings is higher than the opening with rounded corner by about 4%. This may be because of the rounded corner enhanced the Vierendeel mechanism.

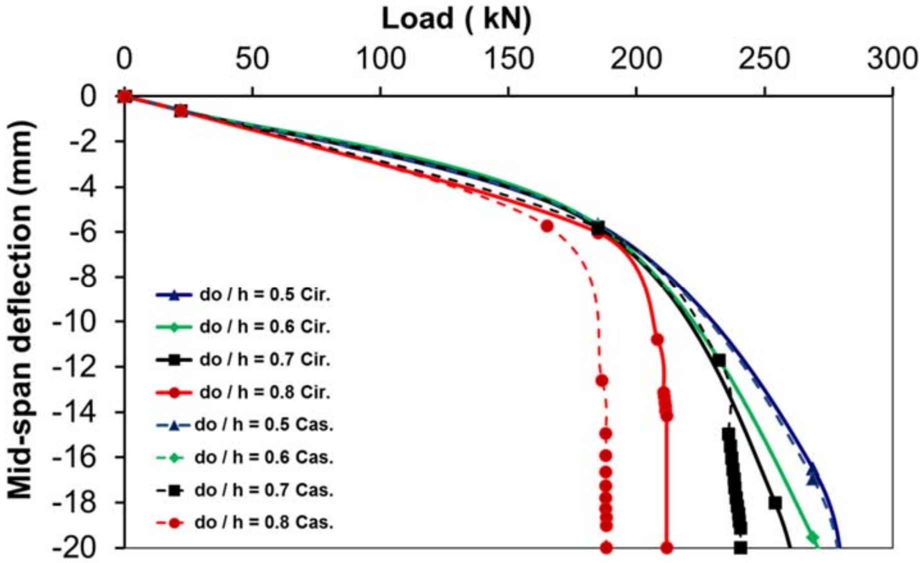
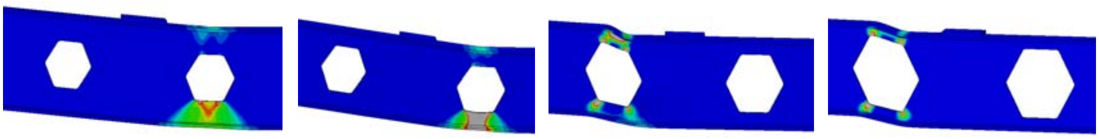
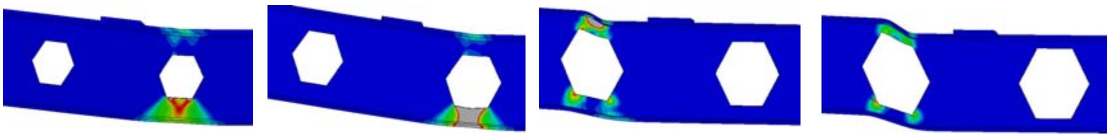


Figure 10: Load-mid-span deflection curves for beams with different castellated and circular web openings sizes



$d_0/h=0.5$ $d_0/h=0.6$ $d_0/h=0.7$ $d_0/h=0.8$

a) Rounded Corner (R.C.)



$d_0/h=0.5$ $d_0/h=0.6$ $d_0/h=0.7$ $d_0/h=0.8$

b) Sheared Corner (S.C.)

Figure 11: Plastic strain for beams with castellated web openings

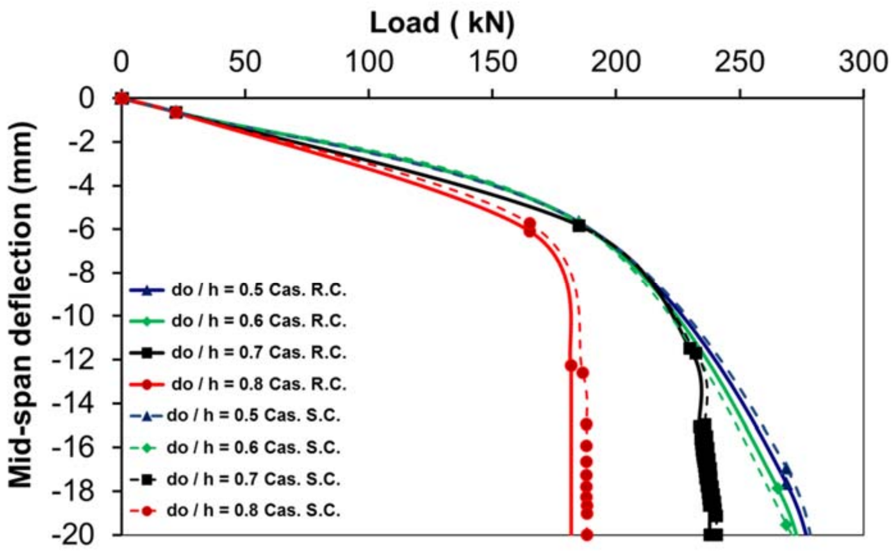


Figure 12: Load-mid-span deflection curves for beams with castellated web openings - rounded (R.C.) and sheared corners (S.C.)

5 FE Results for Elliptical Web Openings

Perforated sections with horizontal and inclined elliptical web openings behave similarly to the typical web opening configurations in terms of failure modes and deformation pattern, as shown in Figures 13&14. When comparing the load-mid span deflections curves between circular and horizontal elliptical web openings, as shown in Figure 15, it is found that perforated sections with elliptical web openings with various sizes cause different reduction of load carrying capacities. As the horizontal ellipses have a wider opening length, the effects due to Vierendeel action are significant. The increase of the web opening length affects the load carrying capacity. This is due to the critical increase in length of the larger web openings, and the geometry of web opening shapes, which result in a different combination of forces acting on the top and bottom tee-sections. As a result, perforated beams with large elliptical web openings present a dramatically decreased load capacity due to a wider opening length compared to circular web openings. Inversely, least affected sections are those with web openings with d_o=0.5h and 0.6h, as their load carrying capacity is relatively high compared to the other web opening sizes and the common failure mode for these cases is flexural failure, as shown in Figure 14.

The inclined elliptical web openings are formed after rotation of the ellipse with angle 30^o clockwise or anticlockwise. This presents lower load carrying capacities than that for the horizontal elliptical web openings. Moreover, when comparing the structural performance of these two perforated sections, it can easily be concluded that apart from the opening length, *c*, the web opening shape also controls the performance due to the movement of the stress concentration points. When comparing the load-mid-span deflections curves between horizontal elliptical and inclined elliptical web openings in Figures16&17, it is found that, rotation of an elliptical web opening with various web opening sizes causes different decreases of load carrying capacities. In more detail, the deformed shapes at failure shows that, in cases when loading perforated beams with inclined elliptical web openings parallel to the tangent of the global bending moment (see Figure 14 b), the ellipse is significantly elongated while its minor axis is shortened by stretching the shape due to the additional deflection. Hence, the total displacement of the beam is significantly high. However in case of perforated beams with an inclined elliptical web openings perpendicular to the tangent of the global bending moment (see Figure 14 c), the reduction of the load carrying capacity may occur due to the additional deflection which increases the depth of ellipse causing reduction in moment and shear capacities of the beam.

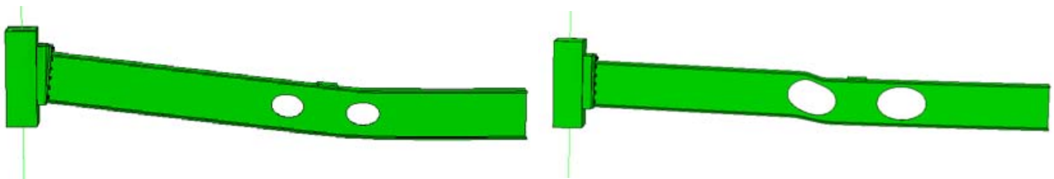
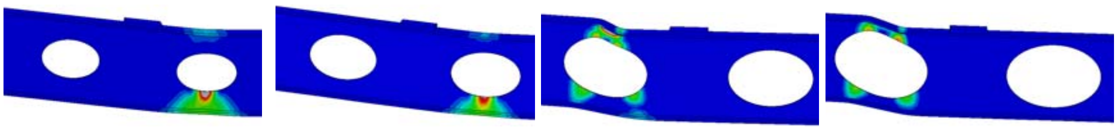
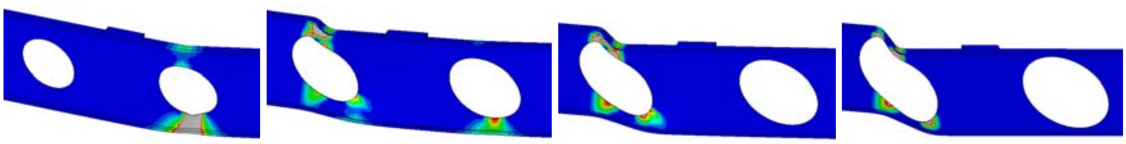


Figure 13: Overall deformed shapes at failure for beams with elliptical web openings



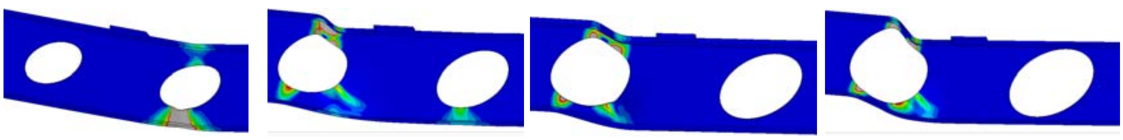
$d_0/h=0.5$ $d_0/h=0.6$ $d_0/h=0.7$ $d_0/h=0.8$

a) Horizontal elliptical openings



$d_0/h=0.5$ $d_0/h=0.6$ $d_0/h=0.7$ $d_0/h=0.8$

b) Inclined elliptical openings (Left)



$d_0/h=0.5$ $d_0/h=0.6$ $d_0/h=0.7$ $d_0/h=0.8$

c) Inclined elliptical openings (Right)

Figure 14: Plastic strain for beams with elliptical web openings

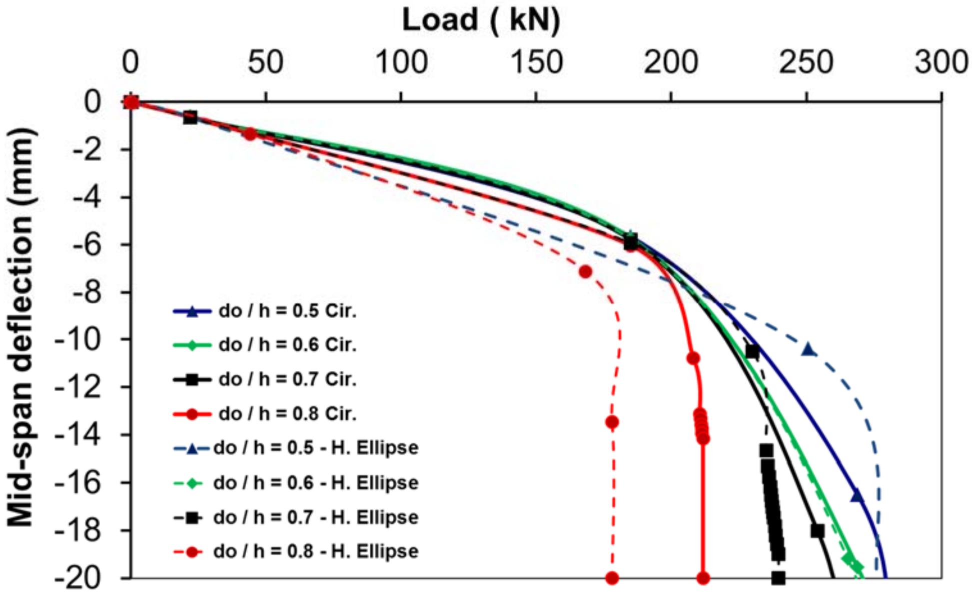


Figure 15: Load–mid-span deflection curves for beams with horizontal elliptical openings and circular web openings

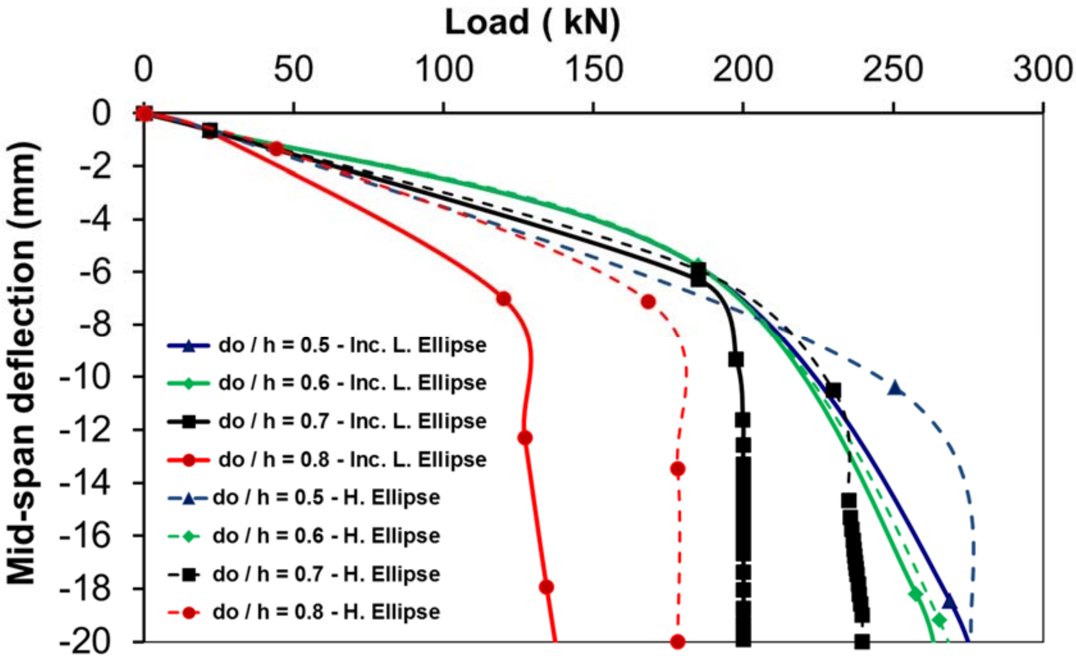


Figure 16: Load–mid-span deflection curves for beams with horizontal and inclined (Left) elliptical web openings

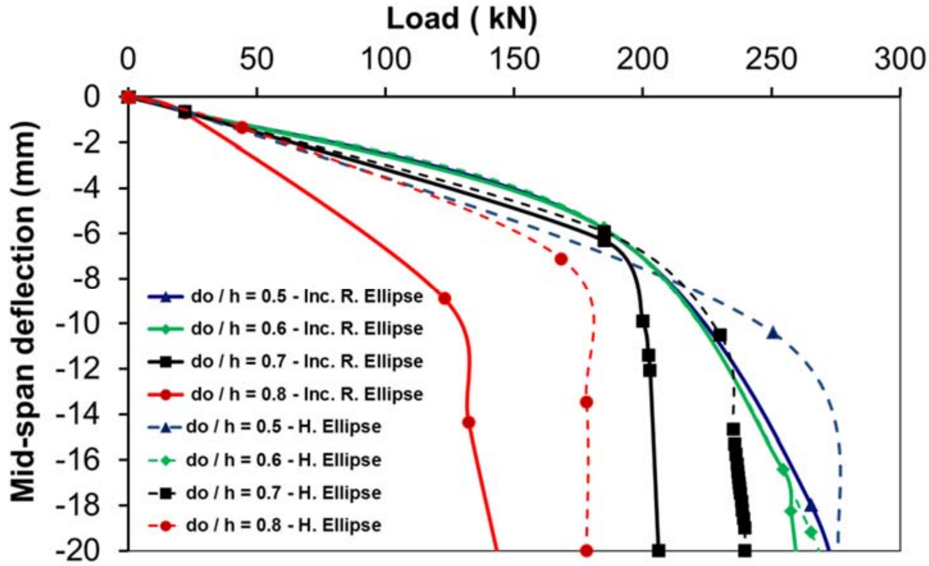


Figure 17: Load–mid-span deflection curves for beams with horizontal and inclined (Right) elliptical web openings

6 FE Results for Square, Rectangular, Parallelogram and Trapezoidal Web Openings

By comparing the results of the beam with square openings with the previous results of circular openings, it can be noticed that the load carrying capacity of the beams with square opening is by far less than that for circular openings, as shown in Figure 18. Furthermore, as shown in Figures 19&20, the Vierendeel mechanism is the common mode of failure for the opening sizes more than $d_0/h=0.5$. The load carrying capacity of beams with square openings dramatically reduced due to the concentration of stresses at the corner of the square opening even if the corner is rounded, as shown in Figure 20. The reduction of the load carrying capacity of square web opening increases with the increase of the opening size. In order to understand the effects of both the shapes and the sizes of web openings to the structural performance of square perforated sections, it is important to relate the load carrying capacity of the perforated sections to the local coexisting forces and moments acting on the tee-sections above and below the web openings. In practice, both the opening depth and length are geometrically related, and thus any increase in sizes in web openings of given shapes will reduce the local axial, shear and moment resistances of the tee-sections. Furthermore, the Vierendeel moment is also increased at the same time.

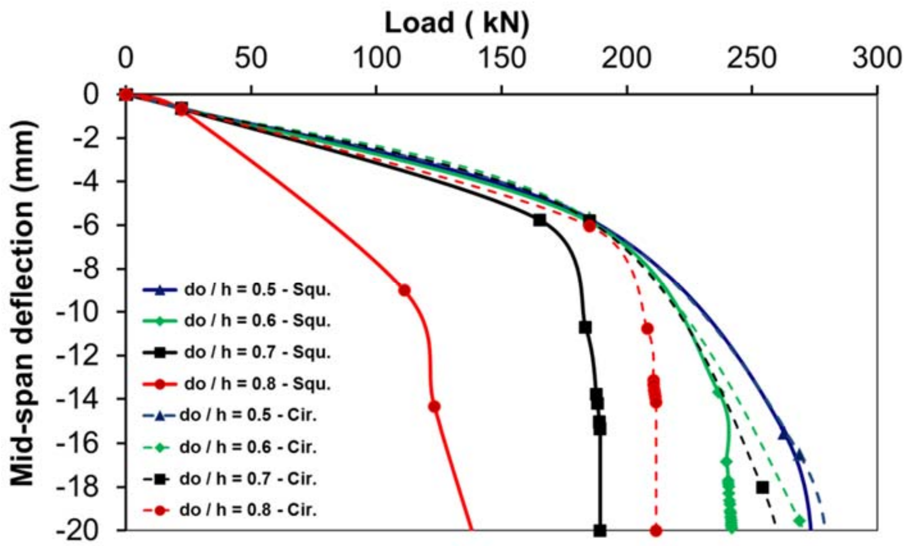


Figure 18: Load-mid-span deflection curves for beams with different square and circular web openings sizes

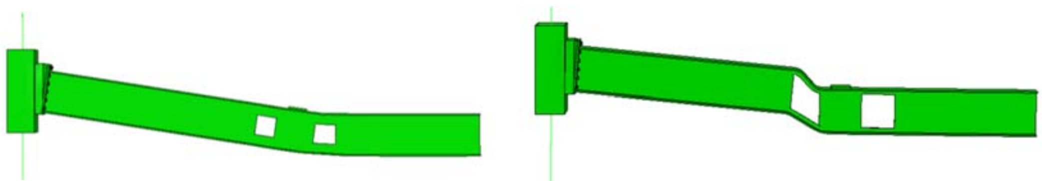
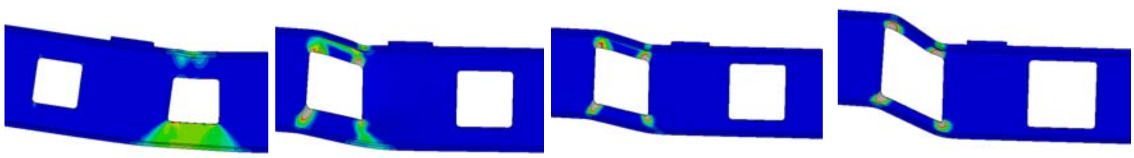


Figure 19: Overall deformed shapes for beams with square web openings



$d_0/h=0.5$ $d_0/h=0.6$ $d_0/h=0.7$ $d_0/h=0.8$

Figure 20: Plastic Strain for Beams with Square Openings Rounded Corner

From the results of the beam with openings of various shapes and sizes considered in this study, it can be clear that, the most important parameter in assessing the structural behaviour of the perforated sections is the critical opening length, c, which controls the magnitude of local Vierendeel moments acting on the tee sections. For web openings with same values of d_o with different values of c, the load capacities of the perforated sections are expected to be inversely proportional to the values of c. This is noticeable in Figure 23, which compares the load carrying capacity for square and rectangular web openings. By increasing the critical opening length, c, and by forming rectangular opening with length $c=2d_0$ the Vierendeel mechanism controls the beam performance for all opening sizes, as shown in Figures 21&22. The reduction in the applied load capacity increases due to the increase of opening length, as shown in Figure 23.

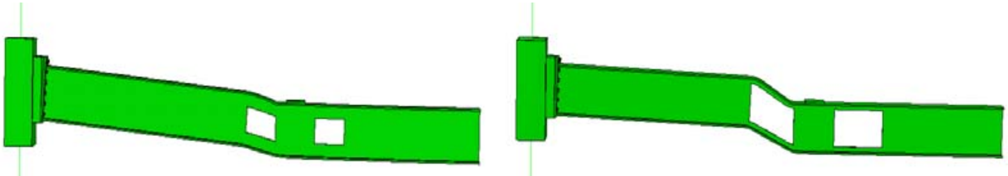
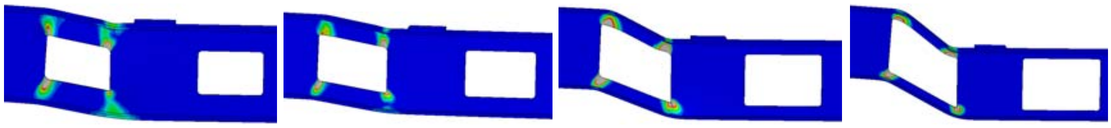


Figure 21: Overall deformed shapes for beams with rectangular web openings



$d_0/h=0.5$ $d_0/h=0.6$ $d_0/h=0.7$ $d_0/h=0.8$

Figure 22: Plastic strain for beams with square openings and rounded corners

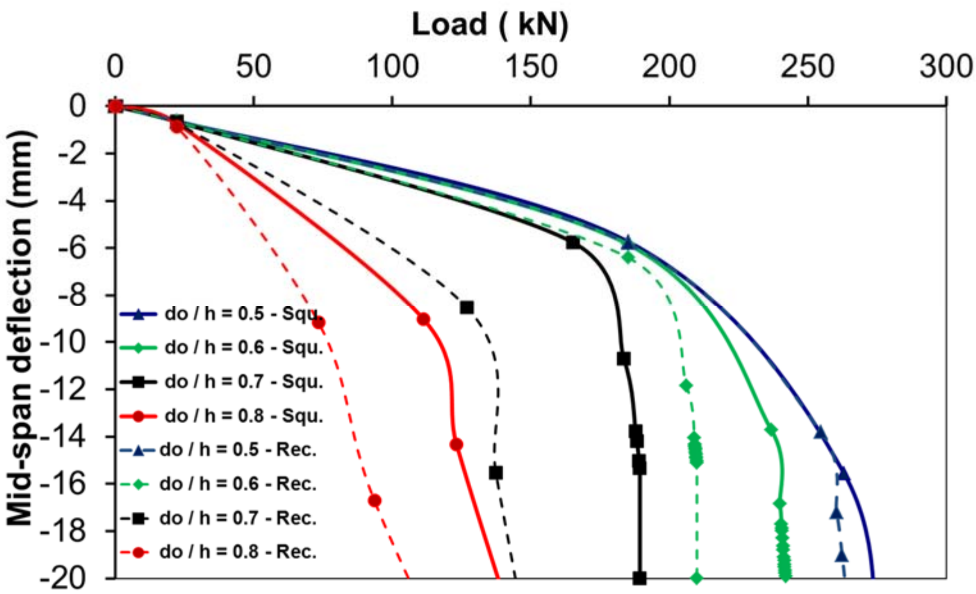
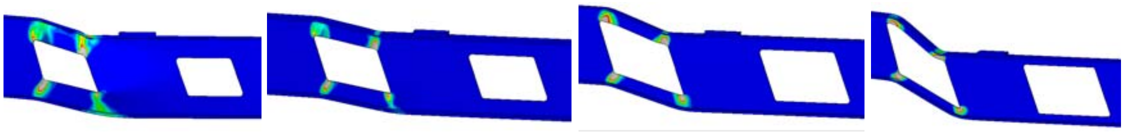
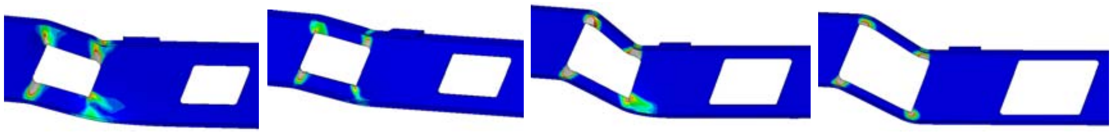


Figure 23: Load-mid-span deflection curves for beams with different rectangular and square web openings sizes

The beams with parallelogram web openings are similar to the rectangular web openings in length c, but the vertical sides of the opening are inclined. Load deflection curves of beams with rectangular web opening together with parallelogram web openings with inclination angle of the vertical sides (+30) degree and (-30) degree are plotted in Figures 25 and 26. As can be seen the load carrying capacities of beams with parallelogram openings are nearly the same as those for rectangular openings for the same opening sizes. This conforms the conclusion that the critical opening length, c, is the most important factor in evaluating the structural behaviour of the perforated sections and controls the magnitude of local Vierendeel moments acting on the tee sections. Also, Figure 24 shows that the common failure mode for beams with the parallelogram openings is Vierendeel mechanism similar to beams with the rectangular web openings.



a) Rounded corner- left (L)



$d_0/h=0.5$ $d_0/h=0.6$ $d_0/h=0.7$ $d_0/h=0.8$

b) Rounded corner- right (R)

Figure 24: Plastic strain for beams with parallelogram web opening

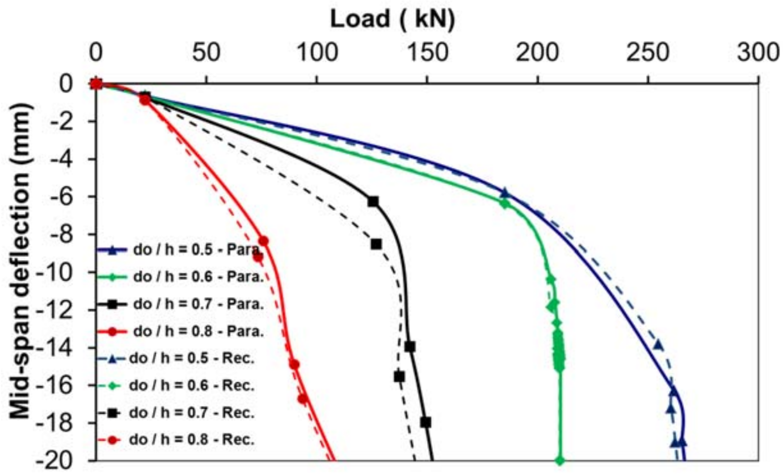


Figure 25: Load-mid-span deflection curves for beams with different parallelogram and rectangular openings sizes

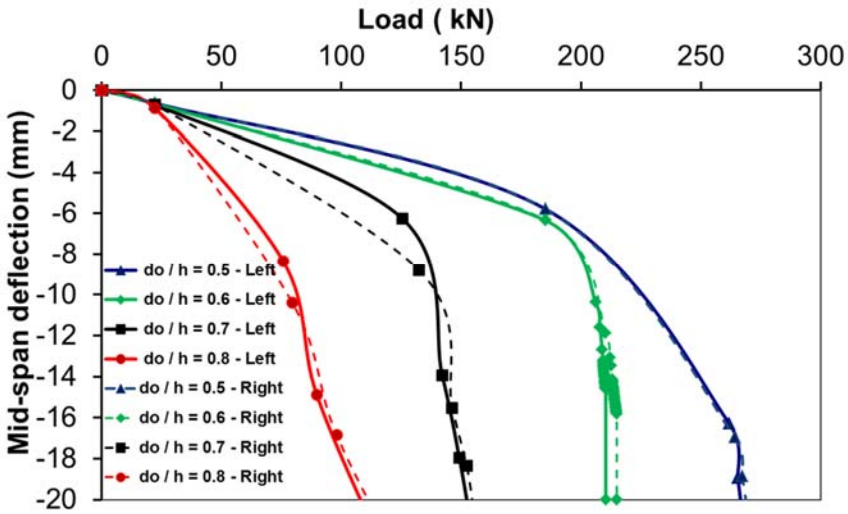


Figure 26: Load-mid-span deflection curves for beams with different angle of inclination of parallelogram openings

Now, it is obvious that the common failure mode for beams with square, rectangular, and parallelogram openings is Vierendeel mechanism. The Vierendeel mechanism is primarily controlled by the critical length of the web openings at the top and bottom tee-sections. To investigate the effect of the length of the opening in compression and tension tee-sections, the horizontal sides of the rectangular opening are being unequal. One of them equals the size of the opening and the other equals twice the opening size, forming a trapezoidal opening shape. Figures 28 and 29 compare the deflection curves for beams with trapezoidal openings using unequal lengths of compression and tension tee-sections and rectangular web openings (i.e. horizontal sides with equal lengths). It can be seen that, the load carrying capacity of the beam increases with the decrease of the length of the compression tee-section while the size of trapezoidal web opening causes different decreases of load carrying capacities. Similarly, the load carrying capacity of the beam with reduced length of tension tee-section is larger than that for rectangular web openings with less amount of increase, as shown in Figure 28. This concludes that, the length of the compression tee-section plays a more important role in Vierendeel mechanism than the tension tee-section. Figure 27 shows the deformed shapes and failure modes for beams with trapezoidal openings using different lengths of tee-sections.

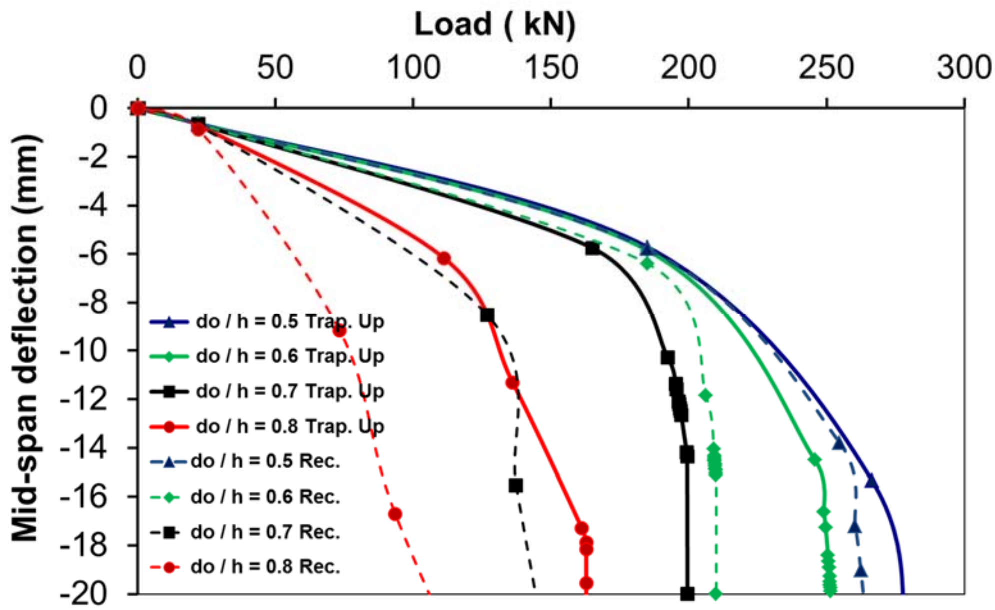


Figure 28: Load-Mid-Span deflection curves for beams with rectangular and trapezoidal web openings (with reduced length of compression tee-section)

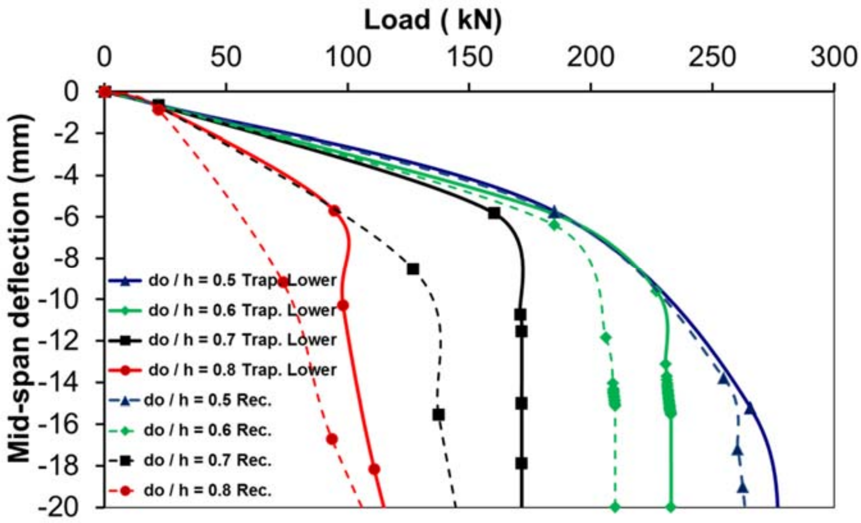
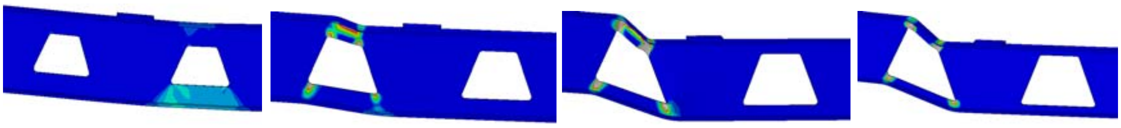
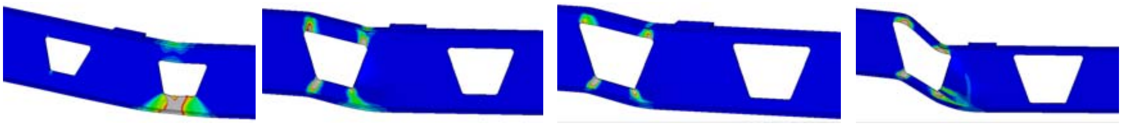


Figure 29: Load-mid-span deflection curves for beams with rectangular and trapezoidal web openings (with reduced length of tension tee-section)



$d_0/h=0.5$ $d_0/h=0.6$ $d_0/h=0.7$ $d_0/h=0.8$

a) Rounded corner - (with reduced length of compression tee-section)



$d_0/h=0.5$ $d_0/h=0.6$ $d_0/h=0.7$ $d_0/h=0.8$

b) Rounded corner - (with reduced length of tension tee-section)

Figure 27: Plastic strain for beams with trapezoidal openings

7 Conclusions

A comprehensive parametric study using finite element method on steel beams with web openings of various shapes and sizes is executed, and all the primary structural characteristics of the steel beams are assessed and compared in details. The study is based on a finite element model with eight-noded solid elements calibrated against test results of steel beams with web openings of similar configurations.

The following conclusions may be drawn:

(1) The ABAQUS modeling showed good correlation with experimental results in terms of load deflection curves and deformed shapes.

(2) The failure modes of beams with openings in structural subassemblies are similar to those for simple beam with openings and the failure modes are common among all beams of various shapes and sizes, namely, shear failure, flexural failure and Vierendeel mechanism.

(3) The presence of web openings may have a severe penalty on the load carrying capacities of structural members, depending on shapes and sizes of the web openings.
(4) Among the shapes of the web openings for beams studied in this paper, the circular web opening shape gives the least reduction of the load carrying capacity.
(5) The load carrying capacities of perforated sections are affected differently by the web opening size.
(6) For all web openings of various shapes and sizes considered in the present study, the most important parameter in assessing the structural behaviour of the perforated sections is the critical opening length, c.
(7) The angle of inclination of the elliptical openings gives a severe reduction in the load carrying capacity of the beam compared to the horizontal elliptical web openings.
(8) The critical opening length, c. of the compression tee-section has a higher effect in the structural behaviour of the perforated sections than all other geometrical parameters of the web openings.
(9) The angle of inclination of vertical sides of rectangular openings has a small effect on the load carrying capacity of beams.

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