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NUMERICAL INVESTIGATION ON FLEXURAL PERFORMANCE OF BUILT-UP STEEL BEAMS WITH DIFFERENT WEB OPENINGS

Hussein Talab Nhabih [1], Mohammad R.K.M. Al-Badkubi [2], Marwa Marza Salman [3]

[1] Department of Civil Engineering, Faculty of Engineering, Babylon University, Babylon, IRAQ
[2] Department of building and construction technology, Islamic University,Najaf, IRAQ
[3] Department of Ceramic and Building Material, Faculty of Materials Engineering, Babylon University, Babylon, IRAQ

Abstract. Recently, the usage of Structural Steel Beams with Opening in the Web has spread extensively in all over the world, in various types of buildings such as high-rise buildings and industrial buildings. There are several advantages in using openings in beams. There for, an analytical investigation was carried out on fourSteel Beams with Opening (SBWO) models by using a powerful nonlinear simulation software ABAQUS. The initiative was to study the overall flexural behaviour of (SBWO’s) and to establish the maximum load carrying capacity, and deflection. Only vertical loads have been considered in the (SBWO’s) performance investigation. The Built-Up sections were tested up to failure. The simulated models were considered to be under simply supported condition at their edges and a uniform distributed load were applied over the upper flange of the beam along all beam's length. The flexural behaviour of beams with different opening shapes were tested and compared. The test results proved to be very useful in selecting the opening shape.

Keywords*:* Finite Element Modeling, Abaqus Computer Program, Flexural Behavior, Built-Up Section, Steel Beam, Web Opening

ЧИСЛЕННОЕ ИССЛЕДОВАНИЕ ИЗГИБА СОСТАВНЫХ СТАЛЬНЫХ БАЛОК С ОТВЕРСТИЯМИ РАЗЛИЧНОЙ ФОРМЫ В СТЕНКЕ

Хусейн Талаб Набих [1], Мохаммад Р.К.М. Аль-Бадкуби [2], Марва Марза Салман [3]

[1] Кафедра гражданского строительства, инженерный факультет, Вавилонский университет, Вавилон, ИРАК

[2] Кафедра строительства и строительных технологий, Исламский университет, Наджаф, ИРАК
[3] Кафедра керамики и строительных материалов, факультет материаловедения, Вавилонский университет, Вавилон, ИРАК

Аннотация. В последнее время использование стальных балок с отверстиями в стенке получило широкое распространение во всем мире, в различных типах зданий, таких как высотные и промышленные здания. Использование отверстий в стенках балок имеет ряд преимуществ. Поэтому было проведено численное исследование четырех моделей стальных балок с отверстиями (SBWO) с помощью программного обеспечения для нелинейного моделирования ABAQUS. Целью исследования было изучение общего сопротивления изгибу балок (SBWO) и определение максимальной несущей способности, а также прогиба. При исследовании характеристик (SBWO) учитывались только вертикальные нагрузки. Нагружение выполнялось вплоть до разрушения. Рассматривались свободно опертые по краям балки. К верхней полке балки по всей ее длине прикладывалась равномерно распределенная нагрузка. Были исследования и сравнение результатов для балок с различными формами отверстий. Полученные результаты исследований могут быть использованы при выборе формы отверстий в стальных двутавровых балках.

Ключевые слова: Конечно-элементное моделирование, компьютерная программа Abaqus, изгиб, составное сечение, стальная балка, отверстие в стенке

I. INTRODUCTION

From about eight decades, a large number of investigations have made by structural engineers looking for an untraditional methods to decrease the charge of steel constructions as much as possible. From designing point of view the maximum potential structural steel strength properties cannot always be achievable due to existence of other design factor such as serviceability. This factor usually accounts in the design process by taking the maximum permissible deflection to be the design factor. Therefore, numerous innovative ways have been suggested to increase the steel member's stiffness without increasing the required weight of steel, significantly.

Thus, steel beams with web opening also known as castellated or cellular beams have been used widely. One of the major benefits of using the openings in the beam in construction is the incorporation of services, such as electric cables as well as ventilation and hydraulic pipes, through the designed section depth of the beams, as shown in Fig.1.

The strength of structural members with web opening has been stated that may have large reduction. This statements were made by researchers like Bower (1968) [2], Lawson (1987) [3], and Darwin (1990) [4].

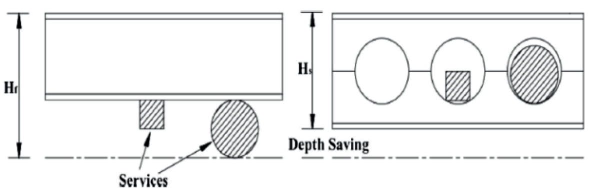


Figure 1. Reduction of beam height by utilizing holes for insertion service combinations [1]

However, the present specifications and design procedure codes for such beams are also difficult to use or inadequate (SCI P355 2011) [5]. This can be because the complexity in understanding and analyzing the performance of steel beams with web openings, and too difficulties to simplify design procedures. Thus, more extensive researches and investigations are needed in order to achieve sufficient information for understanding the behavior of beams with web opening to develop a much simpler design method. There are some analytical and experimental investigations have been made in the past to study SBWOs behavior. Redwood (1969) [6] suggested that by using modified dimensions equivalent rectangular opening, most of the design rules can be applied for steel beams with circular web openings. However, the ultimate strength of steel beams are substantially underestimated as a result of the simplistic approach. Chan and Redwood (1974) [7] used the curved beam analysis and the theory of elasticity to examine stress distribution in elastic range for beams having big circular shape web openings. The investigations made by Olander (1953) [8] and Sahmel (1969) [9] were used to develop a design method at the Steel Building Institute in 1990 in order to find the ultimate strength of steel beams having several circular shape web openings using an explicit approach. Later on in 1998, the method incorporated in Euro code 3 (EN1993-1-3)[10] after minor modification. However, this method also has been recommended to use for steel beams with separate circular shape web openings using a dissimilar set of approximate design methods. Laboratory tests and Numerical investigation on steel beams with circular and rectangular openings have been approved by Thevendran and Shanmugan (1991) [11]. They constructed cantilever and simply supported beams models made from a plexi glass sheet. For computing the critical buckling load for this type of beams the energy technique was proposed. Lawson and Chung (2001) [12] made an theoretical investigation on steel beams having circular and rectangular openings using a large web opening composite beams design method and presented in Euro code 4. Two suggestions were made by Chung et al. (2001) [13] first a practical design method against Vierendeel mechanism for circular web opening steel beams, second the perforated section empirical shear–moment interaction curve. An empirical design method was industrialized by Chung et al. (2003) [14]using generalized moment–shear interaction curve for steel beam with various shapes and sizes web openings. Tsavdaridic and D'Mello (2011) [15] made a study on the web post buckling effective 'strut' action and guess the final vertical shear load strength of web posts using an empirical formula obtained from the particular shapes of web opening. In order to achieve a simplified approach to develop a reliable prediction for moment modification factor K_{LB} in cellular beams an investigation was made by Sweedan (2011) [16]. An experimental investigation was made by Saka and Erdal (2013) [17] and they observed different types of failure modes including post buckling of the web, Vierendeel bending, web buckling and lateral torsional buckling. A through finite element method was performed by Panedpojaman and Thepchatri (2013) [18] and a modified coefficient function were suggested after analyzing 408 nonlinear finite element model fore liable deflection prediction of cellular beams. A numerical and experimental study was made by Boissonnade et al. (2014) [19] and a design procedure for lateral torsional buckling in cellular beam was suggested. Samadhan and Laxmikant (2015) [1] performed an experimental and parametric study on simply supported steel beams with web opening subjected to vertical loading. Iman Satyarno et al. (2017) [20], perform an analysis on castellated steel beam by full scaled rectangular opening shape in which some of the specimens were partially encased in reinforced mortar and some of them without encasing. Made Sukrawa (2017) [21], made a finite element study on reinforced steel beam with large opening in the web subjected to axial forces. Tareq Almusallam et al. (2018), perform an experimental and numerical investigation on behavior of FRP-strengthened RC beams having large rectangular shape web openings in flexural zones. Morkhade et al. (2019) [23], made an effort on study the effect of opening in the web on the ultimate strength of steel beam by trapezoidal corrugated shape web in which it can increase the share capacity without providing the transverse stiffeners.

There are numerous benefits of using SBWOs, some of them can be listed as:

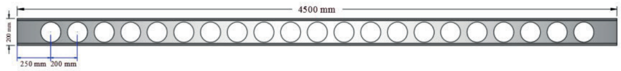
- Incorporation of services within the structural height of the beams.
- Reduction of overall dead weight of the structure which allows smaller foundation sizes.
- Reducing overall costs due to reduction of material consumption.
- Longer spans between columns than traditional structures.

II. SAMPLES DESCRIPTION

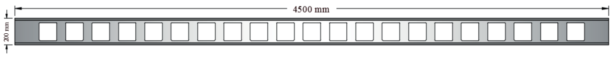
This study signifies an analytical study on flexural performance of built-up section steel beams with different web opening which consists tests on four steel beam models up to failure using a nonlinear simulation software Abaqus to find the better opening type which gives better performance during the application of loading.

In general the test results give an overall understanding of the behavior of these beams. The failure type which controls the behavior of these beams is flexural failure in the section. In the present investigation the load–deflection behavior, the ultimate load-carrying capacity and the failure modes are to be considered. Fig. 2 & 3 illustrated the specification details of the test specimens. These details also listed in Table 1.

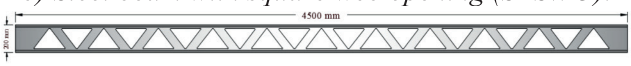
As it is shown in Fig.2a-d, for all steel beam specimens the parameters such as beam overall dimensions and total number of the openings and beam's depth were kept constant in order to investigate only the influence of opening shape on the flexural behavior of the steel beams with web opening exclusively. From practical point of view manufacturing circular web opening is the easiest comparing to other shapes because of the drilling, measuring and residual stresses. Thus, the steel beam having circular shape web opening is used to select other opening shapes dimensions and spacing. As shown in the Fig. 2a, 3the diameter of the circular opening is selected so that the opening be large enough to see the effect of the opening on flexural behavior more clearly, and the spacing between the circular openings is calculated according to the design of openings from BS 5950 part-I (2000) [24] which considers to take opening spacing to its diameter ratio (S/D_o = 1.08–1.5). Also, the web openings considered to start from 250 mm from the ends of the beam. This distance is selected in order to increase the stiffness of the beam at support zone and also not too far from the support so that the opening is spread in all beam's length and practically be possible to use any length for the beam and do not need special manufacturing for different beam's length. Furthermore, to investigate the influence of the opening shape exclusively the dimensions of the other web opening shapes are selected so that the area of the shape remain almost equal to the area of the circular shape. For dissimilar opening shapes for example rectangular, triangular, and hexagonal shape, in order to minimize the high stress concentration which occurs in the opening shape corners, a 5 mm in radius fillet is provided in those regions. As shown in Fig. 2c the spacing between the openings is not large enough to place the triangles with same orientation, so to maintain the opening numbers and spacing the nearby triangle for each opening is flipped upside down.



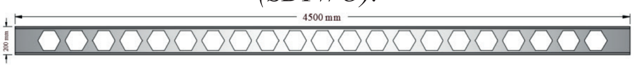
a) Steel beam with circular web opening (SBCWO).



b) Steel beam with square web opening (SBSWO).



c) Steel beam with triangular web opening (SBTWO).



d) Steel beam with hexagonal web opening (SBHWO).

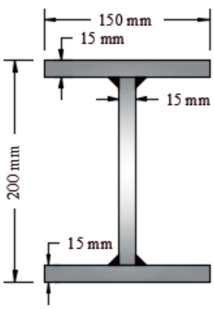


Figure 2. Schematic representation of tested specimens

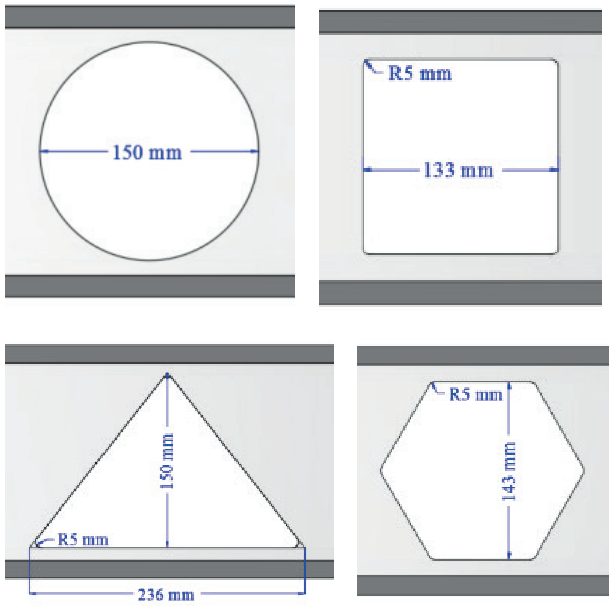


Figure 3. Opening details

Table 1. Samples Identification

No.	Beam Symbol	Length (mm)	Opening Shape	Flange Width (mm)
1	SBCWO	4500	Circular	150
2	SBSWO	4500	Square	150
3	SBTWO	4500	Triangular	150
4	SBHWO	4500	Hexagonal	150

III. FINITE ELEMENT MODELLING OF THE SPECIMENS

The simulated SBWO models have been used to guess ultimate strength capacity and flexural behavior of the samples during the loading time and at the final stage of loading which considered to be the model rupture failure using finite element simulation technique. Thus, a 3-D model with limited finite elements is developed by using a powerful simulation software Abaqus (6.14-4), which can simulate the material properties as well as geometric nonlinearity in beam samples.
Building the models is the starting step in the finite element analysis method. In this step, the

overall structure of the model is formed after that the model divided in to finite elements, each element connected with others at their nodes. It is necessary to define the element type, material properties and overall geometry of the model to build an accurate finite element model. Furthermore, the accuracy and cogency of the adapted sample is verified by comparing the test results to those given by an experimental study made by Samadhan (2015) [1].

A. Modelling of Built-Up Steel Beam with Web Opening

1) Steel Beam Sketch

In order to establish valid and reliable simulated models of the steel beam with web opening the steel beam parts are drew and their characteristics are carefully designated. First, the structure of steel beam is formed after selecting the 3D space modeling, solid extrusion shape, and deformable type, as shown in Fig.4.The beam's cross section dimensions and its length have been simulated according to the specimen identification table shown previously. The simulation of the openings for other types of openings are also done by selecting the 3D space modeling, solid extrusion shape, and deformable type, as shown in Fig.5.

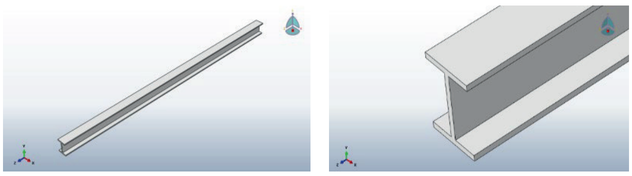


Figure 4. Modelling of solid steel beam part

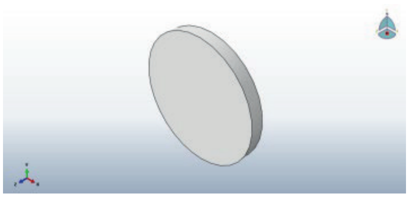


Figure 5. Modelling of solid opening shape part

Finally to achieve the steel beam with web opening models, the solid opening shape part is subtracted from the solid steel beam part. Then, a new complete steel beam with web opening part is created as shown in Fig.6.

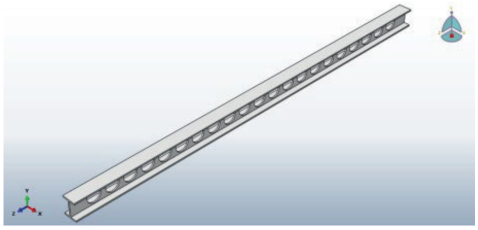


Figure 6. Complete steel beam with web opening model

2) Element Type Selection

In the presented study the element type which adopted to represent the steel beams was a 10-noded 3D stress quadratic tetrahedron elements (C3D10M) which has six degree of freedom at each node. Fig. 7 show the adapted element for steel beams.

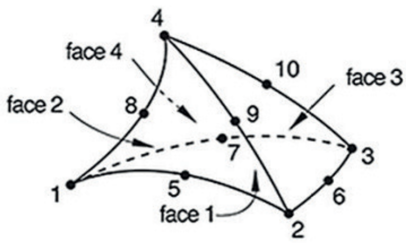


Figure 7. 10-node quadratic tetrahedron element (C3D10M) [25]

The selection of the model mesh density was done in such a way so that each element has the same length of 25mm length. Thus, the total number of element in the beam width are 6 elements and in the length 180 element. Fig. 8 demonstrations the meshed shape of the steel beam.

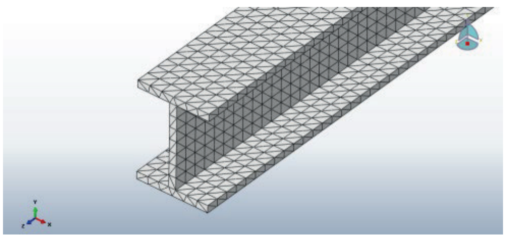


Figure 8. Meshed shape of steel beam model

3) Material Mechanical Properties

The steel material properties in this study taken similar to steel properties in experimental study made by Samadhan (2015) [1], which obtained from tensile test made on a coupons cut of a steel plate. The experiment results such as modulus of elasticity, ultimate stress, and yield stress, are given in Table 2.

Table 2. Properties of Steel Material

f_y (MPa)	f_u (MPa)	E_s (MPa)	υ
350	490	200,000	0.3

A simplified stress–strain curve shown in Fig. 9 is adapted for modelling the steel material mechanical properties along by the von Misses yield criterion having the isotropic hardening law. The adapted properties simulation shown to be adequate in simulating steel material properties due to test results. Also, in here the effect of large deformation have been considered.

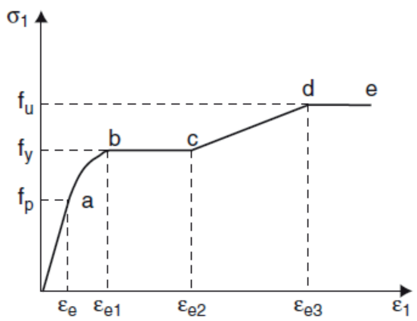


Figure 9. Stress-strain curve for steel [26]

4) Models Boundary Conditions

To make sure of obtaining a unique results in analyzing the deformation and maximum load capacity in the simulated steel beams with web opening the selection of the models end boundary conditions are necessary. In the present research work the steel beams are considered to be simply supported beams. In order to achieve this condition in the simulated models two additional solid extrudes are used at the bottom face of the steel beams. The solid extrudes considered to have rectangular shape with dimensions of (100, 150, 50 mm) in width, length and thickness, respectively. The extrudes considered to be made from hard steel with (f_y = 600 MPa and f_u = 900 MPa), this type of steel is used to ensure that the extrudes will not deform under the ultimate load for the steel beams. The solid extrudes are placed at a distance of 150 mm from the two edges of the steel beams. The left support considered to be hinged support and the right one considered to be roller support. The type of support can be determined by selecting the restricted transition direction. To ensure the nodal action of the supports the center line on the bottom face of the solid extrude are selected to be the line of supports. Fig.10 shows the solid extrude simulation and modelling of the support line location.

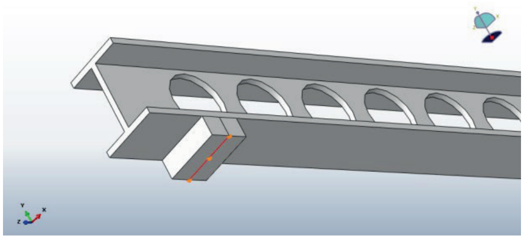


Figure 10. Solid extrude simulation and modelling of the support line location

5) Loading Mechanism

To simulate the applied load on the beam specimen the mechanical pressure type was selected to act on top face of the steel beams as shown in Fig. 11.

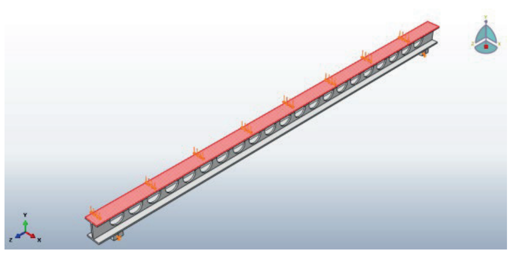


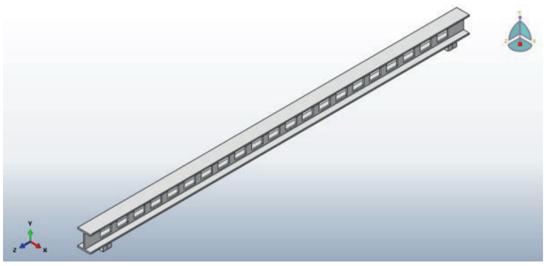
Figure 11. Modelling of loading pressure on top face of the steel beam sample

The applied pressure is distributed evenly at all surface area and increases linearly up to failure of the specimen.

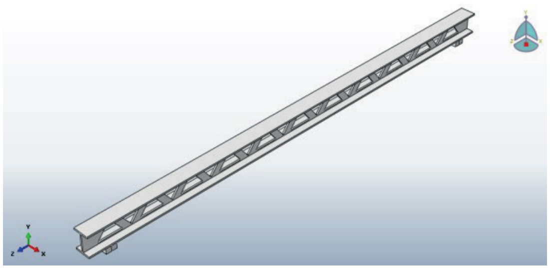
IV. PARAMETRIC STUDY

A parametric study was made after making sure of the accuracy of the used finite element modeling predicting the ultimate load capacity, to investigate the shape of the opening influence on the flexural behavior of steel beams with web openings.

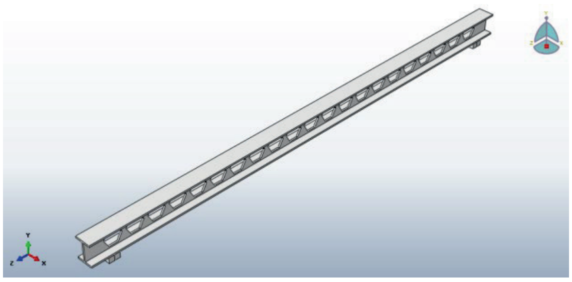
For simulating the other steel beams models with other types opening shapes, similar procedure which was used to simulate the steel beam with circular shape opening in the web model is used. But, with slight difference due to different shapes of the openings. Fig.12 illustrates the other steel beams modeled in Abaqus.



a) Steel Beam with Square Web Opening (SBSWO)



b) Steel Beam with Triangular Web Opening (SBTWO)



c) Steel Beam with Hexagonal Web Opening (SBHWO)

Figure 12. Representation of other steel beams modelled in Abaqus

V. RESULTS AND DISCUSSION

As it was mentioned previously the analysis concerns around the effect of the shape of the openings on the flexural behavior of the steel beams. Fig. 13 shows the applied load and mid-span deflection curve for the different types of the openings considered in the investigation.

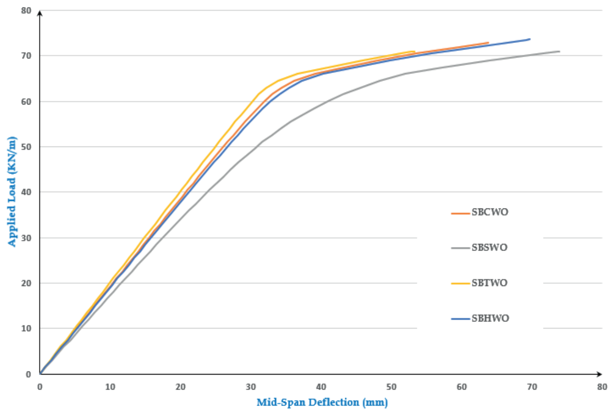


Figure 13. Comparison of load-deflection curves between different types of opening shape

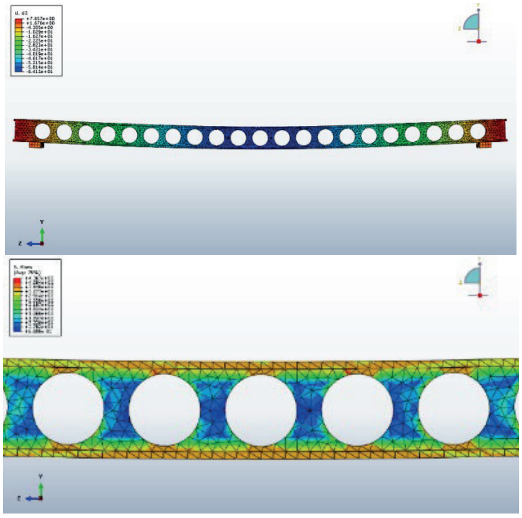
By seeing the load-deflection curves shown in Fig. 13, it can be see that the stiffness of the steel beams with triangular and square web opening are greater and smaller than the stiffness of the other shapes, respectively. For all beams the plastic range of the curves starts from almost (30 mm) mid-span deflection at this point the amount of the applied load on the steel beams are (59.42 KN/m), (56.77KN/m), (55.68 KN/m) and (49 KN/m), for (SBTWO), (SBCWO), (SBHWO) and (SBSWO), respectively. Though, despite of the maximum load carrying capacities and maximum deflections are not in the same order, but in this study it was assumed that any strength of a beam after a mid-span deflection more than (30 mm) (almost after elastic range) is not considered safe strength since the deflection would be so large that it can be considered as failed beam. Thus, in this investigation the steel beam with triangular web opening considered to have the best performance in flexural resistance under the applied load. However, the maximum load carrying capacity and corresponding maximum mid span deflection for every tested beam in this analysis is illustrated in Table 3.

Table 3. FEM Test Results

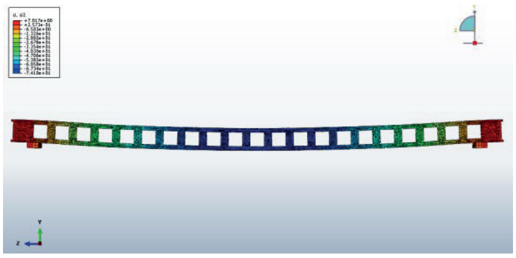
No.	Beam Symbol	*W (KN/m) at Δ = 30 mm*	*W_{max} (KN/m)*	*Δ_{max} (mm)*
1	SBCWO	56.77	72.9	63.82
2	SBSWO	49	70.92	73.89
3	SBTWO	59.42	70.98	53.3
4	SBHWO	55.68	73.61	69.73

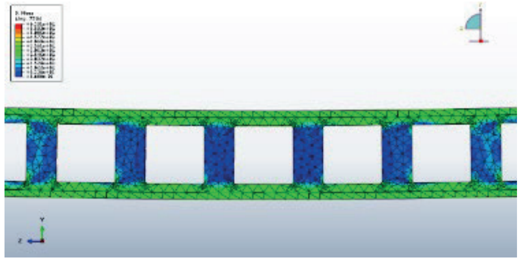
VI. SPECIMENS STRESS DISTRIBUTION AND DEFORMED SHAPE

The following figures, Fig.14, illustrates the stress distribution and deformed shape of the analytically tested samples with different types of web openings by subjecting the distributed load on samples top surface in F.E. analysis models.

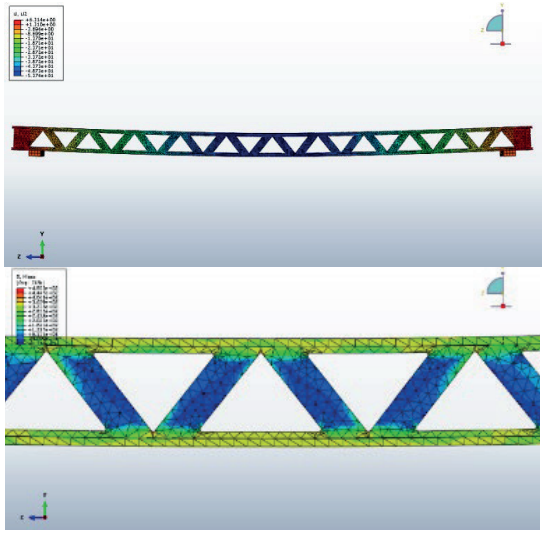


a) The deformed shape and stress distribution for FEM tested specimen (SBCWO)

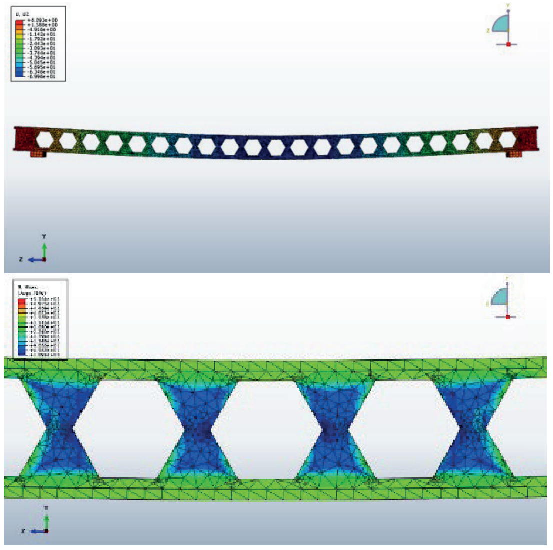




b) The deformed shape and stress distribution for FEM tested specimen (SBSWO).



c) The deformed shape and stress distribution for FEM tested specimen (SBTWO)



d) The deformed shape and stress distribution for FEM tested specimen (SBHWO)

Figure 14. The deformed shape and stress distribution of the tested steel beams with web openings

Form the figure above it can be observed that the stress distribution will be more concentrated at the regions between the openings and it reduces by increasing the width of this region.

VII. CONCLUSIONS

The chief aim of this work was to examine the flexural behavior of steel beam with different types of opening in the web by using a nonlinear simulation software (Abaqus). Thus, some model tests are established on SBWOs. The subsequent results and conclusions are complete in accordance of the obtained simulated SBWO models test results:
1) Test results of the analysis demonstrations that the load carrying capacity and the stiffness of the steel beam with triangular web opening is greater than the other three shapes which are circular, square and hexagonal at the elastic region by (4.66%, 21.26%, 6.71%) respectively.
2) The ultimate load at which the specimen fails will causes very large amount of deflection, thus the applied load which causes 30 mm deflection was the control value of the comparisons.
3) The circular web opening shows almost similar response to flexural stress as the hexagonal opening, this may be due to the shape of the hexagonal geometry which has more internal angles and make it to be more like a circle shape.
4) Furthermore, the square web opening has the least strength and stiffness due to large flexural stress concentration around its corners. Also, the deformations in the rectangular opening sample is greater than other test samples.

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Hussein Talab Nhabih, Department of Civil Engineering, Faculty of Engineering, Babylon University, Babylon, Iraq. E-mail: eng.hussein.t@uobabylon.edu.iq

Mohammad R.K.M. Al-Badkubi, Department of building and construction technology, Islamic University,Najaf, Iraq. E-mail: Mohammad.R.Albadkub@iunajaf.edu.iq

Marwa Marza Salman, Department of Ceramic and Building Material, Faculty of Materials Engineering, Babylon University, Babylon, Iraq. E-mail: mat.marwa.marza@uobabylon.edu.iq

Хусейн Талаб Набих, кафедра гражданского строительства, инженерный факультет, Вавилонский университет, Вавилон, Ирак. Эл. почта: eng.hussein.t@uobabylon.edu.iq

Мохаммад Р.К.М. Аль-Бадкуби, кафедра строительства и строительных технологий, Исламский университет, Наджаф, Ирак. Эл. почта: Mohammad.R.Albadkub@iunajaf.edu.iq

Марва Марза Салман, кафедра керамики и строительных материалов, факультет материаловедения, Вавилонский университет, Вавилон, Ирак. Эл. почта: mat.marwa.marza@uobabylon.edu.iq