E-ISSN: 2528-388X
P-ISSN: 0213-762X

INERSIA
Vol. 22, No. 1, May 2026

Effects of Square Body Openings in Castellated Steel Beams on Stiffness and Natural Frequencies

Guntur Nugroho* and Fayza Aughitri

Civil Engineering Program, Universitas Muhammadiyah Yogyakarta, Yogyakarta 55183, Indonesia

Keywords:
Castella beams
Natural Frequency
Abaqus CAE
Moment of Inertia

ABSTRACT

Castella beams are one of the steel structural innovations that have the advantage of reducing weight without sacrificing bending stiffness, so they are widely used in long-span structures. This study aims to analyze how square-shaped openings affect the natural frequency of castellated beams, considering different numbers of openings and various support conditions. The research was conducted numerically using Abaqus CAE software and theoretically using Stokey's theory. Five models were tested with the number of openings between 9 and 19 and three different support conditions: fixed-fixed, fixed-pinned, and pinned-pinned. Results show that increasing the number of openings significantly decreases the mass and stiffness of the beam, which impacts the natural frequency values of the structure. The analysis results using Stokey's theory yield natural frequency values that tend to be higher than the numerical analysis because it does not consider the local weakening effect due to the openings. The difference between the results of the two approaches reaches 7-904 Hz, depending on the configuration and vibration mode analyzed. The difference is more striking at higher vibration modes because the concentration of local deformation is more dominant. Modifying Stokey's formula by adding an inertial correction coefficient proved to predict the downward trend of the natural frequency more accurately. The results show that the natural frequency values at low vibration modes are in high agreement. Therefore, it is recommended to use this approach, especially in low-vibration mode analysis.

1. Introduction

One type of steel beam that is increasingly popular in the construction world and is widely used in various structural projects is the castellated beam. Steel beams with openings in the body were first applied in construction during World War II to reduce the cost of building steel structures [1]. Castellated beams are designed with various shapes of body openings, including circular, hexagonal, rectangular, diamond, and pentagonal. Body openings in beams extend pipes, cables, and other services across the beam. In modern structural applications, castellated steel beams (CSBs) are used for long-span construction [2] - [3]. Castella steel beams are widely used because they offer excellent structural performance, with advantages such as light weight, ease of construction, adequate strength, and economical use of materials [4]. Lighter beams are easier to handle and install, thus reducing construction time and cost [5] - [6]. With a higher body geometry yet still light mass, castellated beams can resist bending loads more effectively than conventional steel beams. This feature improves structural efficiency and makes it a more economical solution as it can reduce overall construction costs [7]. Structural engineers are not only responsible for designing the safety and serviceability of a structure but also for ensuring that the structure functions according to the needs of its use [8].

The conducted a research analytical study on the behavior of cellular steel beams subjected to lateral torsional buckling to evaluate the effect of various loading conditions on structural stability. Simulations were carried out using ABAQUS software [9]. Researched to analyze the performance of castella composite beams as multi-story buildings carried out experimentally through cyclic loads on beam-column portal models [10]. Research

---

*Corresponding author.
E-mail: guntur.nugroho@umy.ac.id

https://doi.org/10.21831/inersia.v21i2.87871
Received 01 July 2025; Revised 04 May 2026; Accepted 06 May 2026

conducted aims to analyze stress in castella steel beams at web joints with beam plates with hexagonal, octagonal, and diamond openings [7].

The conducted this study investigating the instability of castellated beams under bending and analyzing the interaction between bending modes using the Direct Strength Method (DSM) with a hexagon-shaped opening type [11]. The conducted a study to evaluate the effect of CFRP stiffeners on the load capacity of beams with diamond and hexagonal shaped openings [12]. Research focused on determining the load-carrying capacity and deflection values by comparing hexagonal, circular, square, and diamond openings was conducted by [13]-[14]. Research analyzed the effect of opening height variations on castellated beams using the Reduced Beam Section (RBS) method. This study focused on determining the optimal opening height based on the evaluation of stress, strain, deflection, and structural stiffness [15]. A study aimed at determining the use limit between string and beam-string theory through the ratio parameter of moment of inertia to cable length (I/L), and to identify the effect of bending stiffness on the natural frequency of the cable. The analysis was carried out using numerical methods and experimental testing [16].

Research conducted [17] - [18] discussed the effect of deformation on natural frequency values and rotary inertia in the dynamic response of castella beams. The study found that at higher vibration modes, the influence of shear deformation on frequency reduction becomes increasingly dominant. This indicates that the contribution of shear force cannot be ignored, especially when the structure is subjected to excitation at high frequencies. Meanwhile, rotary inertia is known to decrease the value of vibration frequency. However, the negative influence of the rotary inertia can be compensated by openings in the beam body, which generate additional shear effects that stabilize the frequency. This finding confirms the importance of considering the interaction between swivel inertia and opening configuration in the dynamic analysis of castella beams [17] - [18]. This study examines the effect of the moment of inertia in castella steel beams on natural frequency values by considering circular body openings. The methods used include a numerical approach using software and theoretical analysis based on Stokey Theory. The results showed a difference between the natural frequency values obtained from the two methods [19].

This indicates that the numerical approach could capture the effect of opening geometry details more accurately than the theoretical calculation. Based on previous studies, this research aims to analyze the effect of square-shaped openings in the body of castella beams on the natural frequency values under different boundary conditions, namely fixed-fixed, fixed-pinned, and pinned-pinned. In addition, this study also aims to compare the results of natural frequencies obtained through theoretical approaches using the Stokey formula with the results of finite element-based numerical simulations conducted using Abaqus CAE software.

2. Research Methods

2.1 Materials

In this study, IWF steel material with cross-sectional dimensions of 200 × 100 × 8 × 5.5 mm and a length of 5 meters was used. The openings used are square with a size of 100 mm × 100 mm placed on the body of the profile, according to the illustration shown in Figure 1. The steel material used has an elastic modulus (E) of 200,000 MPa, a density (ρ) of 7850 kg/m³, and a Poisson's ratio (v) of 0.3. This study tested five model variations: a model without openings and body openings with a spacing distance of 155 mm, 200 mm, 325 mm, and 410 mm, and the number of body openings ranging from 9 to 19 openings. All models were compared under three support conditions: fixed-fixed, fixed-pinned, and pinned-pinned. Each model's steel weight per meter decreased as the number of openings increased, from 21.3 kg/m (without openings) to 6.00 kg/m (for 19 openings). Complete data on the model configurations are shown in Table 1.

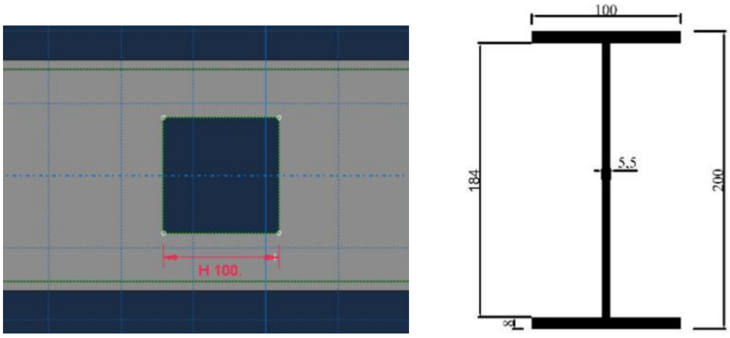


Figure 1. Typical beam section details.

Table 1. Detail of specimens

Support	Modelling	Distance Between Openings (mm)	Opening Diameter (mm)	Number of Openings	Steel Weight (Kg/m)
Fixed - Fixed	M1	-	-	-	21.3
	M2	410	100	9	14.05
	M3	325	100	11	12.44
	M4	200	100	16	8.42
	M5	155	100	19	6.00
Fixed - Pinned	M1	-	-	-	21.3
	M2	410	100	9	14.05
	M3	325	100	11	12.44
	M4	200	100	16	8.42
	M5	155	100	19	6.00
Pinned - Pinned	M1	-	-	-	21.3
	M2	410	100	9	14.05
	M3	325	100	11	12.44
	M4	200	100	16	8.42
	M5	155	100	19	6.00

2.2 Method

This study conducted a numerical analysis using Abaqus CAE software to obtain accurate and detailed results. The model geometry was constructed based on the dimensions of a steel profile with a square-shaped opening placed right in the center of the beam body to evaluate its effect on the dynamic response of the structure. Before the analysis was performed, a convergence test was applied to the element size to ensure the results' stability and the model's suitability. The convergence test results showed the stability of the frequency value in the first mode, so the meshing process was carried out with a distance of 150 mm and resulted in 1,514 elements. The elements used are tetrahedral, which is known to be effective in representing complex geometries. In the analysis stage, natural frequency comparisons were made of the five main vibration modes, ranging from mode shape 1 to mode shape 5, to examine changes in dynamic characteristics due to openings in the beam body.

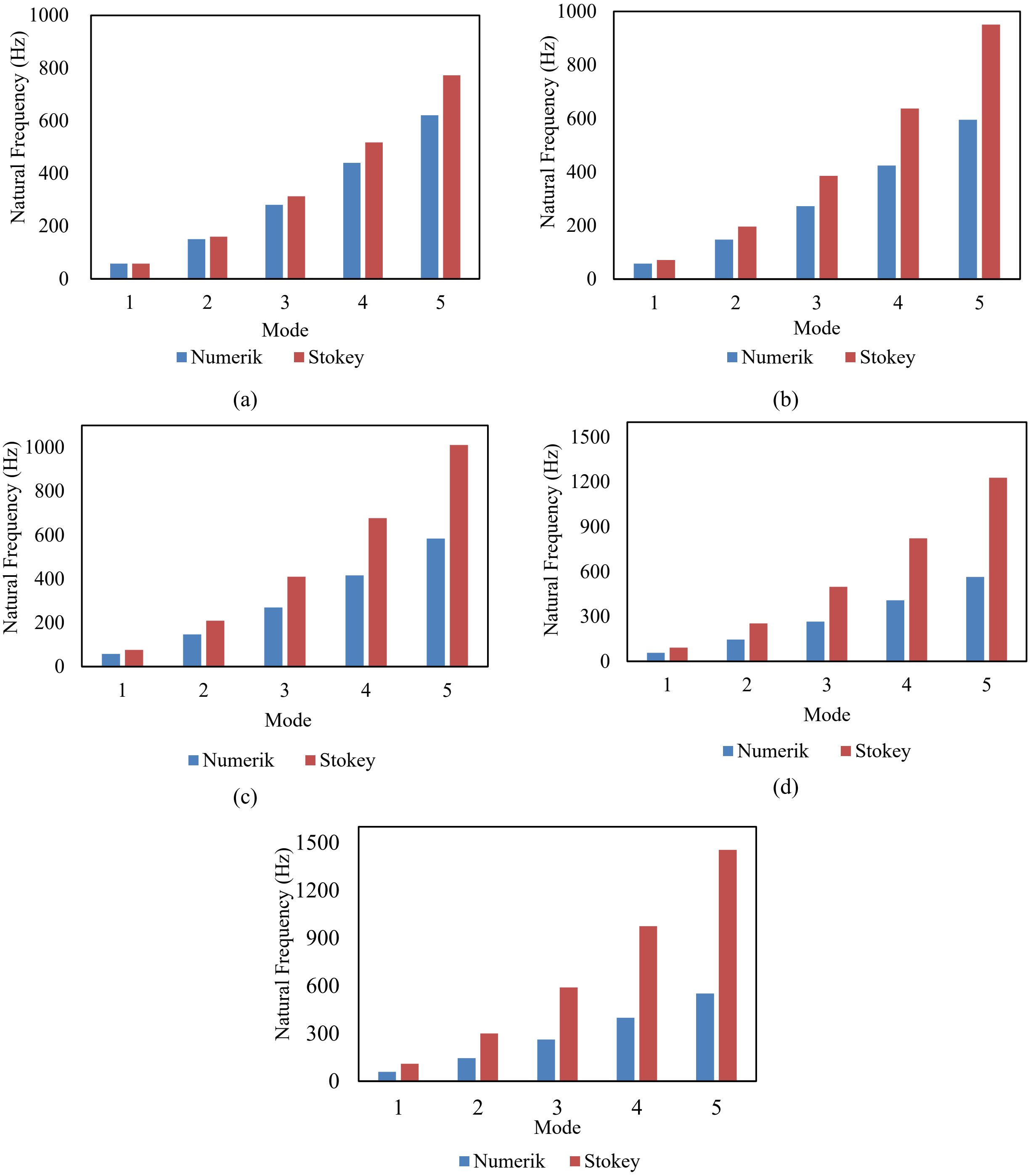
Stokey theory is a mathematical approach in structural dynamics analysis used to determine the natural frequencies and vibration modes of a system. The proposed a formulation for calculating the natural frequency of structural elements as shown in Formula (1) [20].

$$f_n = \frac{k^2}{2\pi L^2}\sqrt{\frac{EI}{m}}\sqrt{1 \pm \frac{FL^2}{EI\pi^2 n^2}} \tag{1}$$

Where f_n is the natural frequency (*Hz*), *L* is the steel length (*m*), *F* is the force (*N*), n is the mode number, *K* is a parameter based on the type of support used, *EI* is the flexural strength (Nm²), and m is the mass (kg/m).

3. Results and Discussion

This study was conducted to analyze the effect of the opening configuration on the castellated profile on the natural frequency of the structure. Based on Table 1, there are 15 models categorized based on the types of fixed-fixed, fixed-pinned, and pinned-pinned support, as well as variations in the number and distance between openings. Model M1 is a beam without openings, so it has the largest steel weight of 21.3 kg/m. Meanwhile, the model with the largest number of openings M5 has the lightest weight of 6.00 kg/m. The distance between openings also plays an important role in determining the dynamic characteristics of the beam. The results of the analysis on the fixed-fixed, fixed-pinned, and pinned-pinned pedestals can be seen in Figure 2 to Figure 4.



(a)

(b)

(c)

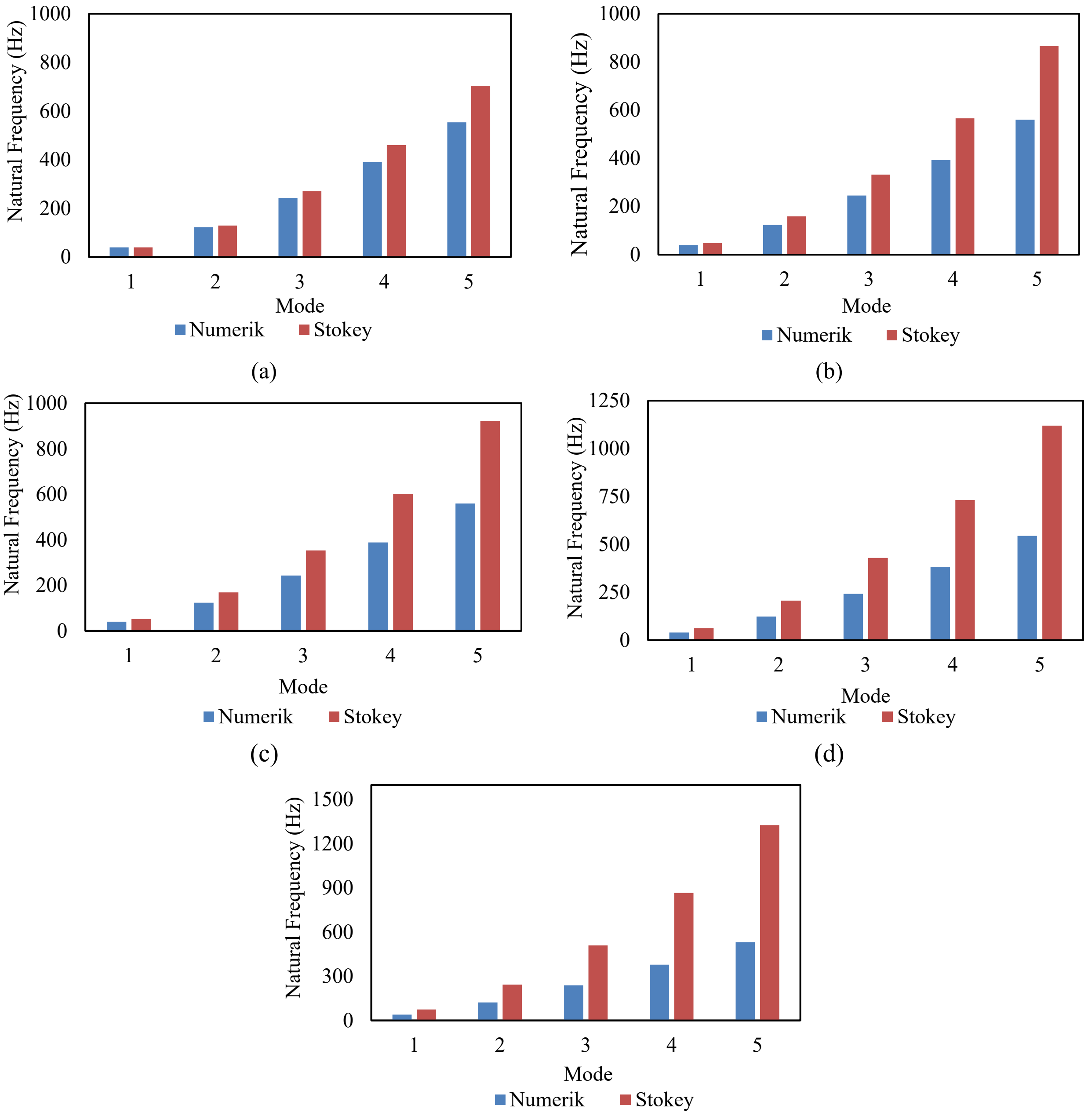
(d)

(e)

Figure 2. (a) M1, (b) M2, (c) M3, (d) M4, and (e) M5 comparison of numerical results and stokey theory on castellated steel beams with varying web openings using fixed-fixed boundary condition

Model M1 shows the same natural frequency value in the first mode between the results of numerical analysis and Stokey's theoretical calculations. This similarity occurs because model M1 has no openings in the profile body, so there is no change in mass or stiffness.

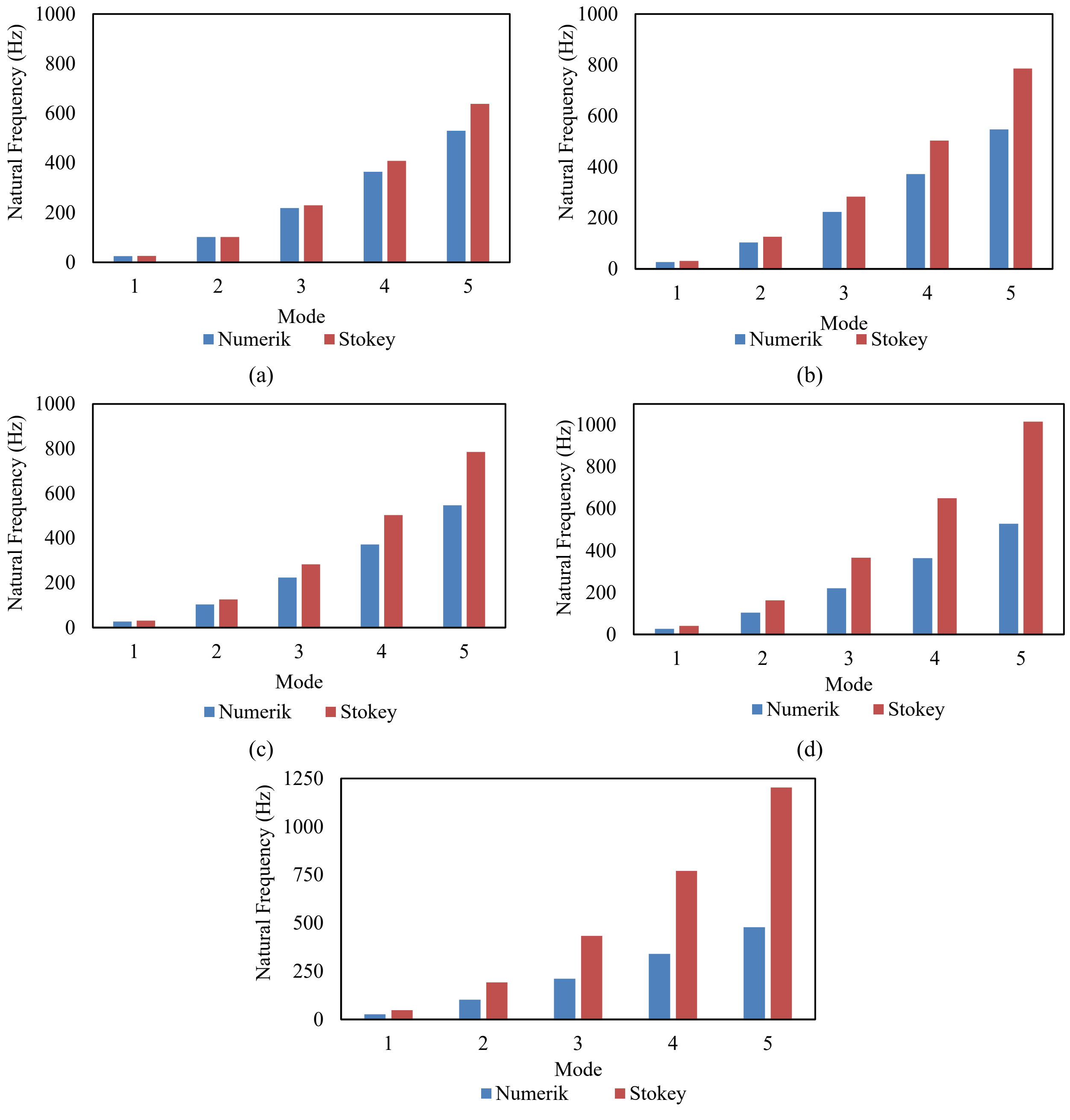
Meanwhile, models M2 to M5 show differences in natural frequency values between the results of numerical analysis and theoretical calculations. The difference in natural frequency values from mode 1 to mode 5 was recorded as 9 Hz to 904 Hz in the fixed-fixed support.



(a) (b) (c) (d) (e)

Figure 3. (a) M1, (b) M2, (c) M3, (d) M4, and (e) M5 comparison of numerical results and stokey theory on castellated steel beams with variations in web openings using fixed-pinned boundary condition

Models M2 to M5 show a difference in natural frequency values between the results of numerical analysis and theoretical calculations using the Stokey approach. The difference was recorded to vary from 9 Hz to 904 Hz under fixed-pinned pedestal conditions. Among all the models tested, model M5 produced the largest difference in natural frequency values.



(a) (b) (c) (d) (e)

Figure 4. (a) M1, (b) M2, (c) M3, (d) M4, and (e) M5 comparison of numerical results and stokey theory on castellated steel beams with variations in web openings using pinned-pinned boundary condition

The pinned-pinned boundary condition exhibits the lowest natural frequency among the three support types when compared to fixed-fixed and fixed-pinned configurations. This is primarily due to the limited ability of the pinned support to resist structural vibrations, resulting in reduced dynamic stiffness. The difference in natural frequency values for models M2 to M5 under this support condition ranges between 11 Hz and 487 Hz.

The analysis based on Stokey's theory resulted in higher natural frequency values than the numerical simulation results for all vibration modes analyzed. Stokey's theory calculates the natural frequencies based on the assumption of uniform distribution of stiffness and mass along the beam length.

This model does not take into account the weakening of the structure due to the presence of openings in the beam body. In contrast, numerical simulations in Abaqus consider geometric influences, including the effects of stress concentration and redistribution of internal forces around openings. In addition, in the numerical model, the steel mass lost due to the openings is also taken into account, resulting in an uneven mass distribution. This condition contributes to the decrease in the resulting natural frequency value. From the mode shape analysis results, it is known that the natural frequency value increases as the mode order increases. However, the difference between theoretical and numerical results also increases at higher modes. This indicates that the influence of local deformation due to the presence of openings is more significant at higher modes of vibration. In the first mode, the vibration is still evenly distributed along the structural element, while in the subsequent modes, the vibration pattern becomes more complex with larger deformations occurring around the opening area.

In addition, based on Stokey's theory, models with smaller spacing between openings, such as M5, tend to have higher natural frequency values than models with larger spacing between openings, such as M2. This phenomenon arises because a larger number of openings in theory is considered not to change the stiffness significantly, while in reality, the local weakening effect is more dominant.

The numerical analysis results show relatively similar natural frequency values between models due to considering the actual stiffness degradation caused by the dense openings. Thus, the results of this discussion confirm that using numerical models provides a more realistic estimation of the exact condition of the structure. Therefore, numerical approaches are highly recommended for designing structures involving complex geometries to obtain more accurate predictions of dynamic behavior.

The difference in values between the results of numerical analysis and calculations using Stokey's theory can be calculated using the formula found in this study. This formula can consider the value of mass and stiffness loss in beams subjected to body openings. Stokey's theoretical approach calculates the reduction in moment of inertia using a coefficient representing the relationship between the percentage reduction in inertia due to the shape and number of openings and the resulting natural frequency value. The percentage reduction in moment of inertia is obtained through calculations based on a specific formula that considers the profile's geometry, the openings' location, and the volume of material lost due to the openings. The percentage reduction in moment of inertia is calculated based on the Formula (2).

$$I_n = I_x - (k \times n) \tag{2}$$

It is the moment of inertia value of the castella beam, *Ix* is the moment of inertia value of the solid steel, *k* is the coefficient 6,664E-07, and *n* indicates the number of openings. The value 6,664E-07 is the coefficient obtained to calculate the moment of inertia for the circular web opening shape. The results of the calculation of the moment of inertia of the castella beam can be seen in Table 2.

After systematically considering and analyzing the correction coefficient values used in Formula (2), the natural frequency values calculated based on modifying the Stokey formula were obtained. This modification helped predict the decreasing trend of the natural frequency in response to the effect of the aperture. The difference between the theoretical calculation based on Stokey's formula and the numerical results obtained from the Abaqus CAE simulation is that the graphs displayed in the analysis show a unidirectional trend pattern.

The theoretical and numerical approaches showed a similar trend in the direction of natural frequency change concerning the variation of the number of openings. The similarity of this pattern confirms that the theoretical approach used is representative enough to describe the general behavior of the structure. In addition, the stiffness correction coefficient *K*, which is included in the calculation through Formula (2), has an important role and is closely related to the applied opening configuration. The geometry of the openings in the primary structural system directly influences the stiffness correction value, which in turn impacts the natural frequency calculation results. Validation of this can be visually observed in Figure 5, which show comparisons between the theoretical and numerical results for various web openings and castellated beam supports.

Table 2. Calculation of moment of inertia of square body opening

Modelling	Number of Openings	Inertia Value of Solid Steel	Coefficient	Castella Steel Inertia Value
M1	-	1.761E-05	6.664E-07	-
M2	9	-	6.664E-07	1.161E-05
M3	11	-	6.664E-07	1.028E-05
M4	16	-	6.664E-07	6.946E-06
M5	19	-	6.664E-07	4.947E-06

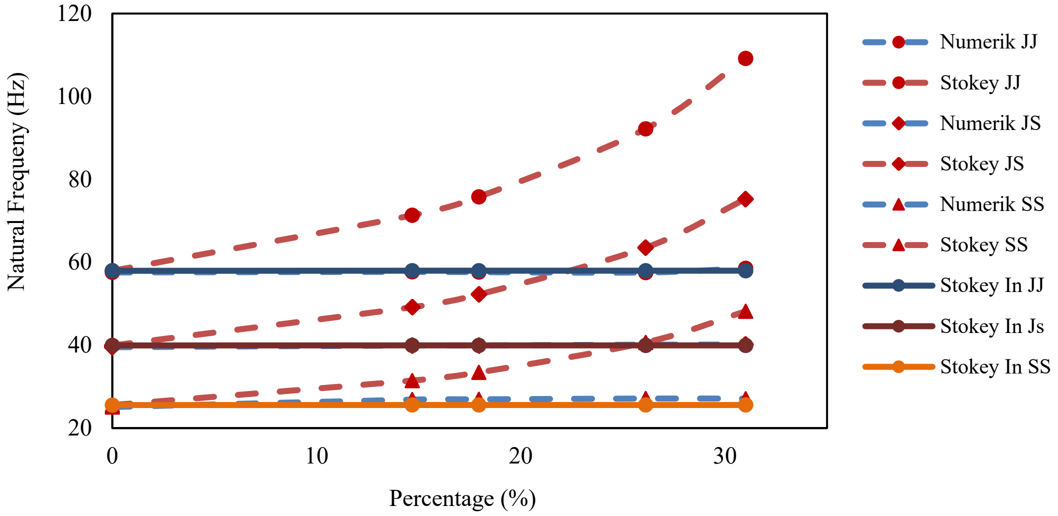


Figure 5. Effect of moment of inertia analysis calculation

The analysis done by [19] found that changing the Stokey theory calculation with coefficients related to the shape and size of the opening affected the natural frequency value. Each variation of opening shape and size has a different effect on the weight and stiffness of the beam. Therefore, it is essential to adjust the analysis to make the results more accurate and represent the actual structural conditions.

4. Conclusions

This study analyzes the effect of square openings in castellated beams on changes in dynamic characteristics, especially natural frequency values, by considering various types of supports. Comparison of natural frequency results was obtained through two approaches, namely numerical methods and theoretical calculations using the Stokey formula.

The openings' configuration significantly affects the castellated beams' mass and stiffness. The more the number of openings, the lighter the mass of the beam and the less the stiffness. This is evident from the comparison between the model without openings (M1), which weighs 21.3 kg/m, and the model with 19 openings (M5), which weighs only 6.00 kg/m. The analysis shows that the natural frequency increases as the number of openings in the beam increases. This increase is more evident and significant in the calculations using Stokey's theory than in the numerical analysis results. The difference is due to Stokey's theoretical approach that does not consider local effects due to the presence of openings, such as mass reduction due to openings. In contrast, the numerical simulation can capture these effects in more detail and more thoroughly.

The natural frequency values based on the numerical analysis show an almost uniform trend in each model. This is due to the ability of numerical analysis to systematically calculate changes in mass and stiffness due to openings in the beam body. Meanwhile, Stokey's theoretical approach cannot thoroughly calculate the mass and stiffness reduction, resulting in significant differences. The numerical simulation results show that the natural frequency values are lower than the theoretical calculation results. The difference between the two methods ranges from 9 Hz to 904 Hz at the fixed-fixed support, 7 Hz to 794 Hz at the fixed-pinned support, and 11 Hz to 487 Hz at the pinned-pinned support. This difference increases at higher vibration modes, indicating the structure's sensitivity to local deformation due to openings.

Modifying Stokey's formula by introducing correction coefficients into the moment of inertia significantly improves the accuracy of natural frequency predictions for castellated beams. By accounting for the number and geometry of web openings, the proposed correction reflects the associated mass and stiffness reductions more realistically. Validation through finite element simulations using Abaqus confirms a strong agreement, particularly in the lower vibration modes. Therefore, this approach is recommended for reliable analytical estimation of natural frequencies in castellated beam design, especially in low-mode vibration analyses.

References

[1] S. G. Morkhade and L. M. Gupta, “Behavior of Castellated Steel Beams: State of the Art Review,” Electron. J. Struct. Eng., vol. 19, no. 1, pp. 39–48, 2019.

[2] V. N. Jadhav, R. R. Kurlapkar, and A. P. Patil,

"Assessment of Lateral-Torsional Buckling Capacity of Mild Steel Castellated Beam with Sinusoidal Web Openings," Asian J. Civ. Eng., vol. 25, no. 5, pp. 4081–4090, 2024, doi: 10.1007/s42107-024-01032-w.

[3] S. M. Hadeed and A. J. H. Alshimmeri, "Comparative Study of Structural Behaviour for Rolled and Castellated Steel Beams with Different Strengthening Techniques," Civ. Eng. J., vol. 5, no. 6, pp. 1384–1394, 2019, doi: 10.28991/cej-2019-03091339.

[4] T. Theopuspitasari Lu and Y. Afriado, "Analisis Perbandingan Struktur Komposit Pelat Beton Balok Baja Sebelum dan Sesudah Kastela," vol. 9, no. 1, 2026.

[5] S. Mathur, M. Senthilpandian, and K. Karthikeyan, "Static and Dynamic Analysis of Steel Beams with Web Openings," J. Phys. Conf. Ser., vol. 1716, no. 1, 2021, doi: 10.1088/1742-6596/1716/1/012016.

[6] A. J. Mehetre and R. S. Talikoti, "Castellated Steel Beams A Torsional Analysis," Int. J. Eng. Adv. Technol., vol. 9, no. 5, pp. 536–540, 2020, doi: 10.35940/ijeat.e9606.069520.

[7] V. W. Yustisia, B. Suswanto, D. Irawan, and D. Iranata, "The Structural Behavior of Castellated Beam with Shape Variation Using Finite Element Methods," IOP Conf. Ser. Mater. Sci. Eng., vol. 930, no. 1, 2020, doi: 10.1088/1757-899X/930/1/012051.

[8] H. El-Dehemy, "Static and Dynamic Analysis Web Opening of Steel Beams," World J. Eng. Technol., vol. 05, no. 02, pp. 275–285, 2017, doi: 10.4236/wjet.2017.52022.

[9] F. P. V. Ferreira, A. Rossi, and C. H. Martins, "Lateral-Torsional Buckling of Cellular Beams According to the Possible Updating of EC3," J. Constr. Steel Res., vol. 153, pp. 222–242, 2019, doi: 10.1016/j.jcsr.2018.10.011.

[10] M. Junus, "Castella Composite Beam Testing to be Used as A Structural Element of Multistorey Buildings in Eastern Indonesian Region," ARPN J. Eng. Appl. Sci., vol. 11, no. 1, pp. 731–736, 2016.

[11] C. M. Weidlich, E. D. Sotelino, and D. C. T. Cardoso, "An Application of the Direct Strength Method to the Design of Castellated Beams Subject to Flexure," Eng. Struct., vol. 243, no. April, p. 112646, 2021, doi: 10.1016/j.engstruct.2021.112646.

[12] S. S. Mali and P. D. Kumbhar, "Comparative Study on Behaviour of Castellated Beams with Diamond- and Hexagonal-Shaped Openings Using CFRP Stiffeners," Asian J. Civ. Eng., vol. 25, no. 1, pp. 939–952, 2024, doi: 10.1007/s42107-023-00823-x.

[13] S. S. Patil and P. D. Kumbhar, "Comparative Study on the Behaviour of Castellated Beams Provided With Hexagonal, Circular, and Diamond-Shaped Web Openings," Asian J. Civ. Eng., vol. 25, no. 1, pp. 359–369, 2024, doi: 10.1007/s42107-023-00780-5.

[14] A. Sayyad and A. Shaikh, "Estimation of Deflections in Cantilever and Fixed Castellated Beams with Hexagonal, Square and Circular Openings," Tec. Ital. J. Eng. Sci., vol. 64, no. 1, pp. 118–127, 2020, doi: 10.18280/ti-ijes.640118.

[15] N. H. Aswad, D. Pongsimpin, T. Asikin, R. M. Rachman, Tachrir, and M. Tumpu, "Analysis of the Effect of High Opening Variation on the Performance of Castellated Beams using the Reduced Beam Section Method," Eng. Technol. Appl. Sci. Res., vol. 15, no. 2, pp. 22059–22064, 2025, doi: 10.48084/etasr.10260.

[16] G. Nugroho, "Natural Frequency of Tension Cable Based on Moment Inertia to Span Ratio: Determination Using Analytical, Numerical and Experimental Study," Int. J. Sustain. Constr. Eng. Technol., vol. 11, no. 2, pp. 89–100, 2020, doi: 10.30880/ijscet.2020.11.02.010.

[17] J. K. Chen, B. Kim, and L. Y. Li, "Analytical approach for transverse vibration analysis of castellated beams," Int. J. Struct. Stab. Dyn., vol. 14, no. 3, pp. 1–10, 2014, doi: 10.1142/S0219455413500715.

[18] J. Z. Gu, "Free Vibration of Castellated Beams with Web Shear and Rotary Inertia Effects," Int. J. Struct. Stab. Dyn., vol. 14, no. 6, pp. 19–21, 2014, doi: 10.1142/S0219455414500114.

[19] F. Aughitri, G. Nugroho, and A. Jamadin, "Dynamic Behavior of Castella Beams : Effect of Web Openings on Stiffness at Natural Frequencies," vol. 28, no. 1, pp. 77–89, 2025.

[20] W. . Stokey, Vibration of systems having distributed mass and elasticity: chapter. 1988.