Original Article

Finite Element Approach for the Bending analysis of Castellated Steel Beams with Various Web openings

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Abstract

The use of perforated steel beams (PSBs) has become of great importance due to their wide application in building construction and their beneficial uses as they are economical in terms of cost in addition to their lightweight. The aim of this study is to investigate the static behavior of castellated beams with different web openings. A 3D finite element analysis is performed using ABAQUS, to find out which type of beam gives the best performance under the same distributed load and fixed support condition. Different shapes are used for the web openings and compared with the basic shape of the hexagon, taking the same area into consideration for all shapes. In this paper, a new design model is developed using more than one shape in the web opening. Displacement and stress results are carried out and compared for various cases.

Keywords: Finite element method, Castellated beams, Steel structures, Static response

Farklı gözenekli çelik petek kirişlerin eğilme analizi için sonlu elemanlar yaklaşımı

Özet

Bina inşaatında geniş uygulama alanına sahip ve hafif olmalarının yanı sıra maliyet açısından da ekonomik olmaları nedeniyle petek çelik kirişlerin kullanımı büyük önem kazanmıştır. Bu çalışmanın amacı, farklı gözenekli petek kirişlerin statik davranışını incelemektir. Benzer üniform yayılı yük ve sınır şartları etkisinde, hangi kiriş tipinin daha iyi performans gösterdiğini belirlemek için ABAQUS yardımıyla 3D sonlu eleman analizi gerçekleştirilmiştir. Gözenekler için aynı alana sahip çeşitli geometrik şekiller kullanılmış olup, altıgen gözenekli durum ile karşılaştırmalar yapılmıştır. Bu araştırmada, birden fazla gözenek şekli kullanılarak yeni bir tasarım modeli geliştirilmiştir. Yer değiştirme ve gerilme sonuçları, çeşitli durumlar için elde edilmiş ve karşılaştırılmıştır.

Anahtar Kelimeler: Sonlu elemanlar, Petek kirişler, Çelik yapılar, Statik davranış

1. INTRODUCTION

Engineers always try to improve the structural elements to reach the best economic and suitable engineering design. The castellated steel beam is one of the important elements in the design of steel structures. Due to the fact that this type of beam is lighter than the other with the same measurements and used as a long span system, economically its reduces the cost of steel structures. One of its practical applications is shown in Figure 1., where these beams are used as roof supports. These important structural elements have occupied an important place in this field. In view of the advantages of castellated members in construction, the finite element method is used to obtain results by using the ABAQUS software. There are various studies that have led to the emergence of several new structural elements like beams of different shapes for web openings or different diameters. The main objective of using the castellated beam is to decrease the cost. Part of the previous works were devoted to developing new methods for analyzing the static and dynamic behavior of these structures.

Few examples were selected from the literature and many of them were interested in changing the shape and diameter of the web openings among these, Deepha et al. [1] used lateral stiffeners for castellated structure and it was found that the ultimate strength can be increased up to 54% and the possibility of reducing the stress concentrations by giving fillets on the corners of the web openings. Mehetre and Talikoti [2] investigated the castellated beam with fillet radius and analyzed the beam by the finite element method using ANSYS software, the result shows the suggested beam has less deflection and it was observed that the bending moment bearing capacity of sinusoidal beam is more than the hexagonal opening beam. Nawar et al. [3] investigated the castellated beam with sinusoidal and elongated circular web opening and from the results, it was concluded that by using these shapes, the bearing capacity of the castellated beams was increased. Wakchaure and Sagade [4] used a Castellated steel beam with a depth of 0.6h, it was observed when the depth of web opening increases, stresses increase, and flexural stiffness of castellated beams decreases. Yustisia et al. [5] used three types of web opening; Hexagonal 60°, Diamond 45°, Octagonal 60°. They obtained the following results; the value of the displacement for the hexagonal profile is 12.839mm, 14.433mm for diamond profiles, and 14,972 for the profile of the octagonal. After comparing the performance graph profile of each type it was found that the hexagonal 60° type has the best performance among other profiles. Preetha et al. [6] made a comparison between the I section steel beam and the rectangular steel beam and the analysis shows the rectangular section gives the best convergence and they have indicated the possibility of enhanced the convergence by improving the mesh or removing rigid body motion. Morkhade et al. [7] used a large depth of beam web openings and used the reinforcement around the web openings to increase the stiffness of castellated beams. There is a 36% increase observed in strength and 44% in the robustness of stiffeners beams compared with reinforced web openings. Khartode et al. [8] investigated the deflection and essential shear buckling strength of hybrid plate girders for various yield stress. Erdal and Saka [9] used the finite element method to verify the results of the experimental work test and investigate the nonlinear analysis of web-post buckling of steel cellular beams and nonlinear behavior of bending. Grilo et al. [10] determined the shear resistance and proposed a new formulation for cellular castellated beams and it gives better results than those obtained numerically. Sweedan [11] was interested in studying the elastic lateral buckling of cellular beams. Bihina et al. [12] made a comparison between the numerical and the experimental results depended on thermal and thermomechanical analysis. Lawson et al. [13] were interested in analyzing the composite asymmetric cellular beams and presented the influence of large web openings. Mohebkhah and Azandariani [14] analyzed the ultimate shear resistance of non-compact castellated beams (CLBs) and proposed a theoretical formula of limit analysis. Janini et al. [15] investigated the numerical modeling on fatigue failure for the various designs of web opening under sinusoidal vibration. Kharode et al. [16] increased the bearing capacity of the castellated beams by using stiffeners. Zakwan et al. [17] studied the nonlinear behavior of cellular steel beam (CSB) when exposed to fire under the applied load.

In this study, the bending response of castellated beams for five different designs of the web openings is investigated by means of the finite element method. Results of displacement and stress are presented for all of the considered cases.

Figure 1: Roof support beams [18].

2. ABAQUS ANALYSIS PROCEDURE

2.1 Element Type and Materials Properties

In this study, the finite-element method (FEM) using ABAQUS [19] software is utilized to investigate the static response of PSBs with various web openings. The geometric dimensions of the web openings are shown in figure 2. The span length of the beam is considered to be 12000 mm. The five different types of web openings used in this study are presented in figure 3. Properties of the web opening are listed in Table 1. The material properties used in this study are; Young''s modulus $E = 2.0 \times 10^5$ MPa and Poisson''s ratio $\nu = 0.27$. In FEM analysis with ABAQUS, S4R element is used. S4R is a 4-node doubly curved thin or thick shell, reduced integration, quadrilateral and stress/displacement shell element, it has a large-strain formulation and reduced integration. For more detailed information about the model see Khennane [20]. Description of the element S4R can be seen from ABAQUS Analysis User's Manual [21].
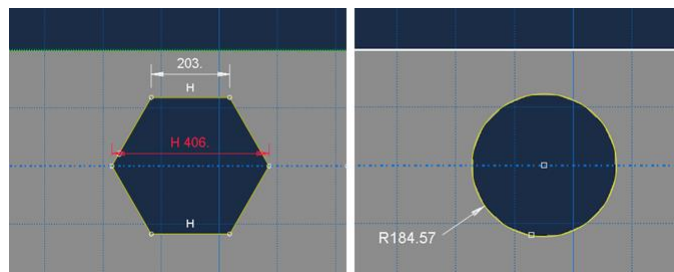

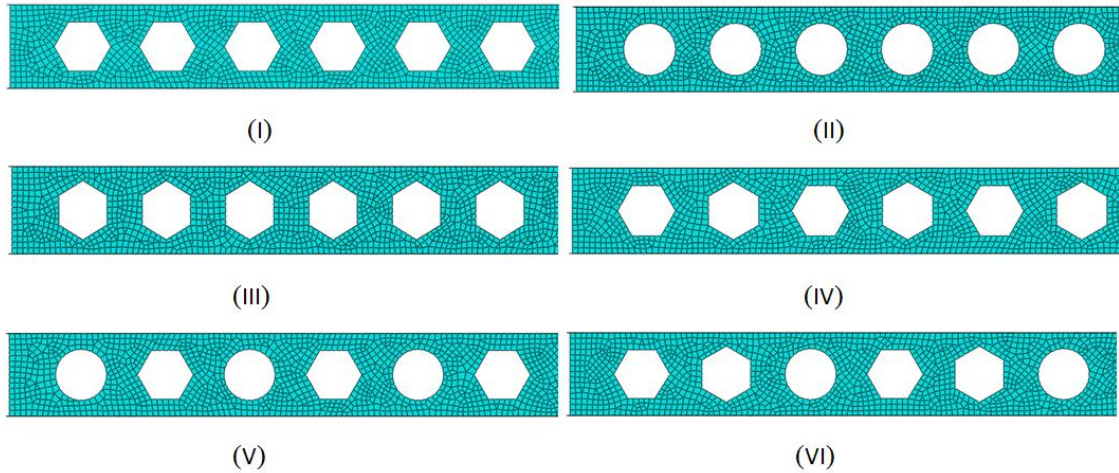Figure 2: Geometric dimensions of the web openings

Figure 3: Type of web openings for castellated beam; (I) Type-A hexagonal web opening, (II) Cellular
web opening, (III) Type-B hexagonal web opening , (IV) Type-A and Type-B hexagonal web
opening,(V) Cellular- hexagonal web opening, (VI) Complex beam web opening.

Table 1. Geometric properties of web openings

Case	Type of web Opening	Area of opening (mm²)	Center to-center distance (mm)	Number of openings
(I)	Type-A Hexagonal (HA)	184.57	609	19
(II)	Cellular (C)	184.57	609	19
(III)	Type-B Hexagonal (HB)	184.57	609	19
(IV)	Type-A and Type-B hexagonal (HAB)	184.57	609	19
(V)	Cellular- hexagonal (CH)	184.57	609	19
(VI)	Complex (CO)	184.57	609	19

2.2 Mesh and Boundary Conditions

In this study, the approximate global size of 40 is used to mesh the considered beam. The boundary conditions are fixed-fixed. The beam is assumed to be subjected under the uniformly distributed load of 1 N/mm². To determine the boundary conditions in ABAQUS, linear and rotational displacements at both ends of the beam are restricted. The loading is illustrated in figure 4.
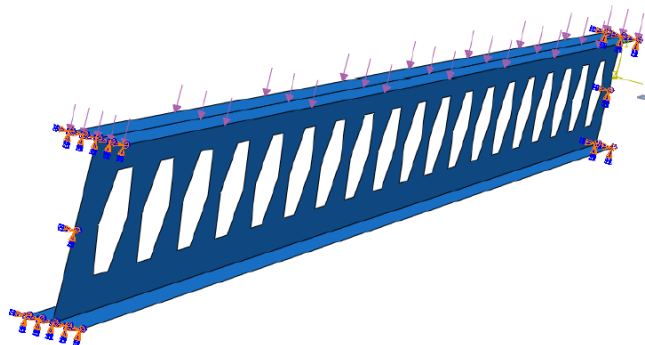

Figure 4: Fixed-fixed castellated beam subjected to uniformly distributed loading

3. RESULTS AND DISCUSSION

3.1 DEFLECTION OF CASTELLATED BEAM

The bending response of the castellated beam is investigated under the given loading in the previous section for HA, C, HB, HAB, CH, and CO web openings. In this section, displacement and rotations are obtained. The transverse displacement values for HA (case I) web opening are presented in Figure 5. From the figure, it can be seen that in this case, the maximum value of the vertical displacement is 125.8 mm. In the same manner, vertical displacement results are obtained and shown in figures 6 – 10 for Case II-VI.

From the comparison of the given figures (5-10) it can be clearly seen that the largest vertical displacement occurs in Case III, while the lowest vertical displacement occurs in case II. The results of the case I and case III are very close to each other. This shows that the displacements obtained for both types of hexagonal web openings are approximately equal. The results of Case V appear to be close to those of case I. The lowest vertical displacement values of the castellated beams with circular web openings (Case II) and the ease of application have caused such beams to be used a lot in practice.
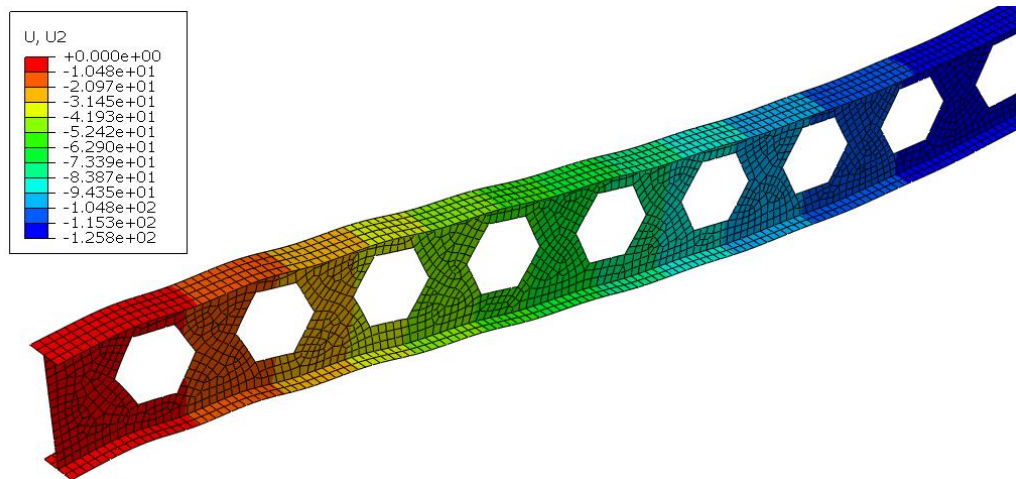

Figure 5: Transverse displacement of fixed-fixed supported HA castellated beam
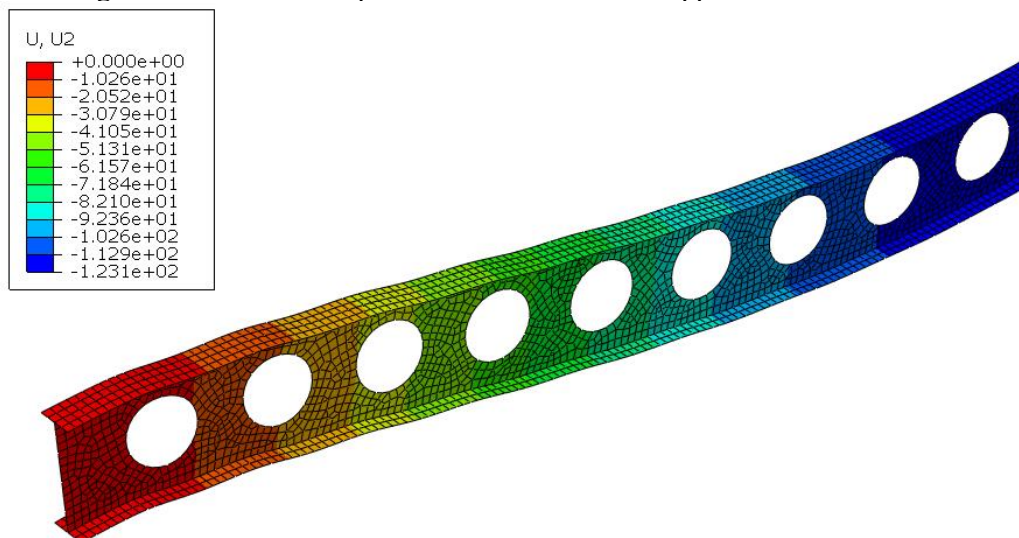

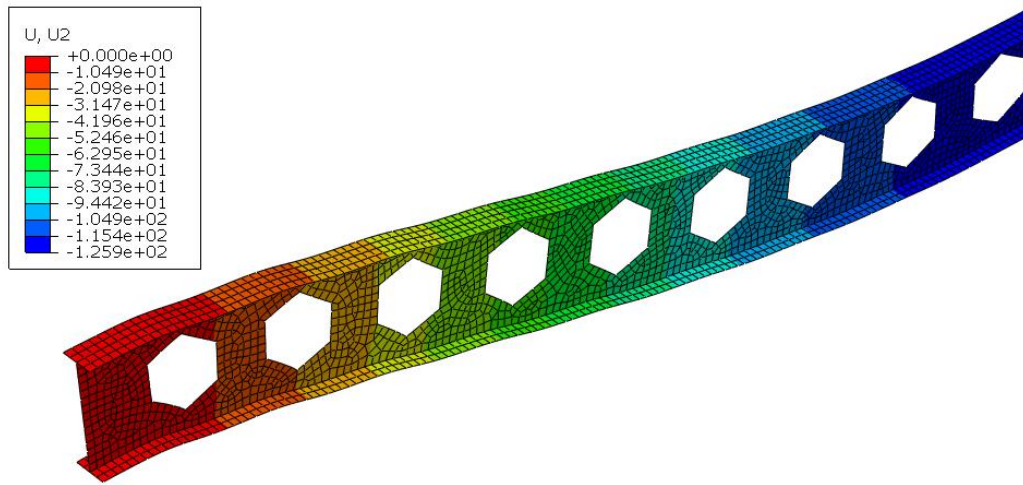Figure 6: Transverse displacement of fixed-fixed supported C castellated beam

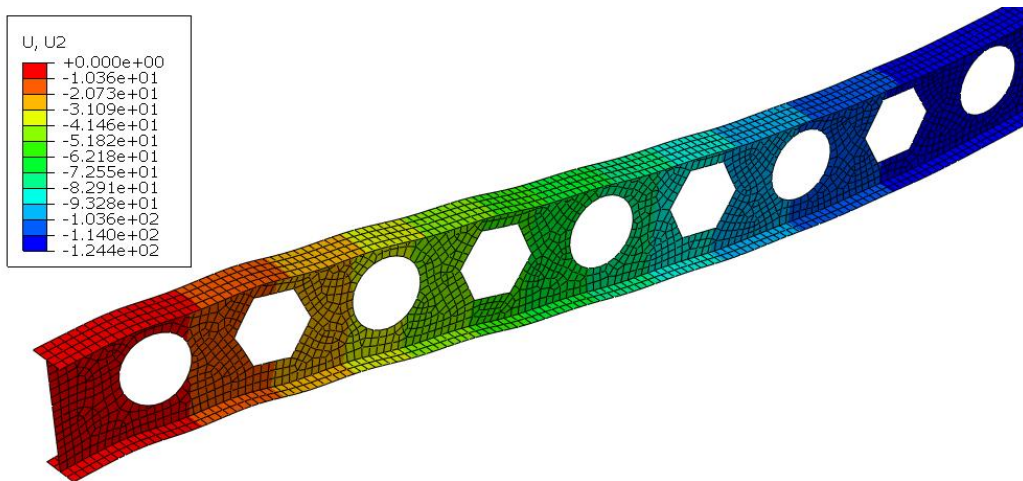Figure 7: Transverse displacement of fixed-fixed supported HB castellated beam

Figure 8: Transverse displacement of fixed-fixed supported CH castellated beam
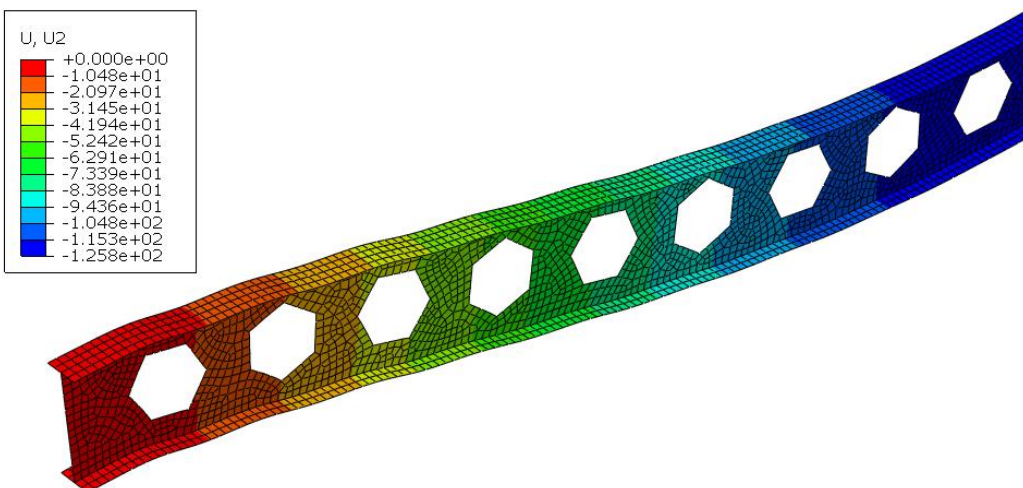
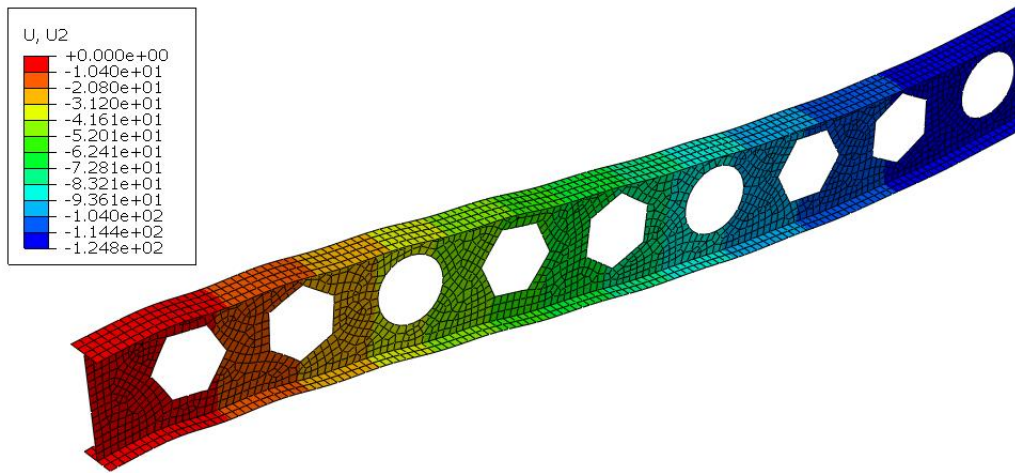Figure 9: Transverse displacement of fixed-fixed supported HAB castellated beam

Figure 10: Transverse displacement of fixed-fixed supported CO castellated beam

3.2 STRESS ANALYSIS

In this section, the stress analysis of the considered castellated beams is carried out with the help of the finite element package program ABAQUS. Von Mises stress values are presented for Case III and Case II in figures 11-12. The comparison of figures 11-12 demonstrates that values of the Von Mises stress have the largest value in Case II and lowest values in Case III. But, it must be noticed that the Von Mises stress generated in the flange of the beam for Case III is greater than those of Case II.

Results for the maximum principal stresses are also compared. Results are presented in figure 13 for Case II and in figure 14 for case III. From the given figures it can be carried out that maximum principal stresses generated in Case II are greater than those of Case III. It has been found the Case II gives the best result of maximum principal stresses.
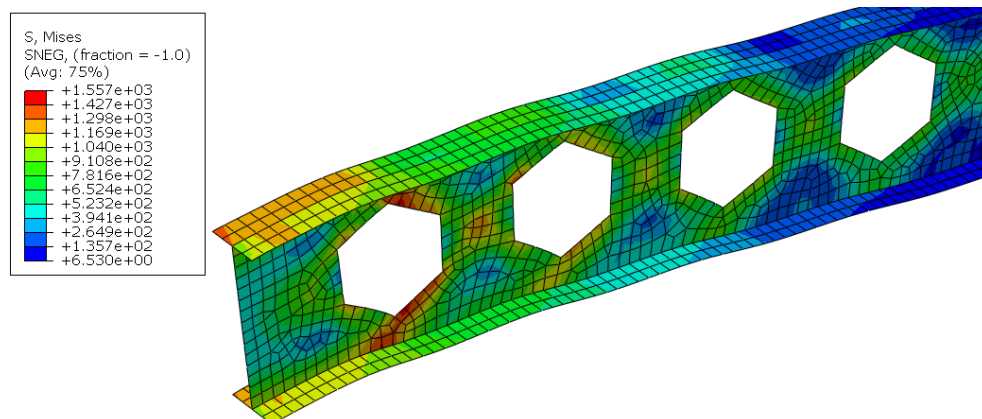

Figure 11: Von-Mises stress values of fixed supported HB castellated beam
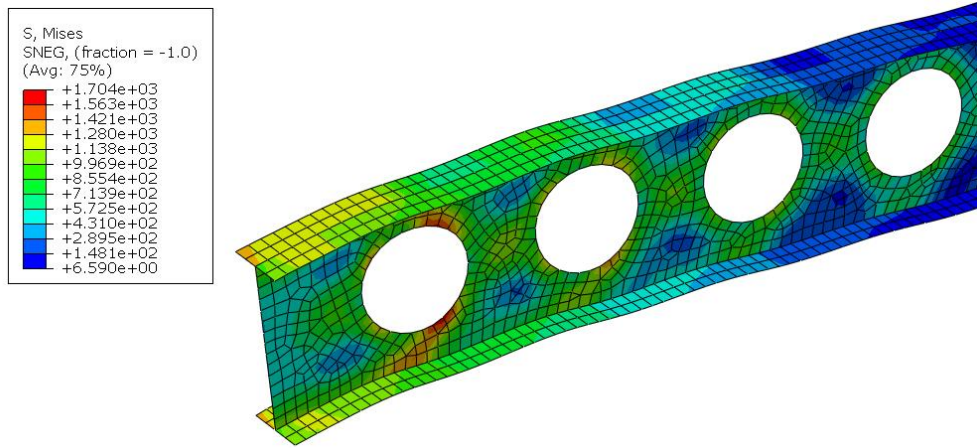
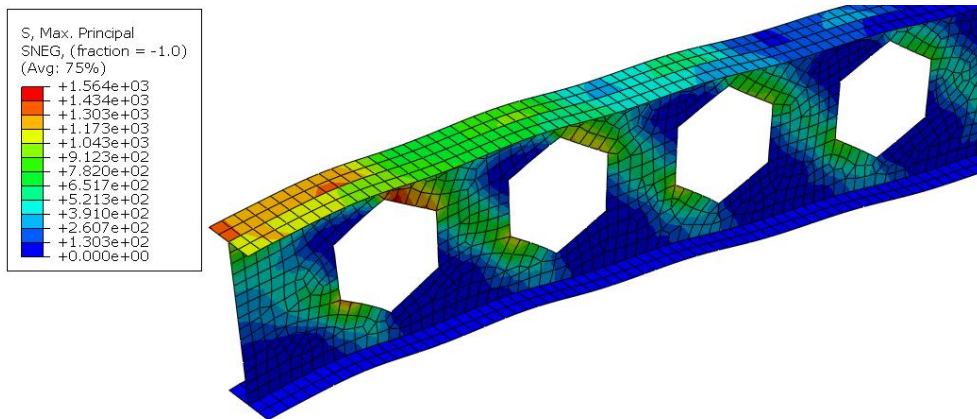Figure 12: Von-Mises stress values of fixed supported C castellated beam

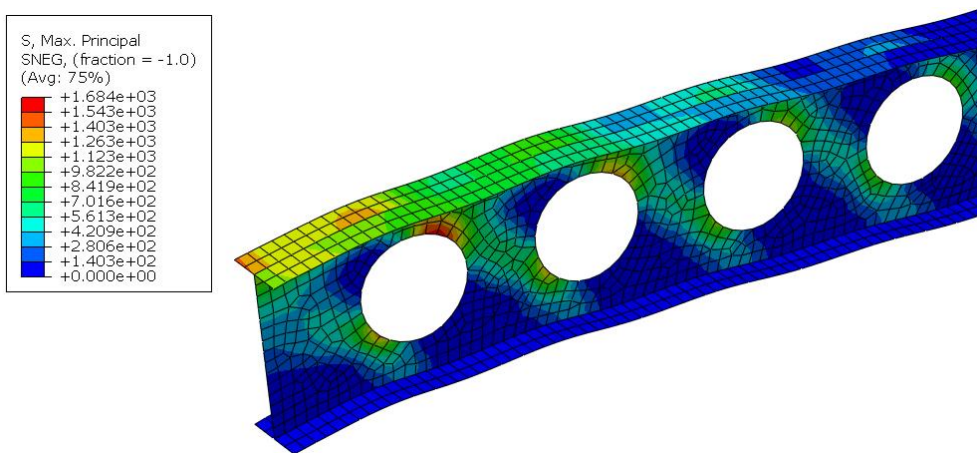Figure 13: The maximum principal stress fixed supported HB castellated beam

Figure 14: The maximum principal stress fixed supported C castellated beam

Comparison of maximum transverse displacements (U2), lateral displacements (U3), and rotational angle about the axis of the beam (UR1) are presented in figures (15-17) for all of the considered cases. The loading and boundary conditions are the same as in the previous sections.
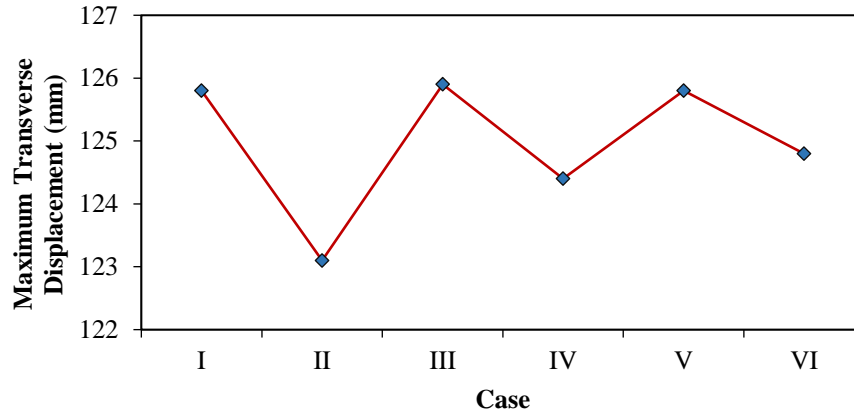

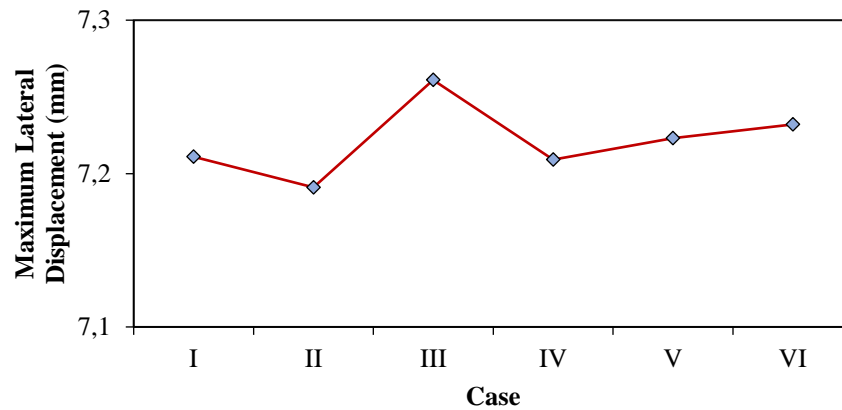Figure 15: Maximum transverse displacement (mm)

Figure 16: Maximum lateral displacement (mm)

Also, the axial displacement (U1), transverse displacement (U2), lateral displacement (U3) and rotation about the axis of the beam (UR1), rotation about the normal axis (UR2) and rotation about the bi-normal axis (UR3) are obtained for all of the cases discussed in the previous section. Results are compared in Table 2.

The comparison studies presented in the given figures (15-17) and Table 2 show that the vertical and lateral displacements have the maximum values when the web opening of the beam is HB (Case III), and the rotation about the axis of the beam has the greatest value in Case VI. As a result of the comparison, it can be found that the most critical web opening against bending and lateral buckling is HB (Case III). On the other hand, the most appropriate web opening is Case II based on the values of linear displacements and rotations.
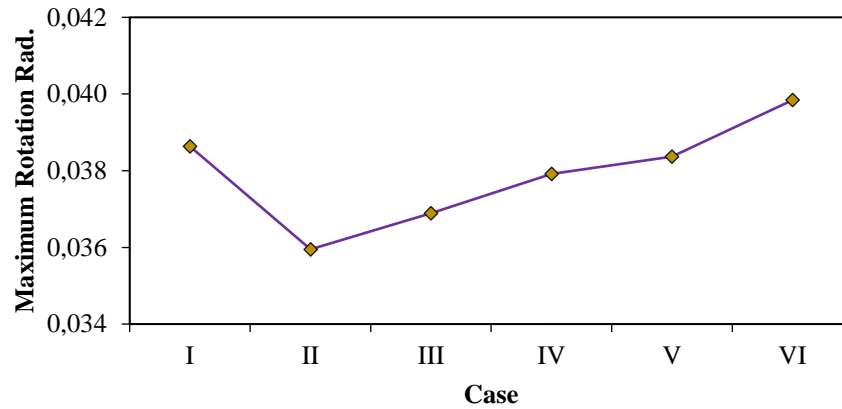
Figure 17: Maximum rotation

Table 2. Comparison of the displacements and rotations of various web openings

Case	U1 (mm)	U2 (mm)	U3 (mm)	UR1 (Rad)	UR2 (Rad)	UR3 Rad)
I	0.01504	125.80000	7.21100	0.03863	0.00174	0.00459
II	0.14630	123.10000	7.19100	0.03595	0.00174	0.00413
III	0.14860	125.90000	7.26100	0.03689	0.00175	0.00440
IV	0.14990	124.40000	7.20900	0.03792	0.00175	0.00458
V	0.15080	125.80000	7.22300	0.03837	0.00175	0.00456
VI	0.14980	124.80000	7.23200	0.03984	0.00174	0.00454

4. CONCLUSION

In this paper, the static response of castellated beams is investigated for various types of web opening by means of the finite element method. Displacement and stress results are obtained and compared. Based on the comparison given in the paper the conclusions are as follows:

- The largest transverse and lateral displacements occur in case III, while the lowest transverse and lateral displacement occur in case II.

- The rotation about the axis of the beam has the greatest values when the web opening is CO and it has the smallest values when the beam is cellular.

- Based on the comparison of the maximum principal and Von-mises stresses it is found that the most appropriate web opening is C.

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