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Dynamic Behavior of Castella Beams: Effect of Web Openings on Stiffness at Natural Frequencies

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Castella Beam, Stokey's Theory, Finite Element Analysis Method, Natural Frequency

Abstract
Steel is widely applied in construction due to its high strength, durability, and flexibility, making it ideal for structural systems such as trusses and portals that span large distances and carry significant loads. Castella beams, with their characteristic web openings, represent a development in steel structural systems that enhances material efficiency. This study investigates the effect of web openings in Castella beams on the implementation of vibration-based structural health monitoring. The method relies on natural frequency as an indicator of internal stresses, applied forces, and structural defects. Key parameters affecting natural frequency include support conditions, mode shapes, length, elastic modulus, mass, and moment of inertia. This research employs numerical modeling using ABAQUS and analytical estimation based on Stokey's Theory. The test specimens consist of International Wide Flange (IWF) and Castella beams with varying numbers of openings. Results show that the natural frequency In the first mode of natural frequency the average value difference is 4 Hz and the highest mode of natural frequency is 227 Hz. Body openings in Castella beams are found to increase natural frequency; however, analytical methods such as Stokey's Theory are limited in capturing the influence of modified mass and stiffness distributions.

INTRODUCTION

Steel is a widely used construction material that is efficient, durable, and malleable. The type of steel profile used in construction innovation is the International Wide Flange (IWF) steel profile. Castellated steel beams are an innovation with IWF profiles designed to increase structural efficiency and strength through the manufacturing process of cutting and recombining IWF profiles, thus it creates regular web openings. The Skoda factory in Pilsner manufactured castella beams which were traded for the first time in the UK in the 1930s, it marked a significant advance in the steel construction industry. Castellated beams have a lighter mass, therefore they are widely applied to beam and column structural elements (De'Nan et al., 2017; Deepha et al., 2020; Yustisia et al., 2020). Castellated steel is commonly used in parking lots, large halls, stadiums, industrial buildings, warehouses, high-rise buildings, and other kinds of buildings (Nawar et al., 2020; Rusli et al., 2018). Studies on body opening configurations in castellated beams were completed in the United States and Canada in the early 1960s involving opening shapes, including square, rectangular, circular, hexagonal, honeycomb, octagonal, diamond, and hexagonal with truncated corners (De'Nan et al., 2017; Yustisia et al., 2020). Opening geometries are generally more often in circular and hexagonal shapes (AKGÖNEN et al., 2020). Research on the development of castellated beams using experimental and finite element numerical methods has been conducted since the 1980s (Gu, 2014). Investigations have been conducted to analyze the Vierendeel mechanism failure of hollow cell steel beams (CSBs) with web openings, as well as propose a practical design method using the modified moment-shear (M-V) interaction equation (Tsavdaridis & D'Mello, 2012; Wang et al., 2014). The static behavior of castellated beams was thoroughly examined, focusing on the hexagon-shaped web opening configuration (DOORI & NOORI, 2021).

Various studies have been conducted to analyze the collapse of steel beams with circular, square, and rectangular web openings, including failure modes, load-deflection behavior, and stress concentration related to the size of the openings, shape, and position (Morkhade & Gupta, 2017). Other researches also analyzed the effect of oval-shaped openings (Setiawan et al., 2018), the impact of circular openings with variations in diameter (MaulanaIlham et al., 2018), hexagonal openings (Frans et al., 2017), and rectangular openings with diagonal stiffeners (Rusli et al., 2018). In addition, the static and dynamic behaviors of castellated steel beams have been investigated, including deflection, stress, shear stress, amplitude, and natural frequency (Mathur et al., 2021), analysis of the ratio of body opening to the web perforation thickness and dimensions (Abdulkhudhur et al., 2020), the effect of dynamic loads on castellated beams with cantilevered supports (Lotfollahi-yaghin & Ahmadi, 2008), and the effect of openings on displacement, stress distribution, and free vibration with a variety of supports such as fixed-fixed, fixed-pinned, and fixed-free (Mezher et al., 2023). The effect of the beam's behavior-to-length ratio (I/L) on the natural frequency value has also been studied (Nugroho, 2020).

Researches on castella beams under static conditions, including analysis of compressive strength, tensile strength, shear force, and displacement, have been conducted by several researchers, including (De’Nan et al., 2017; Deepha et al., 2020; DOORI & NOORI, 2021; Frans et al., 2017; MaulanaIlham et al., 2018; Morkhade & Gupta, 2017; Nawar et al., 2020; Rusli A. et al., 2019; Rusli et al., 2018; Wang et al., 2014; Yustisia et al., 2020). Researches on dynamic conditions, such as natural frequency and amplitude analysis of castella beams, have been conducted by (Gu, 2014; Lotfollahi-yaghin & Ahmadi, 2008). Researches that included static and dynamic analysis of castella beams have conducted by (Abdulkhudhur et al., 2020; Mathur et al., 2021; Mezher et al., 2023). Research on castellated steel beams at natural frequency values with variations in the number of web openings on mass and inertia parameters has never been conducted. This study aims to analyze the effect of changes in mass and stiffness of castella beams on natural frequency.

MATERIALS AND METHODOLOGY

Materials

This study uses IWF profile steel material 200 × 100 × 8 × 5.5 mm with a circular opening type as shown in Figure 1. Elastic modulus E: 200,000 MPa, shear modulus G: 80,000 MPa, Poisson's ratio μ: 0.3, and density ρ: 7.9 kg/cm³. The data on tension and strain of steel tensile test results under the ASTM E 8M-04 standards are taken from the research of (Setiawan et al., 2018). The test specimens consisted of 15 beams with a length of 5000 mm, a body opening diameter of 100 mm, and various fixed-fixed, fixed-pinned, and pinned-pinned ends. The details of the cross-sectional and web opening sizes are shown in Figure 1. Details of the test specimen variations are shown Table 1.

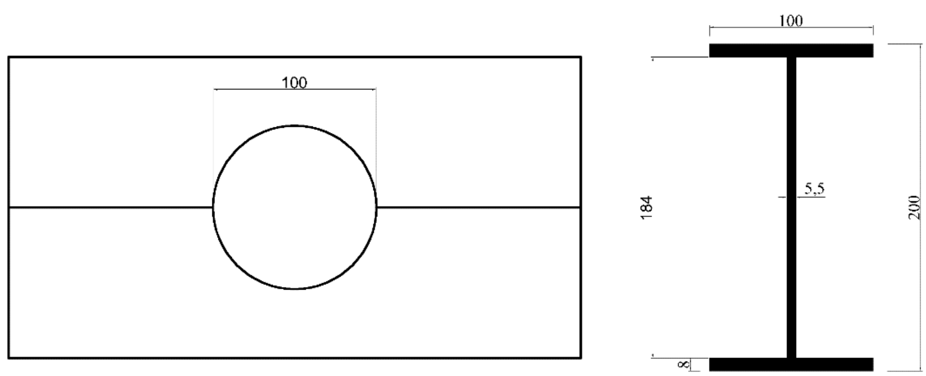


Figure 1. Cross section

Table 1. Details specimens

Support	Modelling	Distance Between Openings (mm)	Opening Diameter (mm)	Number of Openings	Steel Weight (Kg/m)
Fixed-fixed	FF1	-	-	-	21,3
	FF2	410	100	9	18,17
	FF3	325	100	11	17,48
	FF4	200	100	16	15,47
	FF5	155	100	19	14,69
Fixed-pinned	FP1	-	-	-	21,3
	FP2	410	100	9	18,17
	FP3	325	100	11	17,48
	FP4	200	100	16	15,47
	FP5	155	100	19	14,69
Pinned-pinned	PP1	-	-	-	21,3
	PP2	410	100	9	18,17
	PP3	325	100	11	17,48
	PP4	200	100	16	15,47
	PP5	155	100	19	14,69

Methodology

In structural dynamics, the natural frequency of a system is an important parameter that determines its response to vibration excitation. Based on the Stokey's theory, the natural frequency of a beam is affected by the moment of inertia, mass distribution, and forces. When applied to castellated beam systems, the theory shows that an increase in the moment of inertia, which contributes to an increase in beam stiffness, will generally cause the natural frequency to increase. The beam's mass exerts the opposite effect, where an increase in mass tends to decrease the natural frequency due to the rise in mass inertia. One method of natural frequency calculation that also considers the effect of axial loads has been introduced by (Stokey, 1988).

Natural frequency is an important parameter observed in structural health monitoring activities. It is intended that the structure's natural frequency is not the same as the natural frequency of the load, therefore the structure avoids resonance. The analytical theory of natural frequency used in this study is based on (Stokey, 1988), as shown in Equation 1.

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

Where fn 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).

Numerical modeling of castellated steel beams was carried out using ABAQUS CAE 2022 application with a three-dimensional (3D) model approach. Material data was entered according to specifications and gravity force was included in the loading phase to ensure a realistic and accurate simulation of conditions. The support conditions were modeled using idealized support types. Convergence tests were performed using the mesh count parameter to ensure the stability of the natural frequency values. The results are declared convergent when the addition of elements no longer produces significant changes in the calculation results. Once the convergence condition is reached, the numerical results are compared with the analytically obtained natural frequency values to ensure the validity of the numerical method used. The mesh used is tetrahedral (tet) with an element size of 150 mm, resulting in 1514 elements. The convergence test results are shown in Figure 2.

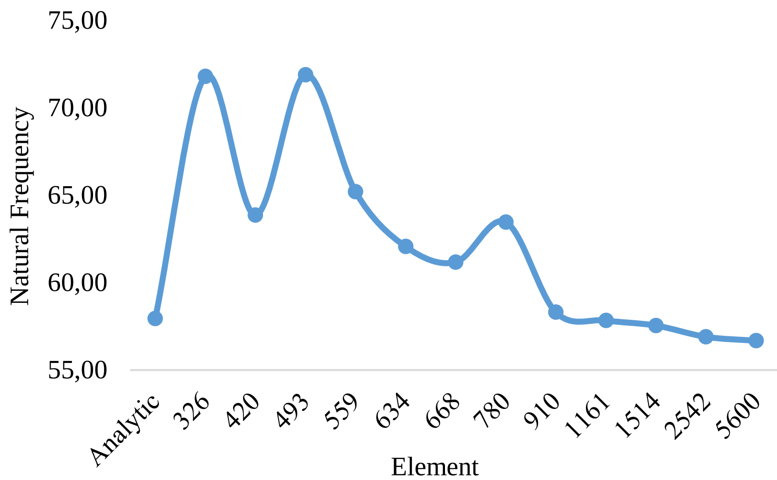


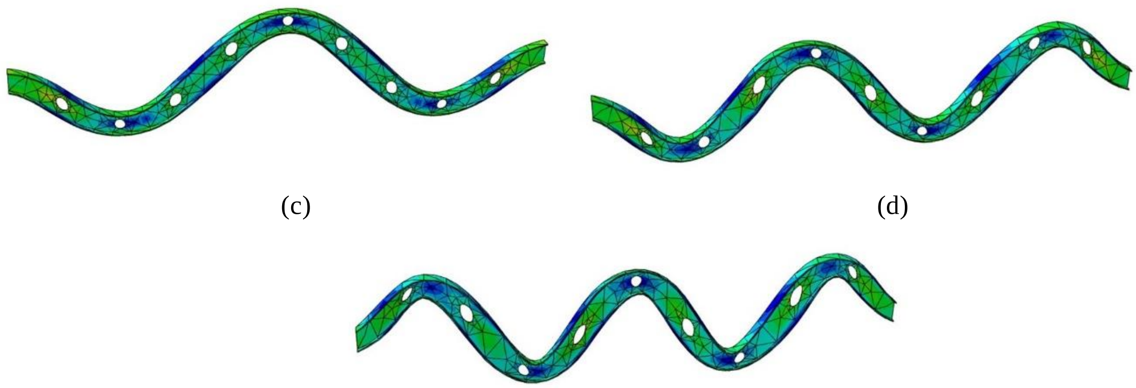
Figure 2. Convergence test

RESULTS AND DISCUSSION

A dynamic analysis study of castellated beams was conducted using 15 different models showed in Table 1. The variations included the distance between openings and the types of support, which were analyzed using the ABAQUS CAE 2022 application. The results obtained from the numerical analysis included natural frequencies and mode shapes. The mode shapes used to review the natural frequencies includes mode shape 1 to mode shape 5, as shown in Figure 3.

From the analysis, it could be concluded that web openings with a circular shape in the modeling of castellated steel beams affect the natural frequency. The more web openings, the more the mass of the castellated steel beam decreases and the natural frequency value increases. It can be seen from the Stokey theory formula in equation (1) that the natural frequency value is inversely proportional to the square root of the mass. If the moment of inertia value decreases, the natural frequency value will decrease because the moment of inertia is proportional to the natural frequency. In the solid profile, the natural frequency values from numerical analysis and Stokey's analysis show similarities at mode shape 1, although there are differences at each subsequent mode shape. Increasing the mode shape leads to higher natural frequency values, with a more significant difference between the two methods as the mode shape increases. For castella beams, the natural frequencies using numerical analysis and theoretical analysis by Stokey have different values. The difference in natural frequency values between numerical analysis and Stokey's analysis occurs because Stokey's theory does not accommodate the change in stiffness due to the increase in the beam profile body. The difference in natural frequency values is greater at higher mode shapes. Therefore, using the natural frequency value at the first mode shape is recommended.

(a) (b)

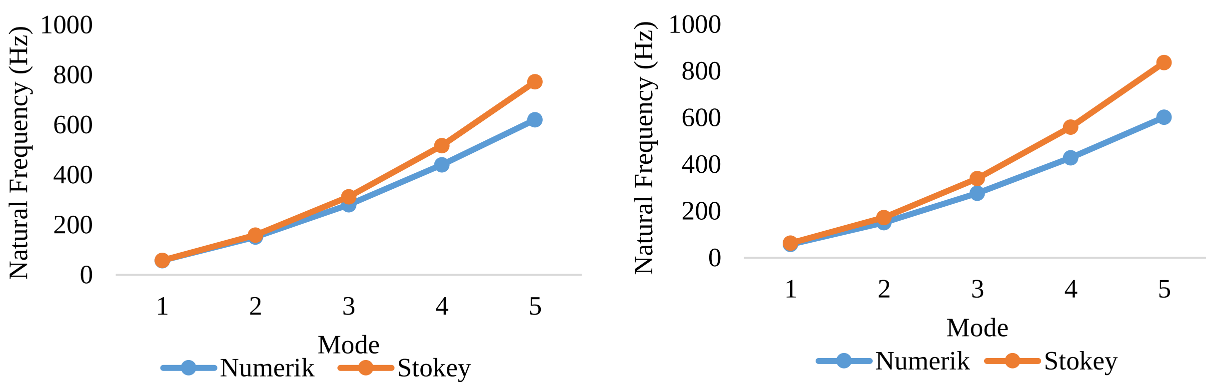


(c) (d)

(e)

Figure 3. (a) First bending mode, (b) second bending mode, (c) third bending mode, (d) fourth bending mode, and (e) fifth bending mode

Analysis of the natural frequency values on the fixed-fixed support can be found in Figure 4, the fixed-pinned support in Figure 5, and the natural frequency values with the pinned-pinned support can be seen in Figure 6. From the 15 models tested on the fixed-fixed, the highest mode one natural frequency value is found on model FF5, which is 58 Hz by numerical analysis and 70 Hz by Stokey's theoretical analysis. The lowest natural frequency value is found in model FF1, which is 58 Hz by numerical analysis and 58 Hz by Stokey's theoretical analysis. At the fixed-pinned support, the highest natural frequency value for mode one is found in model FP5, which is 40 Hz by numerical analysis and 48 Hz by Stokey's theoretical analysis. The lowest natural frequency value for mode 1 is in model FP1, which is 40 Hz in numerical analysis and 40 Hz in Stokey's theoretical analysis. At the pinned-pinned support, the highest natural frequency value for mode one is found in model PP5, which is 27 Hz by numerical analysis and 31 Hz by Stokey's theoretical analysis. The lowest frequency value is found in model PP1, which is 25 Hz by numerical analysis and 25 Hz by Stokey's theoretical analysis. The analysis results on the three types of supports show an increase in the natural frequency value of the castellated steel beam obtained from Stokey 's analysis.



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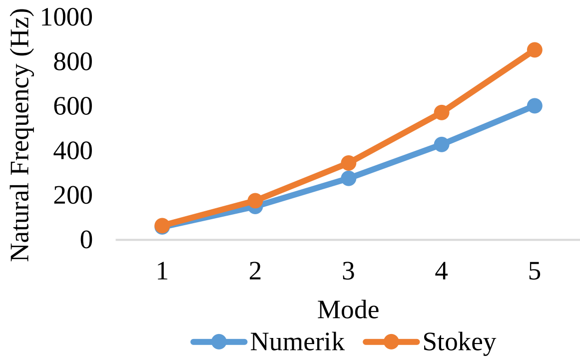

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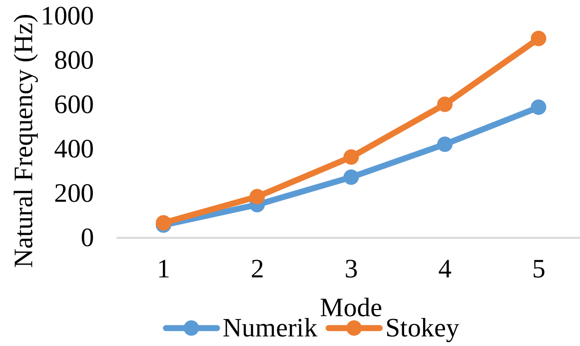

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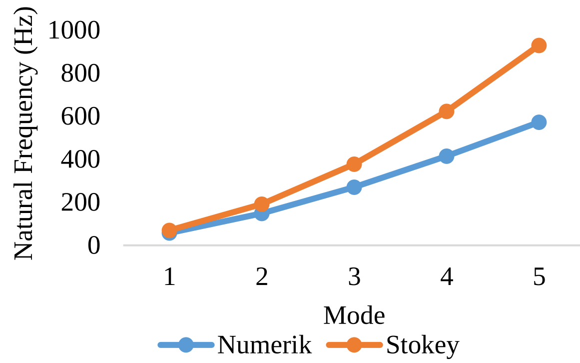
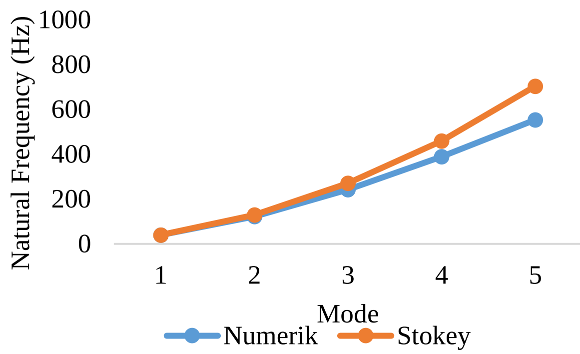


(e)

Figure 4. (a) FF1 modeling, (b) FF2 modeling, (c) FF3 modeling, (d) FF4 modellimg, and (e) FF5 modelling comparison of numerical results and stokey theory on castellated steel beams with varying web openings using fixed-fixed supports



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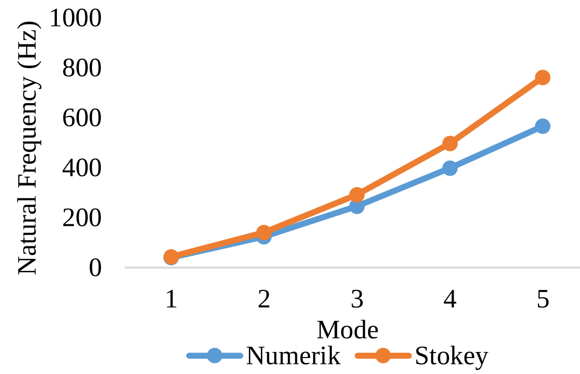

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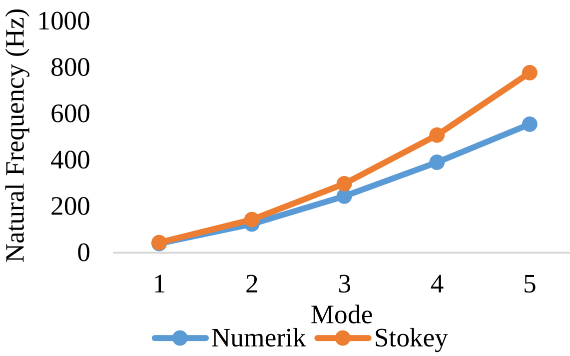

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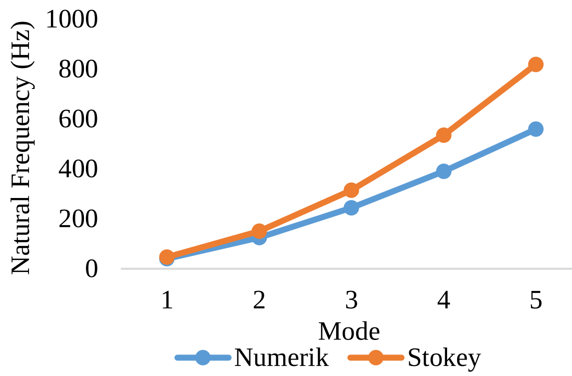

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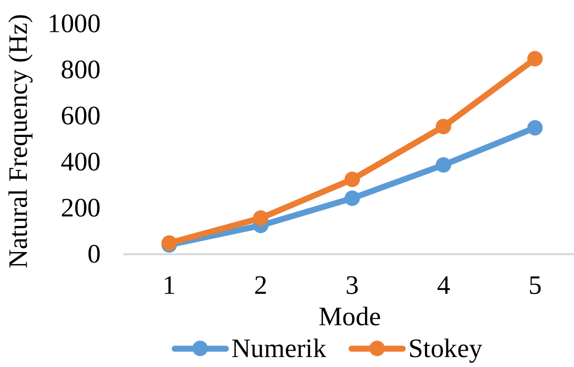
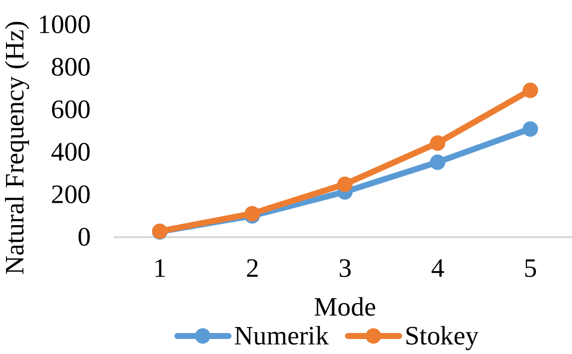


(e)

Figure 5. (a) FP1 modeling, (b) FP2 modeling, (c) FP3 modeling, (d) FP4 modellimg, and (e) FP5 modelling comparison of numerical results and stokey theory on castellated steel beams with variations in web openings using fixed-pinned support



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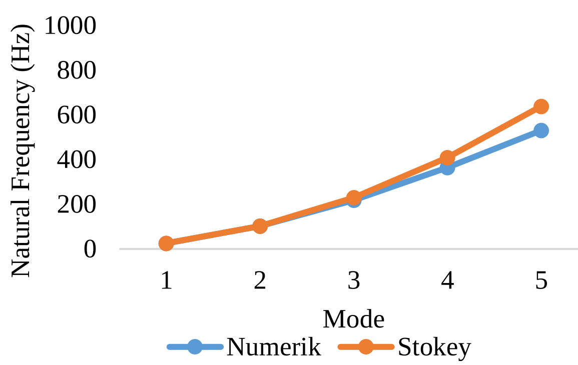

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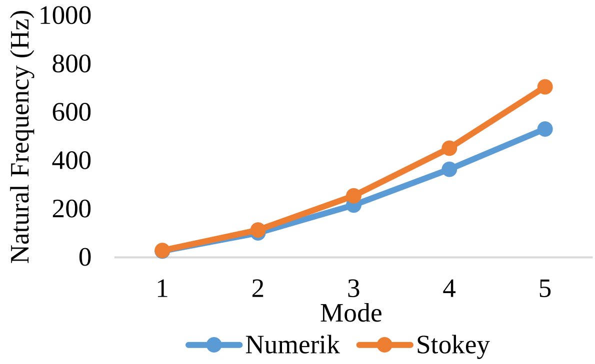

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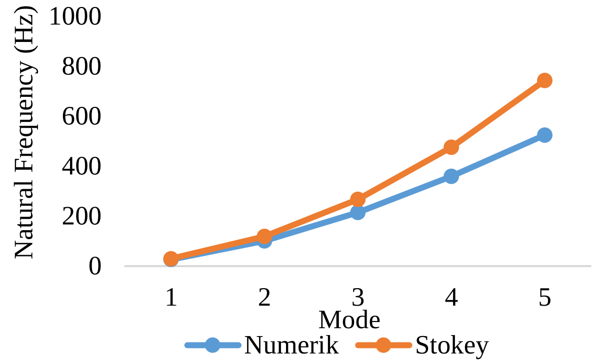

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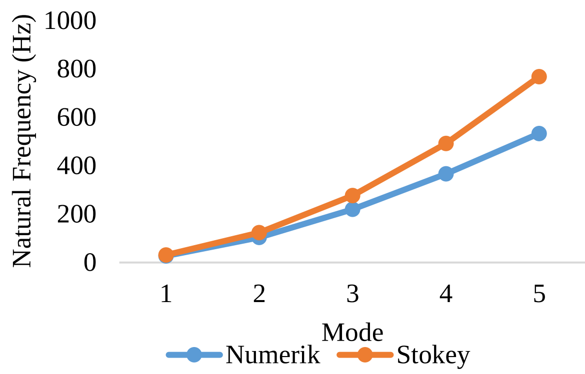

(e)

Figure 6. (a) PP1 modeling, (b) PP2 modeling, (c) PP3 modeling, (d) PP4 modellimg, and (e) PP5 modelling comparison of numerical results and stokey theory on castellated steel beams with variations in web openings using pinned-pinned support

Analysis of natural frequencies using numerical and analytical methods shows differences in each mode shape. The results for each model show that the higher the mode shape, the greater the difference in natural frequency values between analytical and numerical methods. This difference is more significant at higher mode shapes than lower mode shapes. In the first mode of natural frequency, the average difference in value is 4 Hz and the highest mode natural frequency is 227 Hz. Therefore, it is recommended to use a low-mode shape. The analysis results illustrate the effect of web opening, number of web openings, and web opening shape on the beam's natural frequency. The more web openings in a castellated steel beam, the higher the natural frequency value obtained, as shown in Figure 7.

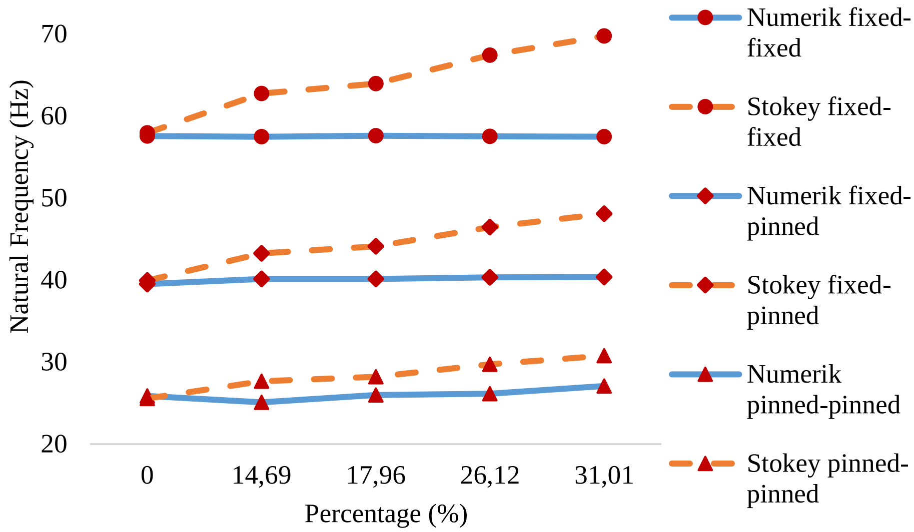

Figure 7. Effect of mass loss value on natural frequency in mode 1

Table 1 shows that increasing the number of web openings can reduce the mass per unit length of the beam. The 410 mm web opening distance has a mass loss percentage of 14.69%, the 325 mm distance has a mass loss percentage of 17.69%, the 200 mm distance has a mass loss percentage of 26.12%, and the 155 mm distance has the highest mass loss percentage of 31.01%. This data shows that the smaller the distance between web openings, the greater the number of openings formed, thus increasing the percentage of mass loss. From Figure 7, it can be seen that there is a significant difference in the percentage of mass loss based on the variation of web opening spacing on various types of castellated steel beam supports. The results of analyzing the effect of mass on natural frequency values using numerical and analytical Stokey's methods have significant differences. This is due to the limitations of Stokey's theory, which can only consider mass reduction due to openings without considering changes in the moment of inertia. If the percentage of mass reduction is more significant and the number of openings is greater, the natural frequency value calculated by Stokey's theory tends to be higher.

The natural frequency values were obtained through numerical analysis and it shows changes due to the addition of web openings. The numerical method approach is more comprehensive, as it automatically considers the effect of changes in mass and moment of inertia in the analysis. The natural frequency values generated by the numerical method are more accurate for analyzing castella beams, especially when considering the effect of the number of openings on changes in mass and inertia. Therefore, the numerical method is more suitable for analyzing the natural frequencies of structures with variations in web openings than Stokey's theoretical calculations, which have limitations in accounting for changes in moments of inertia. To solve the problem, the researcher proposed the moment of inertia calculation method approach. The moment of inertia influenced by the number of web openings can be calculated using the coefficient value in Equation 2.

$$In = Ix - (k \times n) \quad (2)$$

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 2.8774E-07, and n indicates the number of openings. The value 2.8774E-7 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 that, the results of calculating the moment of inertia of the castella beam can be used to calculate the natural frequency value with Stokey's theory in Equation 1. The results of calculating the natural frequency of the castella beam due to the effect of web opening variations are shown in Figure 8.

Table 2. Calculation of Moment of Inertia of Circle Opening

Modelling	Number of Openings	Inertia Value of Solid Steel	Coefficient	Castella Steel Inertia Value
1	-	1,76093E-05	2,8774E-07	-
2	9	-	2,8774E-07	1,50197E-05
3	11	-	2,8774E-07	1,44442E-05
4	16	-	2,8774E-07	1,30055E-05
5	19	-	2,8774E-07	1,21423E-05

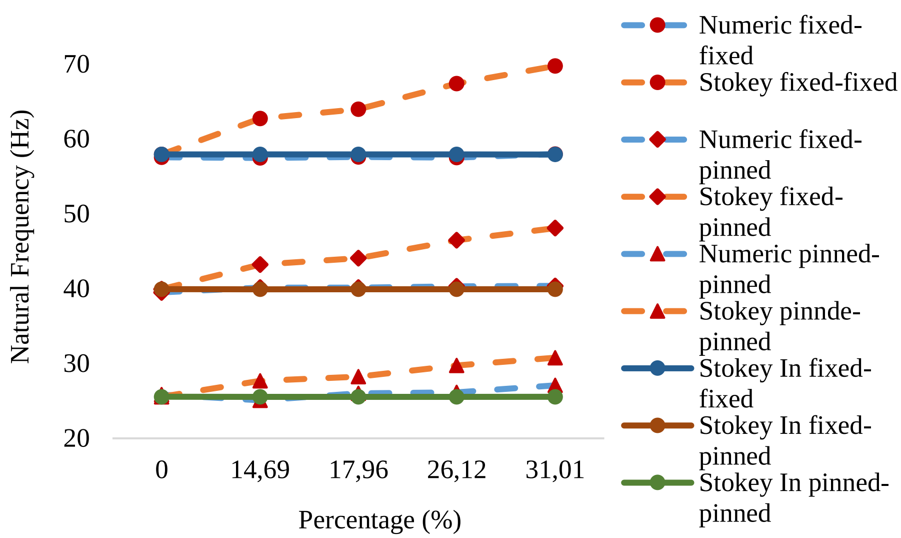

Figure 8. Calculated moment of inertia effect

From the analysis, it can be concluded that web openings with a circular shape in the modeling of castellated steel beams affect the natural frequency. The more web openings, the more the mass of the castellated steel beam decreases and the natural frequency value increases. It can be seen from the Stokey's theory formula in equation (1) that the natural frequency value is inversely proportional to the square root of the mass. If the moment of inertia value decreases, the natural frequency value will decrease because the moment of inertia is proportional to the natural frequency. In the solid profile, the natural frequency values from numerical analysis and Stokey's analysis show similarities at mode shape 1, although there are differences at each subsequent mode shape. Increasing the mode shape leads to higher natural frequency values, with a greater difference between the two methods as the mode shape increases. For castella beams, the natural frequencies using numerical analysis and theoretical analysis by Stokey have different values. The difference in natural frequency values between numerical analysis and Stokey's analysis occurs because Stokey's theory does not accommodate the change in stiffness due to the increase in the beam profile body. The difference in natural frequency values is greater at higher mode shapes. Therefore, using the natural frequency value at the first mode shape is recommended.

Mezher (2023) performed numerical analysis on castellated beams using the ANSYS application, which showed various variations in the shape and size of web openings. The modeling results show that the size of the web opening can increase the natural frequency value. The natural frequency values for each web opening shape at various types of supports are similar. This research shows that numerical analysis of castella beams produces consistent values due to the reduction in mass and moment of inertia of evenly distributed web openings (Mezher et al., 2023). Nugroho (2018) conducted a numerical analysis using the ABAQUS application to model a 6×40×2000 mm strip rod. This study also compared the results of theoretical and numerical analysis. In the strip modeling, the natural frequency values obtained through Stokey's theoretical and numerical analysis show the same results in the first mode (Nugroho, 2020). From the research conducted, this study presents a theoretical moment of inertia analysis for circular openings considering the influence of the solid profile's inertia and the number of openings in the web. This approach allows for calculating natural frequency values based on Stokey’s analysis with higher precision. The analytical results obtained have a reasonable degree of accuracy, thus making a significant contribution to understanding the behavior of structures with circular openings.

CONCLUSION

Analysis of numerical and analytical methods on castellated steel beams with varying web openings influenced by the distance between web openings and the type of support has different results. The analytical results that have been obtained using the ABAQUS CAE 2022 application and analytical calculations using Stokey's theory are as follows:

1. Based on Stokey's analysis, the natural frequency values increase as the number of web openings in castellated steel beams increases. In the numerical analysis, the change in natural frequency value also increases with the increase in web openings, although the increase is not significant. The conclusion section contains a summary of research results and research implications.
2. Mass loss and inertia changes in castellated steel beams can affect the natural frequency values in the stokey’s analysis. In each steel model tested, the percentage of mass loss increases as the number of web openings increases, which causes the natural frequency value to increase. The decrease in the moment of inertia value causes a reduction in the natural frequency value. The difference in results between the numerical and analytical methods occurs because Stokey's theory cannot analyze changes in the moment of inertia. As a result, the natural frequency values calculated by Stokey's theory tend to be higher, especially in models with larger openings.
3. The higher the mode shape, the greater the difference in natural frequency values between Stokey's theory's numerical and analytical methods. So, taking the frequency value at low mode shapes is recommended.
4. The differences in results between the numerical and analytical methods might be due to the inability of Stokey’s theory analysis to calculate the value of the moment of inertia concerning the web opening. However, this problem can be overcome by using a moment of inertia calculation involving the coefficient and number of openings as in formula (2) so that changes can be calculated accurately.

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