Influence of the Web Opening Shapes on the Bending and Free Vibration Responses of Castellated Steel Beams

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Abstract - In recent years, the use of castellated beams has increased significantly across all types of structures. The castellated beam is one of several methods for reducing the weight and cost of steel in construction. In this study, the static and dynamic behavior of castellated beams is investigated via the three-dimensional finite element method. The primary objective of this study is to investigate in detail the effect of web opening shapes on displacement, stress values, and free vibration of castellated beams. The investigation is done using ANSYS 22 R1. In the analysis, 4 different web opening types circle, square, pentagon, and hexagon are used. To generate the models via the finite element method a 10-node tetrahedral type finite element is implemented. This study will employ a linear isotropic homogeneous material with the mechanical properties of steel. As boundary conditions, fixed – fixed, fixed – pinned, and fixed – free are considered. The results for circular, square, pentagon, and hexagon castellated beams made from IPE120, IPE180 and IPE240 profiles are presented in detail. Based on the results, it is seen that the type of web opening has a significant effect on the displacements, von-Mises stresses, maximum shear stress and free vibration values of the considered structures.

Keywords: Castellated Beam, Total Displacement, Finite Element Method, Free Vibration, Maximum Shear Stress, Von Mises Stress

1. Introduction

The usage of castellated beams has become very popular due to their advantageous structural applications such as they are light, cheap, have relatively high resistance, and can be assembled fast at the construction site. These applications make use of the increased strength and cost of castellated beams[1]. In the 1930s, castellated shapes were manufactured by the Skoda factories in Pilsner and were first traded in the United Kingdom [2].In the mid-1930s, an engineer working in Argentina, Geoffrey Murray Boyd, castellated beam, which was one such improvement in built-up structural members [3].

Studies on web opening configurations involving square, rectangular, circular, concentric, and eccentric openings of steel beams were completed in the early 1960s in the United States and Canada [2] . A castellated beam is made from a standard I-beam through the use of a cutting and welding process. Since the 1980s, researchers have studied castellated beams using both experimental and finite element numerical methods [4]. Various methods have been used to study the response of castellated beams [5].

The theoretical basis of the castellated beam is an attempt to increase the profile height of the beam while creating openings in the web of the profile, thereby increasing its moment of inertia while decreasing its self-weight. The failure mode of the structure is affected by modifications made to the castellated beam. The formation of a Vierendeel mechanism, lateral torsional buckling of the web post, rupture of a welded joint in a web post, lateral torsional buckling of the entire span, formation of a flexure mechanism, and buckling of the web post were all possible modes of failure [6]. The openings are typically hexagonal, square, or circular in shape. The beams with holes in the shape of a circle are called cellular beams[7]. The main reasons for fabricating castellated beams are (a) increasing section height, which enhances moment of inertia, section modulus, stiffness, and flexural resistance; (b) decreasing profile weight, which reduces structure weight and saves construction work; (c) optimum utilization of existing profiles; (d) no need to plate girders; and (e) the passage of services[8]. Vibration analysis is critical for the design of structures subjected to dynamic loadings [9]. The free vibration analysis of I-section beams is well understood and covered in many textbooks. However, difficulties arise for castellated beams due to web openings, which cause not only section property variation along the longitudinal axis of the beams but also shear weakness of the web. The latter necessitates an analysis that accounts for the shear effect[10]. Mathur et al. [11] performed the static and dynamic analyses of the castellated steel beam section (ISMB 300) to compare deflection, stress distribution, shear stress, amplitude, and natural frequency. ANSYS 18 is used to investigate. El-Dehemy[12] the ABAQUS software to analyze the nonlinear static and dynamic steel beam openings with different positions and supporting conditions.

Lotfollahi andAhmadi [13] used ANSYS to study castellated beam dynamics. First, the dynamic properties and mode shapes of plain-webbed and castellated cantilever beams were studied. Large web openings may reduce castellated beams' dynamic load-carrying capacities. Plainwebbed and castellated beams were then subjected to a white-noise dynamic load. Dynamic cantilever castellated beam properties depend on the loading pattern. Akgönen et al. [14] A 3D Finite Element Analysis (FEA) was performed to determine the flexural and elastic lateral-torsional buckling behavior of a cellular beam using the shape and quality of European steel. The finite element model was verified using a literature-based experiment (FEM). Doori and Noori [15] the static behavior of castellated beams with varying web apertures ABAQUS is used to do a 3D finite element analysis to determine which type of beam provides the highest performance under the same distributed load and fixed support condition. Abdulkhudhur et al. [16] evaluate the shear buckling capacity of floor steel beams with circular web perforations under static and dynamic loads. Web-to-thickness ratio and perforation size were used. ANSYS software was used to simulate all models as three-dimensional problems. Salah [17] used a developed Finite Element (FE) model, the current study predicts the up to failure behavior of hybrid castellated beams (HCBs). In their study, 410 MPa steel was used for flanges and 250 MPa for web. ANSYS was used for the analysis. Morkhade et al [18] used the finite element model including geometric and material nonlinearity. Failure modes, load–deflection behavior of samples, and stress concentration with opening size, shape, and position were studied. Hosseinpour and Sharifi [19] studied the web distortion's effect on steel beam buckling. To this purpose, a series of nonlinear finite element (FE) models were constructed and well verified against an experimental work on the distortional buckling of castellated beams; both material nonlinearities and initial geometric imperfections were carefully applied to the models. Vivek et al. [20] analyzed the free and harmonic vibration of steel thin-walled tapered cantilever beams with and without web openings.

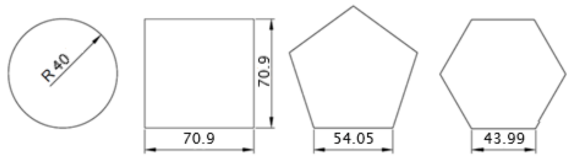
Frans et al. [21] studied the hexagonal castellated beams studied numerically for opening angle and spacing. ABAQUS/CAF v6.11 was used to develop a finite element model based on the Von misses failure principle. Soltani et al. [22] employed the MSC/NASTRAN model to predict the developed the behavior of castellated beams with octagonal and hexagonal holes, both material and geometric nonlinearities were considered in the numerical model. Shaikh and Autade[23] studied in this the experiment in the castellated beam was investigated of buckling capacity of the web post with a fillet corner, hexagonal web opening was compared to the circular opening as Concentrated load or reaction point over a web-post . Finite element analysis was done by using ANYSIS 14. The results pointed out that using of a vertical stiffener reduces the deflections about 20% compared to these without stiffeners, while using of a diagonal and vertical stiffener with each other reduces deflection about 60 % compared to the castellated beam without stiffeners. Wang et al. [24] adopted the finite-element method in study of elastic buckling behavior in castellated beams at the web-post which subjected to vertical shear. Zaarour[25] tested twelve of the castellated beams until reach to fail with respecting the buckling of web-post between holes. In the same direction, the buckling loads were calculated using a finite element method in addition to the experimental method. Redwood and Demirdjian [26] tested four castellated beams.Web post-buckling was the focus of the study which was observed in all beams of the test. Buckling loads were predicted by elastic analysis by using the finite element method. The test results showed that the buckling load non-sensitive to the ratio of (moment/shear). Estrada et al. [27] compared the costs of a castellated beam and standard wide flange beams. The results explained that the castellated beams were more advantageous compering with unaltered standard wide flange beams at the same load capacities.

The literature survey shows that the influence of the web opening shapes on the static and dynamic analysis of castellated steel beams has been not investigated by using the 3D finite element method (FEM) via ANSYS 2022 R1 yet. This paper aims to examine the static and dynamic response of castellated beams with the aid of the finite element method. The effects of different boundary conditions and the web opening geometries (square, circle, pentagon, and hexagon) of the castellated beams on the displacements, stresses, and free vibration characteristics are parametrically investigated.

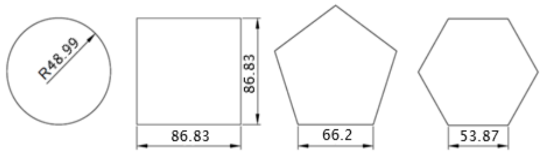
To present this research paper in a better way, it is organized as follows: Section 2 shows the materials and gives information about the finite element type used in the analysis. Section 3 presents the numerical results and discussion. and Section 4 gives the most important conclusion of this paper.

2. Materials and Method

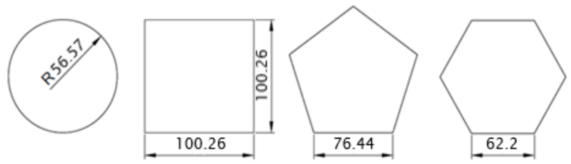
This study analyzes castellated beams with different geometries using the ANSYS Workbench 2022 R1 based on the finite element method. IPE120, IPE180, and IPE240 profiles are used in the analyses; each profile contains four different web opening types (circle, square, pentagon, and hexagon).The geometric properties of the web opening of these beams are shown in Figure 1. and the material properties are presented in Table 1.



(a) IPE120



(b) IPE180



(C) IPE240

Fig. 1: web opening geometric

Table 1. Material properties

Young's Modulus Pa	Poisson's Ratio	Bulk Modulus Pa	Shear Modulus Pa
2.E+011	0.3	1.6667E+011	7.6923E+010

The length of the castellated beam is taken as 3 meters. In all types, the opening number is 15, the distance between the centers of the opening (α) is 0.18 m, and the length (β) between the support and the center of the opening is 0.24 m. These features are summarized in Table 2.

Table 2. Geometric properties of web opening

Model	Profil type	Web opening type	Area opening (mm^2)	α (m)	β (m)
I	IPE120	circular	5026.55	0.18	0.24
II	IPE120	Square	5026.55	0.18	0.24
III	IPE120	pentagon	5026.55	0.18	0.24
IV	IPE120	hexagon	5026.55	0.18	0.24
V	IPE180	circular	7539.89	0.18	0.24
VI	IPE180	Square	7539.89	0.18	0.24
VII	IPE180	Pentagon	7539.89	0.18	0.24
VIII	IPE180	Hexagon	7539.89	0.18	0.24
IX	IPE240	circular	10053.61	0.18	0.24
X	IPE240	Square	10053.61	0.18	0.24
XI	IPE240	pentagon	10053.61	0.18	0.24
XII	IPE240	hexagon	10053.61	0.18	0.24

In the finite element solution of the problem in the hand with ANSYS, the three dimensional SOLID187 is used.The element is defined by 10 nodes while each node has three degrees of freedom. The SOLID187 has a quadratic shifting behavior and is suitable for modeling of the finite element irregular mesh. The degrees of freedom in the elements consist of translations in the direction of the x, y, and z axes. More detailed information about the theory of this element and the geometry of this element can be found in [28]

In this research, no changes were made to the "Mesh" settings of the program while creating the finite element mesh of the systems. The number of elements and nodes for each case is presented in Table 3.

Table3. Finite element mesh properties

Model	Number of element	Node number
I	5128	11002
II	4505	9468
III	3257	6595
IV	5209	11157
V	5289	11660
VI	4146	8820
VII	4455	9605
VIII	4856	10614
IX	5458	12442
X	3676	8160
XI	3951	8894
XII	4301	9875

Three different boundary conditions have been taken into account fixed – fixed, fixed–pinned, and fixed–free shown in Table 4, 'i' denotes the left end of the beam, while 'j' stands for the right end of the beam. In order to define the support boundary conditions, the "Fixed" condition in the interface of the program for the fixed support is used. for the pinned support using the "Remote Displacement" command. No boundary conditions were entered for the free end.

Table 4: Boundary conditions

Type of the support	Boundary conditions	
	i	j
Fixed – Fixed (F-F)	Fixed Condition	Fixed Condition
Fixed – Pinned (F-P)	Fixed Condition	Remote Displacement
Fixed – Free (F-FR)	Fixed Condition	-----

2.1 Static Analysis

After modelling the analysis is carried out in ANSYS2022 software and results are obtained for deformation, equivalent (von-mises) stress and maximum shear stress. Graphs are prepared from the results and comparison is done.

2.2 Dynamic Analysis

After modeling, analysis results are obtained for the natural frequency and mode shapes are obtained.

3. Numerical results and discussion

In this study, the static and dynamic analysis of castellated beams are carried out with the help of three-dimensional finite elements. The ANSYS [29] Workbench package is used in the analysis. The effect of the web opening shapes on the performance of the structural elements is investigated in detail. The pressure is applied to the top of the beam, and its value was taken as 1000 Pa. It is worth mentioning that there is no specific reason for choosing this load. It is considered only to investigate the effect of web opening type on the static response of the castellated beams. Three types of profiles used in this study are IPE120, IPE180, and IPE300 profiles for castellated beams. For each one of these profiles, 4 different web opening types (circle, square, pentagon, and hexagon) are used. In this context, only the web opening type is changed by keeping the length of the beam, the web opening area, and the distance between the openings equal in the cases for each profile. The material properties are assumed as in Table 1.

3.1 Static Analysis

Thirty six different models are generated and analyzed using the finite element procedure. To outline the effect of web opening on the static response of the considered structure, results are obtained for values of web opening type and boundary conditions**.**

The total displacement values obtained for all models will be discussed first in this section.The results obtained are shown in Figure 3 for the fixed-fixed boundary condition and are given in Table 5 for the other boundary conditions.

When Figure 11 and Table 5 are examined in all support conditions, the largest total displacements in the castellated beam occur in the case of a square web opening, and the smallest total displacements occur when a pentagon web opening is used in profile IPE120, while the smallest displacements occur when a hexagon web opening is used in other profiles. The total displacement values of castellated beams with circular web openings are approximated when hexagonal web opening geometry is used. Profil type and deflection curves for all support conditions of castellated beams are presented in Figures (2–10).

Table 5. Maximum total displacement values for castellated beam (m).

Support Condition	Profil	Model	Maximum dispacement (m)
Fixed - Fixed	IPE120	I	2.499E-05
		II	2.554E-05
		III	2.425E-05
		IV	2.508E-05
	IPE180	V	1.030E-05
		VI	1.098E-05
		VII	1.044E-05
		VIII	1.028E-05
	IPE240	IX	5.989E-06
		X	6.736E-06
		XI	6.089E-06
		XII	5.958E-06
Fixed- Pinned	IPE120	I	4.893E-05
		II	4.960E-05
		III	4.820E-05
		IV	4.905E-05
	IPE180	V	1.873E-05
		VI	1.955E-05
		VII	1.890E-05
		VIII	1.872E-05
	IPE240	IX	9.935E-06
		X	1.085E-05
		XI	1.008E-05
		XII	9.926E-06
Fixed - Free	IPE120	I	1.046E-03
		II	1.048E-03
		III	1.043E-03
		IV	1.047E-03
	IPE180	V	3.621E-04
		VI	3.656E-04
		VII	3.649E-04
		VIII	3.638E-04
	IPE240	IX	1.667E-04
		X	1.701E-04
		XI	1.672E-04
		XII	1.664E-04

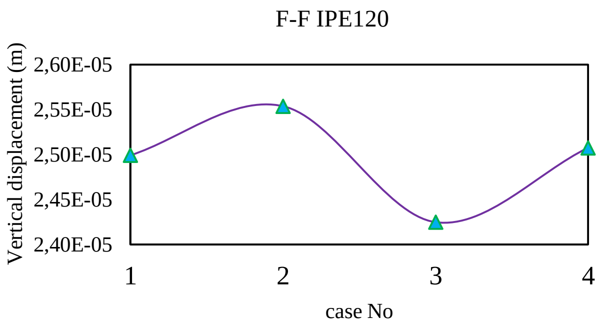


Fig. 2: Profil type – deflection curve for fixed –fixed castellated beam

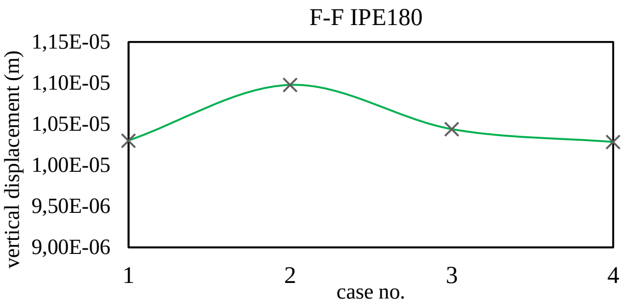


Fig. 3: Profil type – deflection curve for fixed –fixed castellated beam

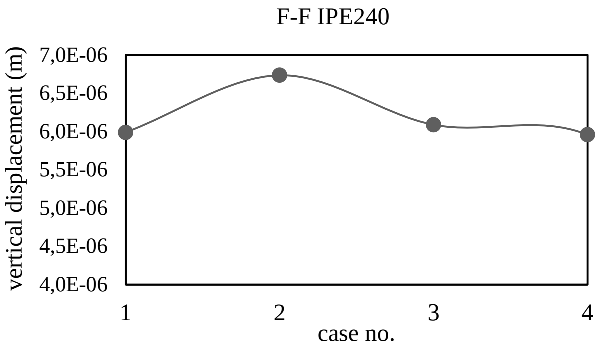


Fig. 4: Profil type – deflection curve for fixed –fixed castellated beam

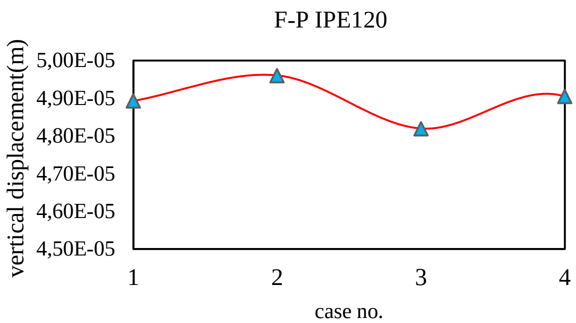


Fig. 5: Profil type – deflection curve for fixed –pinned castellated beam

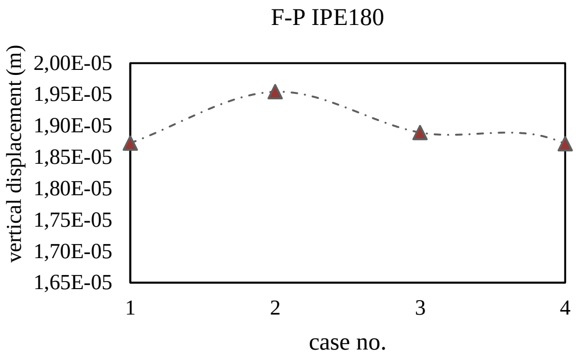


Fig. 6: Profil type – deflection curve for fixed –pinned castellated beam

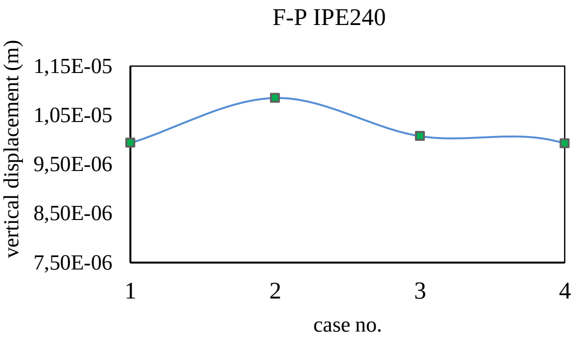


Fig. 7: Profil type – deflection curve for fixed –pinned castellated beam

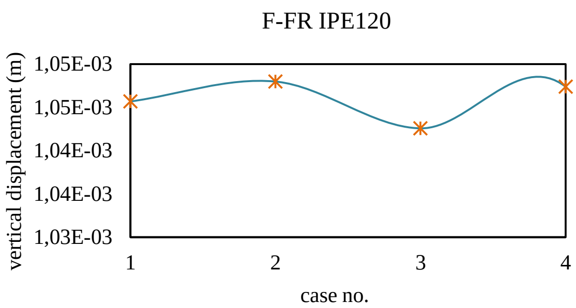


Fig. 8: Profil type – deflection curve for fixed –free castellated beam

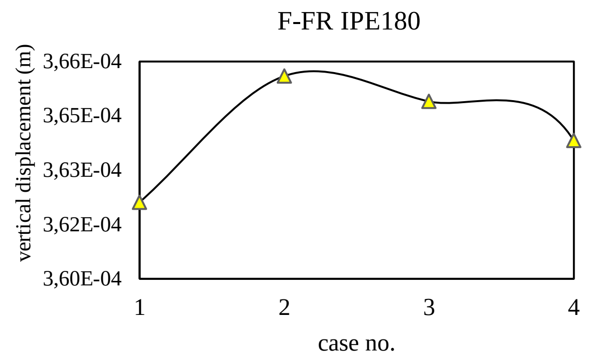


Fig. 9: Profil type – deflection curve for fixed –free castellated beam

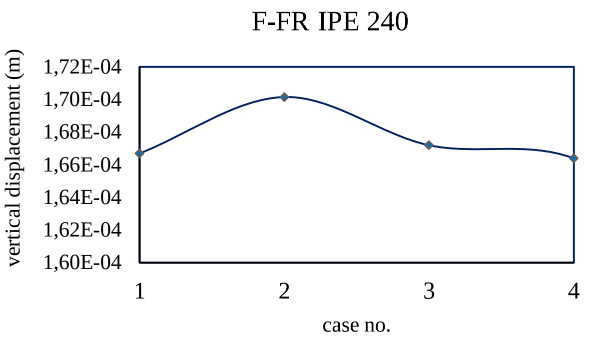


Fig. 10: Profil type – deflection curve for fixed –free castellated beam

Table 6: Maximum von Mises stress values for castellated beam (pa)

Support Condition	Profil	Model	Maximum von mises stress (pa)
Fixed - Fixed	IPE120	I	1.107E+06
		II	1.428E+06
		III	1.081E+06
		IV	1.661E+06
	IPE180	V	8.556E+05
		VI	1.040E+06
		VII	1.286E+06
		VIII	1.105E+06
	IPE240	IX	8.531E+05
		X	8.748E+05
		XI	7.840E+05
		XII	7.272E+05
Fixed- Pinned	IPE120	I	1.403E+06
		II	1.914E+06
		III	1.378E+06
		IV	2.173E+06
	IPE180	V	1.061E+06
		VI	1.229E+06
		VII	1.242E+06
		VIII	1.443E+06
	IPE240	IX	1.076E+06
		X	1.132E+06
		XI	1.003E+06
		XII	9.242E+05
Fixed - Free	IPE120	I	5.759E+06
		II	5.689E+06
		III	5.711E+06
		IV	6.874E+06
	IPE180	V	2.912E+06
		VI	2.932E+06
		VII	2.861E+06
		VIII	3.702E+06
	IPE240	IX	1.998E+06
		X	2.212E+06
		XI	2.037E+06
		XII	1.930E+06

The von Mises stress values are obtained as a result of the static analysis for all models considered within the scope of the study and are given in Figure 12 for the fixed-pinned boundary condition. The minimum and maximum von Mises stress values calculated for all other boundary conditions are given in Table 6. submitted for review.

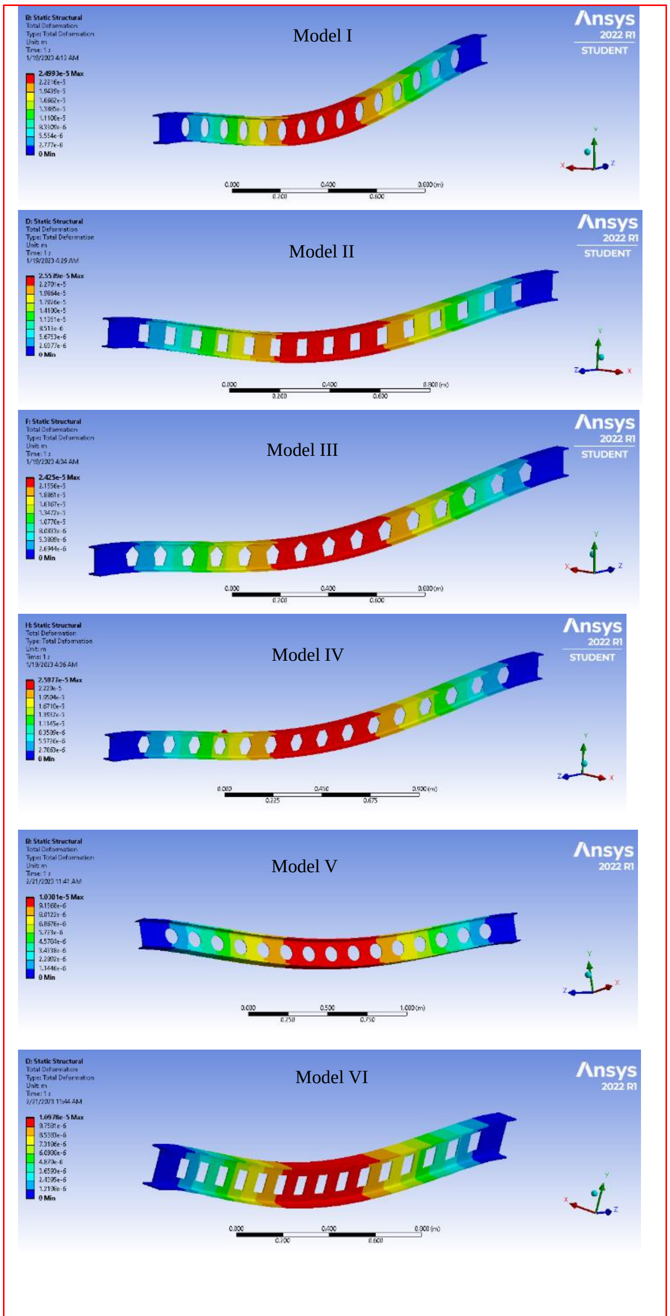
As seen in Figure 12 and Table 6, the lowest von Mises stress values for the IPE120 profile occur when a pentagon web opening is used. For the IPE180 profile, these values are the lowest when circular web opening is used in fixed-fixed and fixed-pinned, while these values are the lowest when pentagon web opening is used in fixed-free. The lowest von Mises stress values for the IPE240 profile occur when a hexagonal web opening is used. When the hexagonal web opening type is used for both profiles IPE120 and IPE180, von-Mises stresses take the highest values. While profile IPE 240 has a square web opening type, von-Mises stresses are the highest. .

In order to better determine the effect of the web opening geometry on the static behavior of the castellated beams, the maximum shear stress values are also obtained. These values are given in Figure 13 for the cantilever beam. These values are presented in Table 7 for all other support conditions. When Table 7 and Figure 13 are examined, the maximum shear stress values for the IPE120 and IPE180 profiles in fixed-fixed and fixed-pinned support cases are the lowest when castellated beams with circular openings are used.

Table 7. Maximum shear stress values for castellated beam (pa).

Support Condition	Profil	Model	Maximum shear stress (pa)
Fixed - Fixed	IPE120	I	5.622E+05
		II	7.895E+05
		III	5.903E+05
		IV	8.669E+05
	IPE180	V	4.301E+05
		VI	5.792E+05
		VII	6.845E+05
		VIII	5.861E+05
	IPE240	IX	4.285E+05
		X	4.840E+05
		XI	4.155E+05
		XII	3.837E+05
Fixed- Pinned	IPE120	I	7.044E+05
		II	1.057E+06
		III	7.195E+05
		IV	1.142E+06
	IPE180	V	5.402E+05
		VI	6.824E+05
		VII	6.788E+05
		VIII	7.666E+05

	IPE240	IX	5.435E+05
		X	6.265E+05
		XI	5.414E+05
		XII	4.993E+05
Fixed - Free	IPE120	I	2.806E+06
		II	2.880E+06
		III	2.875E+06
		IV	3.554E+06
	IPE180	V	1.494E+06
		VI	1.499E+06
		VII	1.520E+06
		VIII	1.963E+06
	IPE240	IX	1.013E+06
		X	1.234E+06
		XI	1.112E+06
		XII	1.019E+06



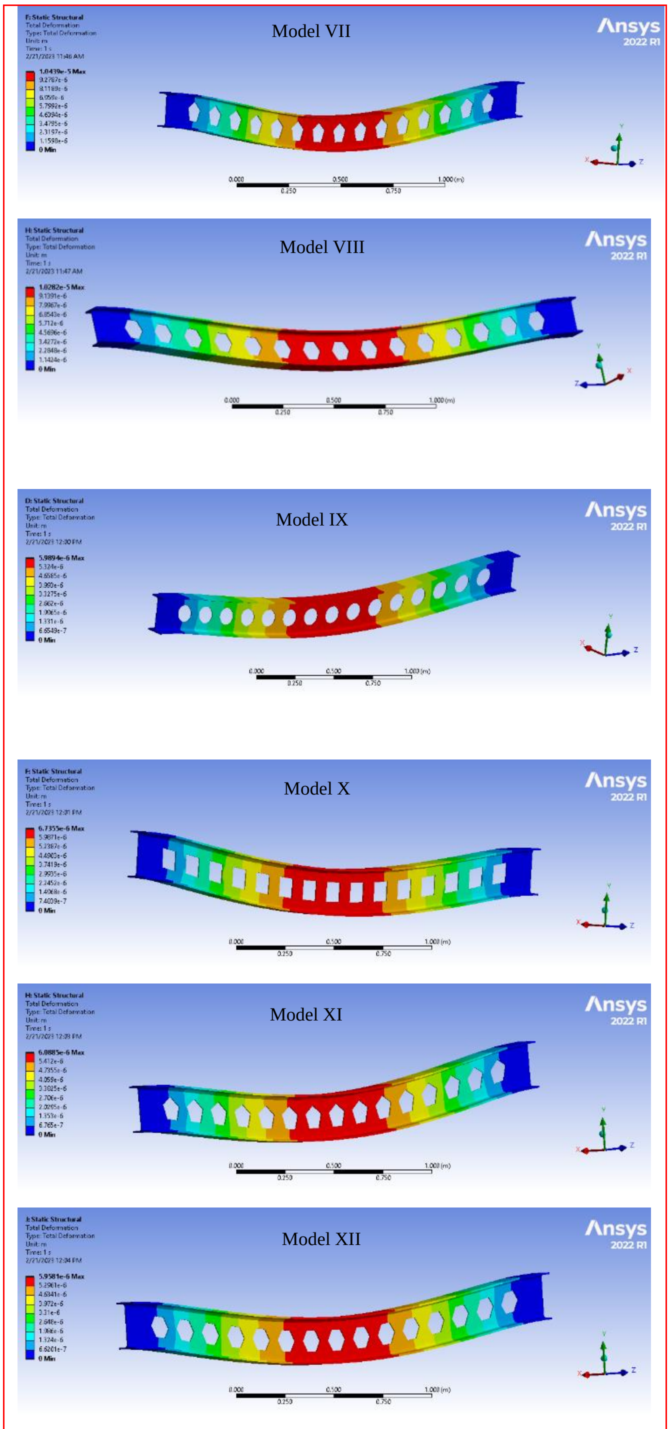
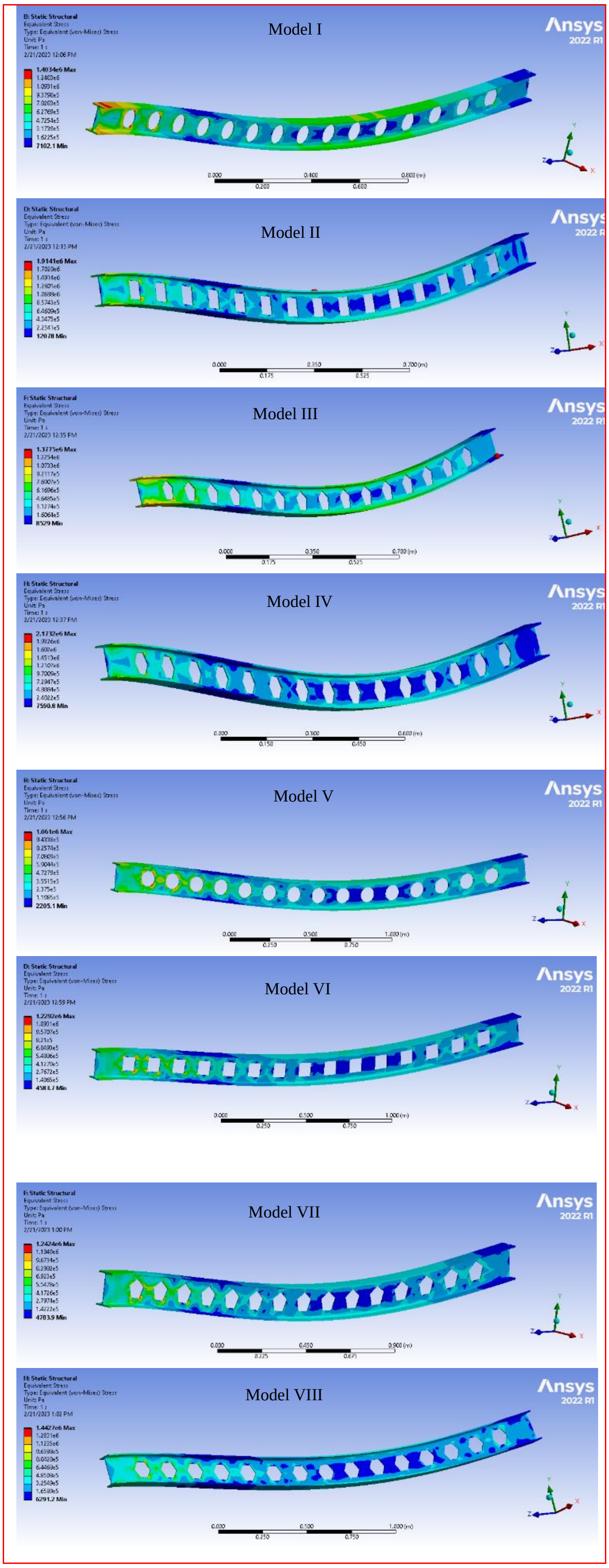


Fig. 11: The total deformation for fixed – fixed castellated beam

For the IPE 240 profile, the lowest maximum shear stress values occur when a hexagonal-type opening is used. For a cantilever beam, the IPE120, IPE180, and IPE240 profiles with a circular opening have the lowest maximum shear stress. As can be clearly observed in Tables (5-7) the results gained we can arrange the beam from lower to higher von mises stress based on the beam supports comparison: fixed – fixed, fixed – pinned, and lastly fixed – free.



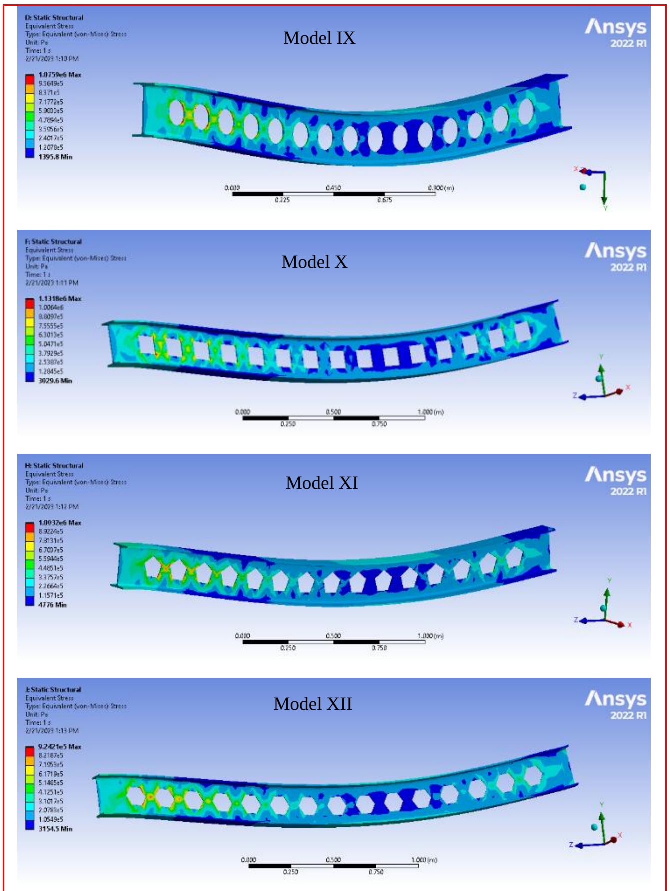
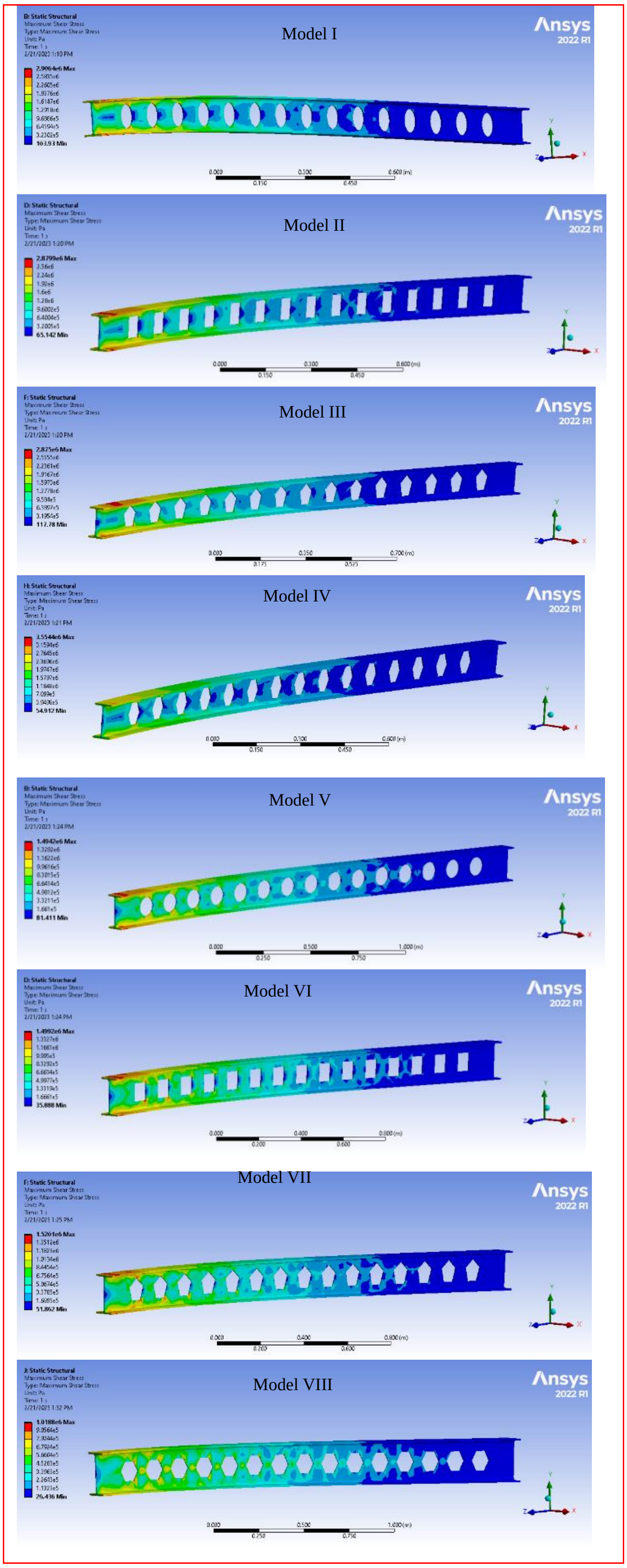


Fig.12: The von Mises stress distributionfor fixed-pinned castellated beam



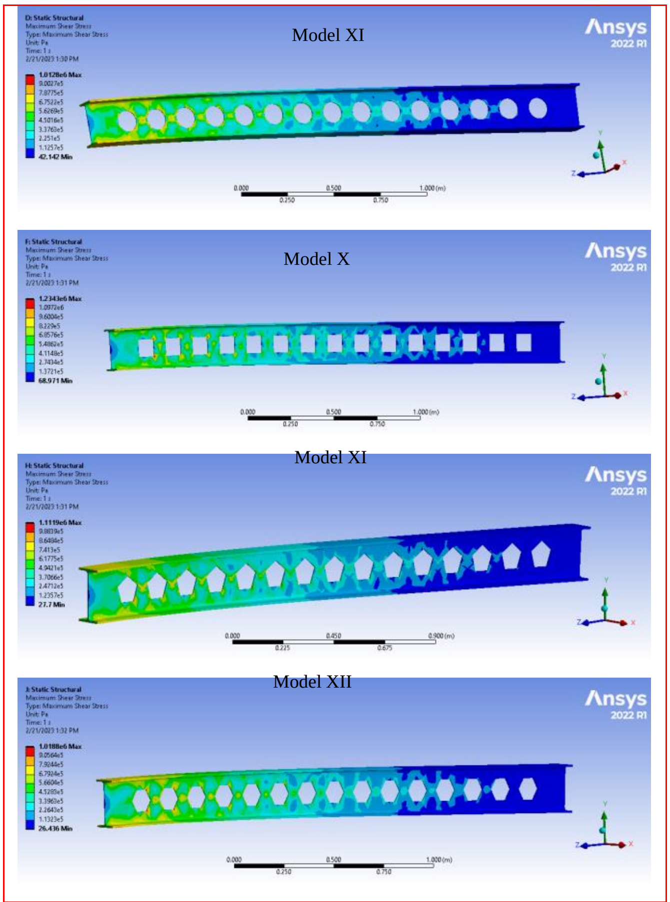


Fig.13: The maximum shear stress for fixed – free castellated beam

3.2 Dynamic analysis

Thirty-six different models are generated and analyzed using the finite element procedure. To outline the effect of web opening on the free vibration response of the considered structure, results are obtained for values of web opening type and boundary conditions.

Table 8. shows some of the essential aspects of the free vibration response of castellated steel beams. From the given comparisons, it is easy to see the influence of the web opening type on the natural frequencies. The five modes have the highest frequency in the pentagon. In the fixed -fixed support the lowest frequency is in the circular in the first, fourth, and fifth modes, and in the hexagonal in the second and third modes. The hexagon has the lowest frequency in the first, second, and fourth modes of fixed-pinned support; the square in the third mode; and the circular in the fifth mode. The lowest frequency in a cantilever beam is in the hexagon in the first, third, and fourth modes; in the square in the second mode; and in the circular in the fifth mod. The comparison of the natural frequency is shown in figures(14-16).

Table 9 shows that the five modes have the lowest frequency in the square. In the fixed -fixed support the highest frequency is in the circular in the first mode and in the pentagon in the second and third modes. The hexagon has the highest frequency in the fourth, and fifth modes. In the fixed-pinned support, the highest frequency is in the circular in the first mode, and the pentagon in the second, third, and fourth modes. The highest frequency in a cantilever beam is in the circular in the first, second, and fourth modes; in the hexagon in the third mode; and in the pentagon in the fifth mode. The comparison of the natural frequency is shown in figures(17-19).

Table 10 demonstrated that for the fixed -fixed support, the highest frequency is in the pentagon in the first mode, in the square in the second, in the hexagon in the third and fourth modes, and in the circular in the fifth mode. The hexagon has the lowest frequency in the first and second modes, and the circular has the lowest frequency in the third and fourth modes; the pentagon has the lowest frequency in the fifth mode.

In the fixed-pinned support, the highest frequency is in the hexagon in the first, second, and fourth modes; in the pentagon in the third; and in the circular in the fifth mod.The circular has the lowest frequency in the first and third modes, and the square has the lowest frequency in the second, fourth, and fifth modes.

In the case of a cantilever beam, the highest frequency is in the square in the first mode, in the hexagon in the second and third modes, and in the pentagon in the fourth and fifth modes. The circular has the lowest frequency in the first and fourth modes, and the square has the lowest frequency in the second, third, and fifth modes. The comparison of the natural frequency is shown in figures(20-22).

The Ansys results indicated that the increase in size of the web opening increased the Frequency.

Table 8. Natural frequencies castellated beam with profil IPE120 (Hz)

Support Condition	Model	Mod	Natural frequency (HZ)
Fixed - Fixed	I	1	30.282
		2	56.783
		3	83.228
		4	94.102
		5	126.99
	II	1	30.295
		2	56.74
		3	83.262
		4	93.029
		5	128.63
	III	1	31.03
		2	85.962
		3	86.334
		4	95.755
		5	170.8
	IV	1	30.265
		2	56.429
		3	83.195
		4	93.892
		5	127.21
Fixed- Pinned	I	1	20.853
		2	24.2
		3	66.932
		4	67.413
		5	76.601
	II	1	20.856
		2	23.982
		3	66.486
		4	67.416
		5	77.981
	III	1	21.291
		2	36.736
		3	67.672
		4	69.381
		5	120.74
	IV	1	20.834
		2	23.646
		3	66.829
		4	67.375
		5	76.824
Fixed - Free	I	1	4.7169
		2	15.727
		3	24.199
		4	29.568
		5	76.597
	II	1	4.7145
		2	15.697
		3	23.981
		4	29.569
		5	77.977
	III	1	4.8126
		2	15.783
		3	30.185
		4	36.738
		5	85.22
	IV	1	4.7137
		2	15.707
		3	23.645
		4	29.544
		5	76.819

Table 9. Natural frequencies castellated beam with profil IPE180 (Hz)

Support Condition	Model	Mod	Natural frequency (HZ)
Fixed - Fixed	V	1	42.738
		2	59.384
		3	116.64
		4	129.3
		5	144.58
	VI	1	42.691
		2	58.977
		3	116.52
		4	125.1
		5	144.23
	VII	1	42.73
		2	59.626
		3	116.71
		4	128.5
		5	144.63
	VIII	1	42.713
		2	59.172
		3	116.59
		4	129.33
		5	144.83
Fixed- Pinned	V	1	21.587
		2	29.453
		3	73.825
		4	94.613
		5	95.469
	VI	1	21.255
		2	29.422
		3	73.115
		4	93.42
		5	94.506
	VII	1	21.445
		2	29.454
		3	74.571
		4	94.643
		5	95.02
	VIII	1	21.414
		2	29.438
		3	73.809
		4	94.579
		5	95.481
Fixed - Free	V	1	6.6758
		2	21.587
		3	23.534
		4	41.75
		5	73.825
	VI	1	6.6697
		2	21.255
		3	23.445
		4	41.71
		5	73.115
	VII	1	6.6694
		2	21.445
		3	23.478
		4	41.738
		5	74.571
	VIII	1	6.6727
		2	21.414
		3	23.547
		4	41.73
		5	73.809

Table 10. Natural frequencies castellated beam with profil IPE240 (Hz)

Support Condition	Model	Mod	Natural frequency (HZ)
Fixed - Fixed	IX	1	55.45
		2	68.795
		3	149.05
		4	151.47
		5	173.98
	X	1	55.486
		2	68.834
		3	142.7
		4	149.13
		5	174.23
	XI	1	55.518
		2	68.833
		3	149.12
		4	150.4
		5	173.91
	XII	1	55.434
		2	68.77
		3	149.22
		4	151.78

		5	173.97
Fixed- Pinned	IX	1	22.008
		2	38.282
		3	80.02
		4	116.88
		5	121.58
	X	1	22.004
		2	38.288
		3	79.975
		4	112.08
		5	121.44
	XI	1	22.011
		2	38.312
		3	80.044
		4	116.3
		5	121.59
	XII	1	22.039
		2	38.267
		3	79.977
		4	117.08
		5	121.62
Fixed - Free	IX	1	8.7129
		2	22.01
		3	30.967
		4	54.287
		5	80.033
	X	1	8.7232
		2	22.005
		3	30.64
		4	54.335
		5	79.986
	XI	1	8.7171
		2	22.012
		3	30.925
		4	54.343
		5	80.049
	XII	1	8.72
		2	22.041
		3	31.018
		4	54.302
		5	79.987

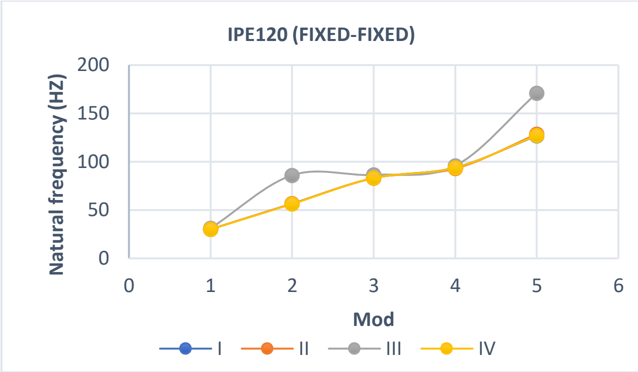


Fig. 14: Comparison of the natural frequencies for F-F with profile IPE 120 of castellated steel beams.

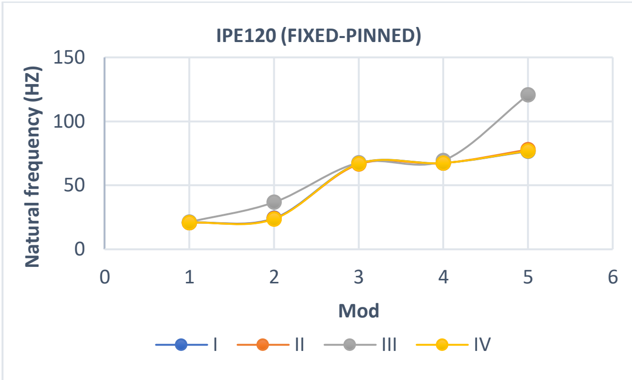


Fig. 15: Comparison of the natural frequencies for F-P with profile IPE 120 of castellated steel beams.

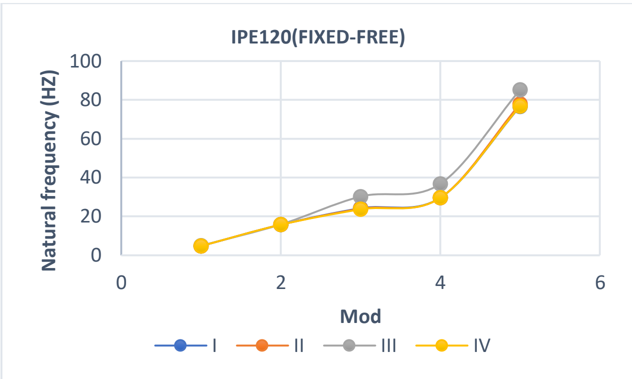


Fig. 16: Comparison of the natural frequencies for F-FR with profile IPE 120 of castellated steel beams.

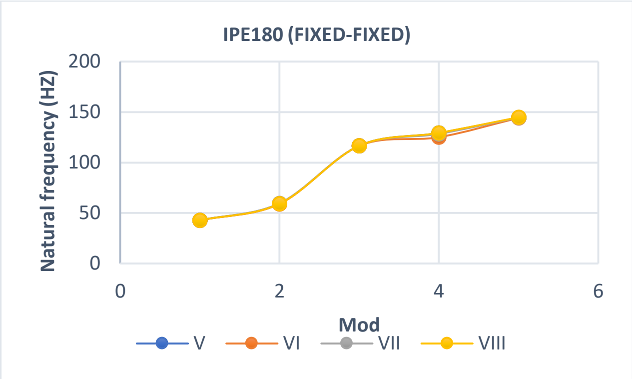


Fig. 17: Comparison of the natural frequencies for F-F with profile IPE 180 of castellated steel beams

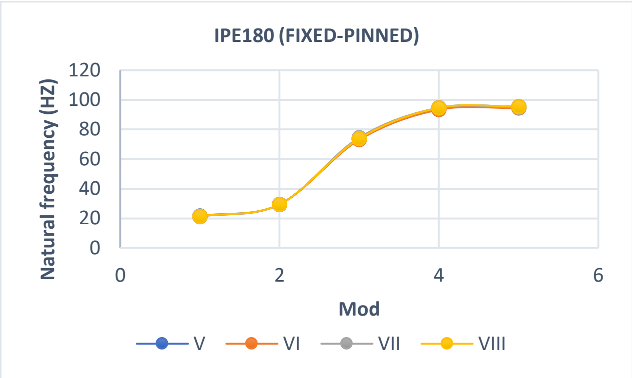


Fig. 18: Comparison of the natural frequencies for F-P with profile IPE 180 of castellated steel beams

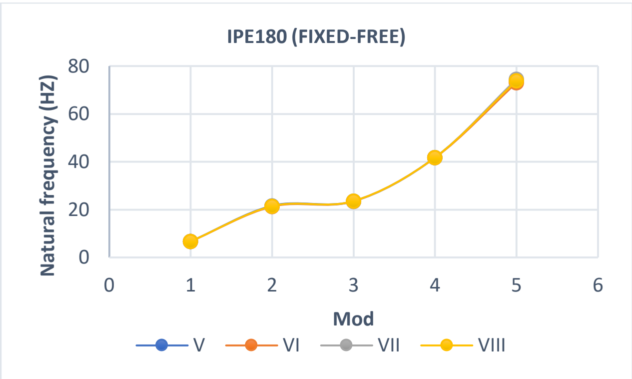


Fig. 19: Comparison of the natural frequencies for F-P with profile IPE 180 of castellated steel beams

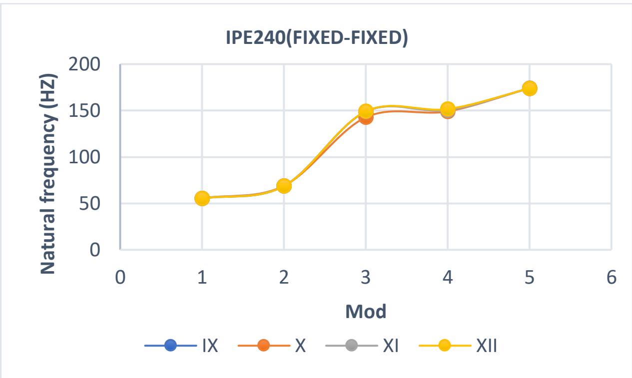


Fig. 20: Comparison of the natural frequencies for F-F with profile IPE 240 of castellated steel beams

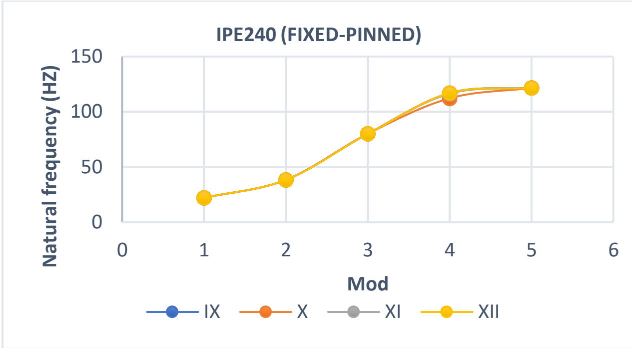


Fig. 21: Comparison of the natural frequencies for F-P with profile IPE 240 of castellated steel beams

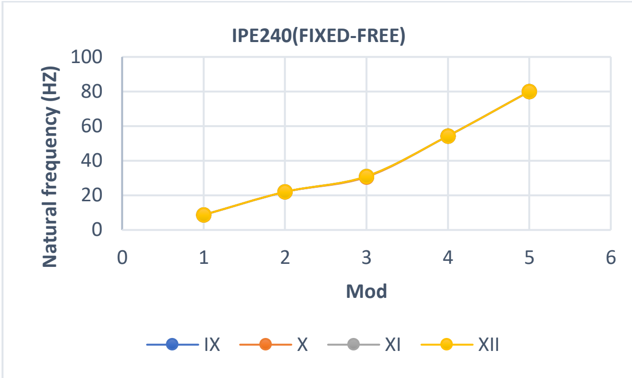
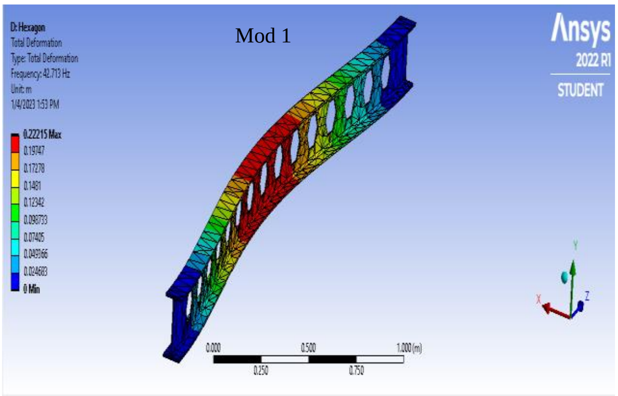
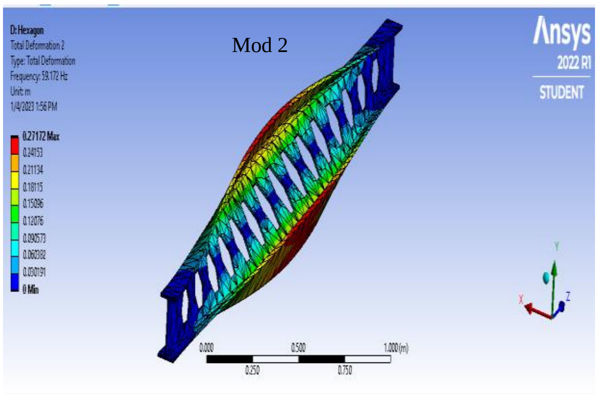
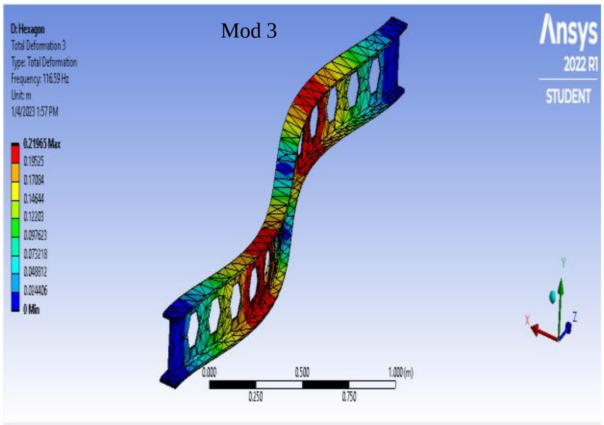


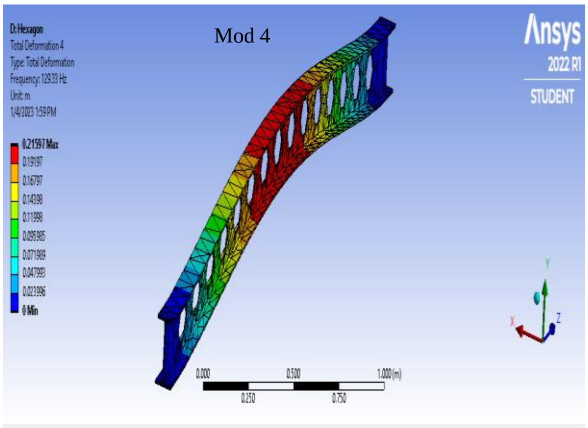
Fig. 22: Comparison of the natural frequencies for F-FR with profile IPE 240 of castellated steel beams

The mod shapes for Fixed-Fixed are presented for profile IPE180 case VIII in fig.23









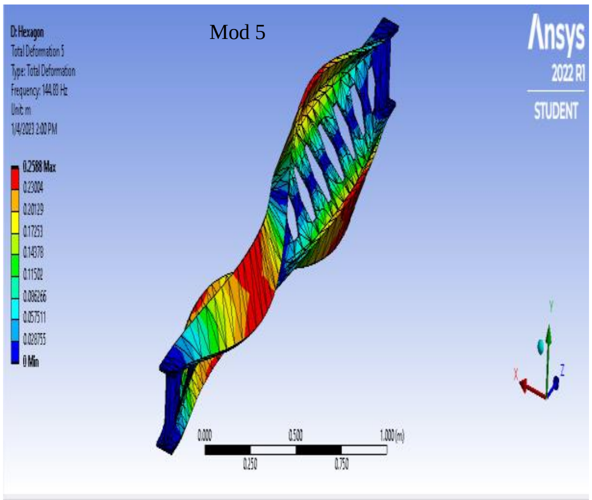
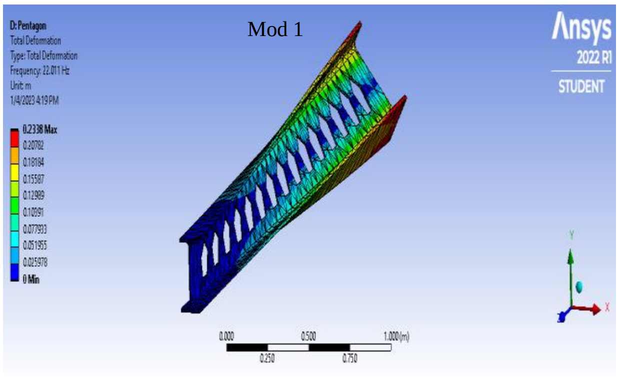
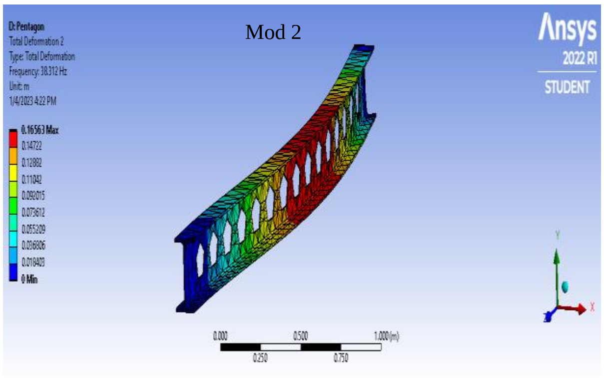
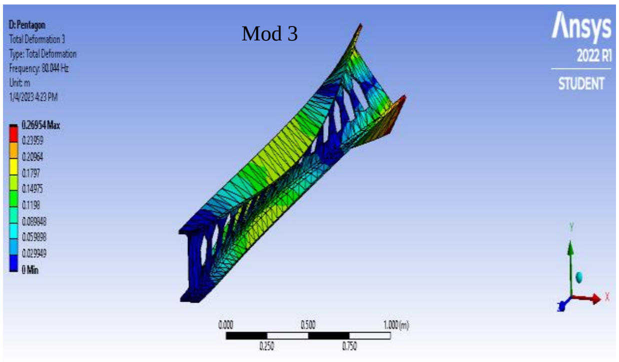


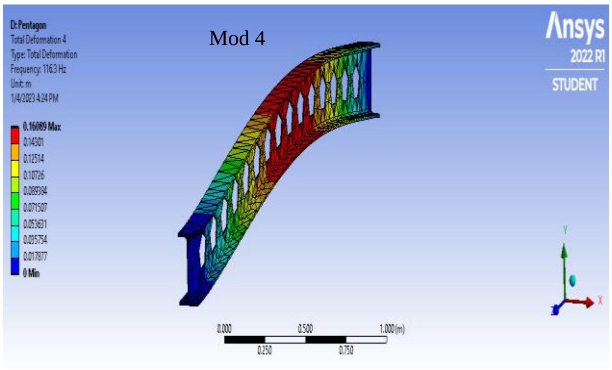
Fig. 23: The mod shapes for fixed – fixed castellated beam with profil IPE180 case VIII

The mod shapes for Fixed-Pinned are presented for profile IPE240 case XI in Fig.24









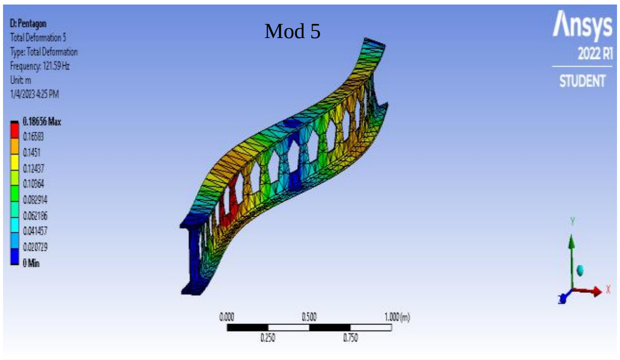
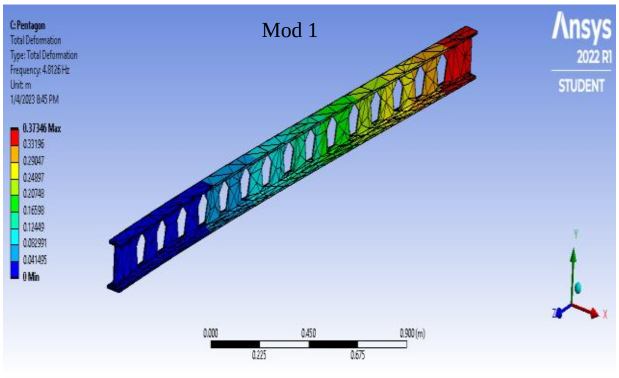
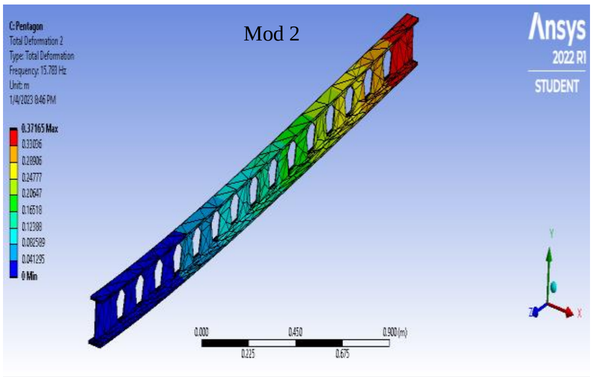
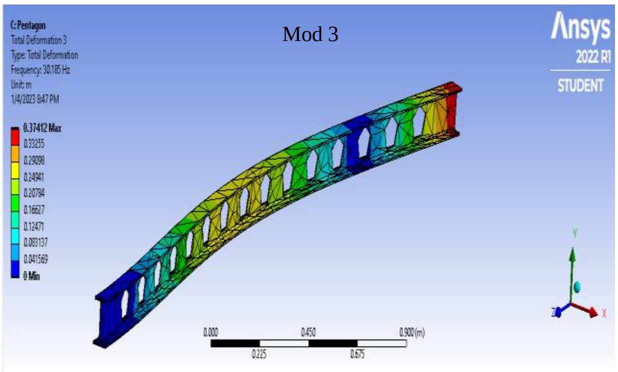


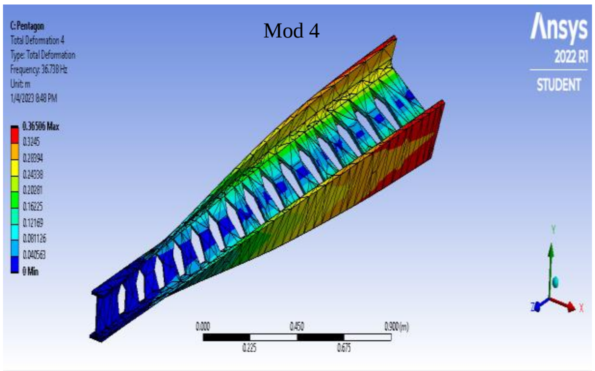
Fig. 24: The mod shapes for fixed – pinned castellated beam with profil IPE240 case XI

The mod shapes for Fixed-Free are presented for profile IPE120 case III in Fig.25









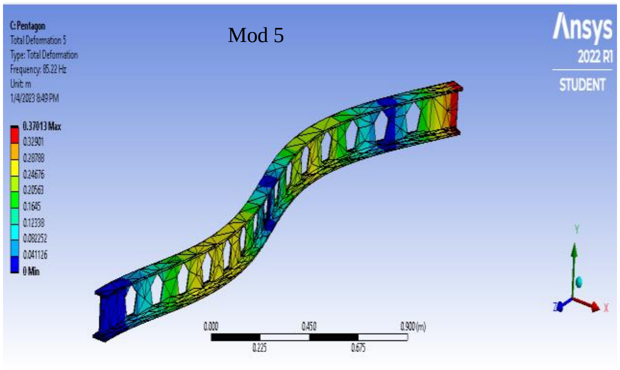


Fig. 25: The mod shapes for fixed – free castellated beam with profil IPE120 case III

4. Conclusions

In this study, the effect of web opening type on the static and dynamic behavior of castellated beams was investigated theoretically. The ANSYS Workbench program, based on the finite element method, was used in the analysis. Three-dimensional finite element models of the considered structural elements were established. Four different types of spaces were used: circular, square, pentagonal, and hexagonal. In order to perform the static and dynamic analysis of castellated beams made of IPE120, IPE180, and IPE240 profiles, fixed-fixed, fixed-pinned, and fixed-free boundary conditions are used. The most important results of the study are summarized below.

Static analysis:

The largest total displacements in the castellated beam occur in the case of a square web opening, and the smallest total displacements occur when a pentagon web opening is used in profile IPE120, while the smallest displacements occur when a hexagon web opening is used in other profiles. When hexagonal web opening geometry is used, the total displacement values of castellated beams with circular web openings are close to each other. As expected, the largest total displacements occurred in the fixed-free state.

Von-Mises and maximum shear stress values are affected by the type of web opening as well as the type of profile and support conditions. The largest von Mises stress values for IPE120 and IPE180 profiles occur when a hexagonal opening is used. The largest von Mises stress values for the IPE240 profile occur when a square opening is used.

The maximum shear stress values for the IPE 120 profile are largest in castellated beams with a hexagonal opening. For the IPE 180 profile, the largest maximum shear stress values occur when a pentagon opening type is used for fixed-fixed support, while the largest maximum shear stress values occur when a hexagon opening is used for fixed-pinned and fixed-free support. For the IPE 240 profile, the largest maximum shear stress with a square opening is used.

Dynamic analysis:

The influence of the web opening type and boundary conditions on the natural frequencies is investigated, and the following results can be concluded. Higher frequencies were recorded at F-F beams, and lower frequencies were recorded at F-FR beams. The type of web opening is essential for the value of the free vibration characteristics. The highest free vibration responses of IPE120 are observed while the pentagon web opening is used. For all other profiles it has seen the geometry of the web opening does not have any significant influence on the free vibration frequencies. Also the amplitude of vibrations is not effected by the type of the web opening.

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