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Numerical Analysis of the Effect of Opening Shape and Spacing on the Damping Ratio of Castellated Beams

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Abstrak

Balok castellated banyak diaplikasikan pada struktur baja modern karena karakteristiknya yang ringan dan kekakuannya yang tinggi. Meskipun sebagian besar penelitian sebelumnya berfokus pada frekuensi alami dan perilaku kekakuan, perhatian terbatas diberikan pada kinerja redaman balok kastela dengan geometri bukaan web yang berbeda. Studi ini menyelidiki pengaruh bentuk bukaan dan jarak spasi terhadap rasio redaman (ζ) balok kastela baja IWF dengan menggunakan simulasi elemen hingga di Abaqus. Rasio redaman diperoleh dari kurva peluruhan getaran bebas melalui metode penurunan logaritmik, yang mampu menentukan nilai redaman secara sederhana namun tetap akurat hanya berdasarkan data kurva tersebut. Pendekatan ini dinilai sesuai untuk diaplikasikan pada struktur baja, mengingat material ini umumnya memiliki tingkat redaman yang relatif rendah. Hasilnya menunjukkan bahwa balok solid menunjukkan rasio redaman awal sebesar 3,3%, sedangkan bukaan melingkar mempertahankan nilai redaman yang relatif stabil antara 2,9-3,1%. Sebaliknya, bukaan persegi mengurangi ζ secara lebih signifikan, mencapai nilai serendah 2,6%. Penelitian ini merekomendasikan penggunaan bukaan melingkar pada balok baja castellated, karena konfigurasi tersebut menunjukkan kinerja struktural yang lebih baik dan nilai respon yang mendekati baja solid dibandingkan dengan bukaan persegi. Temuan ini menyoroti bahwa geometri bukaan dan jarak spasi secara signifikan mempengaruhi disipasi energi getaran balok castellated. Hasil penelitian ini memberikan wawasan yang berguna untuk desain struktur baja yang peka terhadap getaran, khususnya pada aplikasi bentang panjang.
Kata Kunci: *Abaqus CAE, Balok baja, IWF Kastela beam, Rasio Redaman,*

Abstract

Castellated beams are widely applied in modern steel structures due to their lightweight characteristics and high stiffness. While most previous studies have focused on natural frequency and stiffness behavior, limited attention has been given to the damping performance of castellated beams with different web-opening geometries. This study investigates the effect of opening shape and spacing on the damping ratio (ζ) of IWF steel castellated beams using finite element simulations in Abaqus. The damping ratio was derived from the free-vibration decay curve using the logarithmic decrement method, which allows the damping value to be determined accurately from the curve data. This method is particularly suitable for steel structures, as steel typically has low damping. Results indicate that the solid beam exhibits a baseline damping ratio of 3.3%, while circular openings maintain relatively stable damping values between 2.9–3.1%. In contrast, square openings reduce ζ more significantly, reaching values as low as 2.6%. This study suggests adopting circular web openings in castellated steel beams,

as this configuration demonstrates superior structural performance and yields response values closer to those of solid steel than square openings. These findings highlight that opening geometry and spacing significantly affect the dissipation of vibration energy in castellated beams. The outcomes provide useful insights for designing vibration-sensitive steel structures, particularly for long-span applications.
Keywords: Abaqus CAE, Balok baja, IWF Kastela beam, Rasio Redaman,

A. Introduction

Castella beams are a popular type of beam in construction and are widely used in various structural projects. Castella beams have different shapes of openings in the body, including circular, hexagonal, rectangular, and pentagonal (Abdulkhudhur et al., 2020; Akgonen et al., 2020; Deepha et al., 2020; Doori & Noori, 2021; Jaini et al., 2020; Mezher et al., 2023). Body openings in castellated beams are facilitate the installing of underfloor utilities, such as water pipes, sewage lines, ventilation systems, and cables (Rugge & Pasnur, 2017; Soltani et al., 2012). Castella steel beams have a taller cross-section without increasing weight, resulting in a lighter weight than ordinary steel beams and increasing the profile's moment of inertia for load resistance. Castellated steel beams offer economic advantages by reducing material use, lowering the overall cost of building steel structures (Doori & Noori, 2021; Yustisia et al., 2020). These advantages of steel castellated beams make them an efficient choice in various structural applications. The main benefit of castellated beams is the increase in cross-sectional depth, up to 50% compared to conventional beams. This increase directly contributes to increased stiffness and vertical bending capacity, which can increase by up to 40%. With increased cross-sectional depth, castellated beams can withstand greater loads without undergoing significant deformation, improving overall structural performance (Hadeed & Alshimmeri, 2019; Sameer S. Fares et al., 2016; Sawai & Waghmare, 2018).

Vibration is one of the most important elements in structural engineering practice. Although relatively small and seemingly insignificant, vibration can still excite certain parts of the structure at their resonant frequencies. To optimize the performance of structures under earthquake loads, strong winds, and other transient vibrations, damping is widely used. Damping is fundamental to regulating the dynamic behavior of structures, enhancing their stability and safety. The damping level directly affects both the system's response amplitude and the natural frequency. Accurate estimation of the damping ratio is vital in structural design, as it governs the reliability of dynamic behavior predictions under seismic and wind loads. Any inaccuracy can lead to unrealistic responses, reducing both safety and efficiency (Kumar et al., 2014; Mevada & Patel, 2016; Suda et al., 1996). Damping serves as a practical measure of energy dissipation in vibrating structures, making it a key parameter for assessing structural response during the design stage. (Li et al., 2000).

Table 1. Recommended value of damping ratio from (AEC, 1963)

Type of Structure	Damping Ratio (%)
Bare steel structures, welded	0,5 - 2
Bare steel structures, riveted	2 - 3
Concrete structures	7
Mansory structures	15 - 40
Fluid containers, ground supported	0,5
Fluid containers, elevated	

From 1985 to 1996, a number of studies examined the dynamic response of building structures to clarify the definition of the structural damping ratio. These investigations primarily focused on identifying factors influencing both the natural frequency and the magnitude of the damping ratio (Jeary, 1986; Suda et al., 1996; Tamura & Suganuma, 1996). Entering the 2000s, research on damping ratios in buildings expanded through measurements on full-scale structures, (Li et al., 2000) utilized Artificial Neural Network (ANN) and Auto-Regressive (AR) approaches in their analysis, while (Satake et al., 2003) examined 137 steel-framed buildings, 25 reinforced concrete (RC) buildings, and 43 steel-reinforced concrete (SRC) buildings in Japan. Furthermore, (Tamura & Yoshida, 2008) emphasized the dependence of damping ratios on building amplitude. Since 2010, dynamic analysis has increasingly focused on comparing structural materials, particularly in relation to natural frequencies and damping ratios. Research conducted by (Papageorgiou & Gantes, 2010) investigated irregular steel–concrete composite structures in terms of damping, while (Kudu et al., 2015) This research investigated the modal damping ratio of steel structures through Operational Modal Analysis (OMA) on a three-story steel model. Since 2016, dynamic analysis studies have increasingly emphasized the comparative performance of structural materials. Furthermore, (Mevada & Patel, 2016) analyzed the natural frequency and damping ratio of three materials: steel, brass, and aluminum.

Zhou et al. (2021) analyzed the effect of the vertical equivalent damping ratio on nuclear reactor buildings with seismic isolation systems. The results indicate that an increase in the vertical damping ratio can significantly reduce the seismic response of the structure, highlighting damping as a key factor in the effectiveness of isolation (Zhu et al., 2021). Analysis of damping ratio values in concrete with a mixture of used tire powder as a substitute for fine aggregate was carried out by (Mufid Kusuma et al., 2021). Research by Hashm et al., (2024) highlighted that material analysis in structural engineering has progressed to a more advanced stage with the application of the Finite Element Method (FEM). The adoption of FEM has enabled researchers to model complex structural behavior more accurately, particularly under dynamic loading conditions. Within this context, their study focused on the behavior of castellated steel beams, which are widely used due to their material efficiency and high strength-to-weight ratio (Hashm et al., 2024). While, Kaveh & Ardebili (2025) conducted a study aimed at developing a method to determine the equivalent damping ratio in concrete/steel mixed structures considering soil-structure interaction (SSI) (Kaveh & Ardebili, 2025), (Mevada & Patel, 2016) conducted a study to estimate the natural frequencies and damping ratios of aluminum, brass, and mild steel cantilever beams with LabVIEW software on experimental tests and validated the results with vibration analysis and harmonic analysis using ANSYS. Meanwhile, Miranda et al., (2024) researched to investigate the internal damping ratios in undamaged and damaged conditions for normal-strength concretes (NSC) and high-strength concretes (HSC) (Miranda et al., 2024). Research by Mezher et al., (2023) research was conducted on the behavior of castellated beams on static (displacement, von Mises stress, maximum shear stress) and dynamic (natural frequency) responses, which were investigated through the finite element method using the ANSYS application (Mezher et al., 2023). Research analyzing the seismic performance of steel frames with conventional, castellated, and cellular beams using the RSA method was conducted by (Patil & Kurlapkar, 2025).

The damping ratio represents a fundamental parameter in structural dynamics, as it determines how a system reacts to dynamic actions including wind and earthquake excitations. Beyond predicting structural responses, damping evaluation is also essential for assessing building performance, safety, and functionality from the preliminary design phase. Damping is the dissipation of energy during vibration, resulting in a gradual reduction in amplitude until a steady state is reached. Based on their mechanisms, damping can be classified as system, internal, and external, each of which contributes to the structure's resistance to dynamic loads (Qu et al., 2024; Yun et al., 2024). In seismic design, the damping ratio directly affects structural displacement and stress, making it a critical factor in both the design process and the evaluation of structural performance after an earthquake (Dai et al., 2020).

Studies on the effects of variations in opening shape and size on the damping ratio, primarily using numerical approaches, remain relatively limited. An in-depth understanding of the dynamic characteristics of structures is essential for designing more adaptive and responsive structures to vibration effects. Therefore, this study evaluated the impact of variations in the configuration of circular and square openings in castellated steel beam bodies on damping ratios. The primary objective of this research is to examine the influence of web opening geometry—specifically circular and square shapes—along with the spacing ratio between consecutive openings (s/d), on the damping ratio (ζ) of castellated steel beams. The configuration of these openings plays a crucial role, as it directly affects the stiffness distribution, mass characteristics, and consequently the dynamic response of the beams. By analyzing these variations, the study aims to clarify how opening design contributes to the damping capacity of castellated structures. A numerical analysis was carried out using Abaqus CAE, employing the free-vibration decay method to evaluate the structural response. The results of this study are expected to provide new insights into the dynamic performance of castellated steel beams and to serve as a reference for designing steel structures that are safe, efficient, and comfortable under dynamic loads.

B. Research Methods

1. Materials

This Research uses a numerical method with Abaqus CAE to analyze the IWF 200.100.8.5.5 steel profile, with a total length of 5 meters. The steel material used has mechanical properties in the form of an elastic modulus (E) of 200,000 MPa, a density (ρ) of 7850 kg/m^3, and a Poisson's ratio (ν) of 0.3. The boundary condition of the support uses a fixed-fixed boundary conditions at both ends of the beam. The body openings were circular with a diameter of 100 mm and square with a side length of 100 mm, with distances between openings of 410 mm, 325 mm, 200 mm, and 155 mm, respectively. The material specifications applied are based on predefined parameters. A 50 kN load was applied at the beam's midspan to evaluate its structural response. The modeling process used a mesh size of 150 mm with tetrahedral-type elements.

2. Models

The test specimens consisted of nine models: eight castellated steel beams with circular or square web openings, and one solid steel beam without openings, serving as the control specimen. The selection of nine specimens was determined to ensure that the experimental matrix was both representative and efficient. This number was considered sufficient to capture the essential variations in geometry and boundary conditions while maintaining analytical clarity and computational feasibility. By combining a control model with multiple castellated variants, the study could isolate the effect of web openings from other structural parameters, thereby enhancing the validity of the findings.

Table 2. Details of specimen

Model	Opening Type	Distance Between Openings (mm)	Number of Openings
M1	Without Openings	-	-
MC1	Circle	410	9

MC2		325	11
MC3		200	16
MC4		155	19
MR1	Square	410	9
MR2		325	11
MR3		200	16
MR4		155	19

Figure 1. IWF solid steel

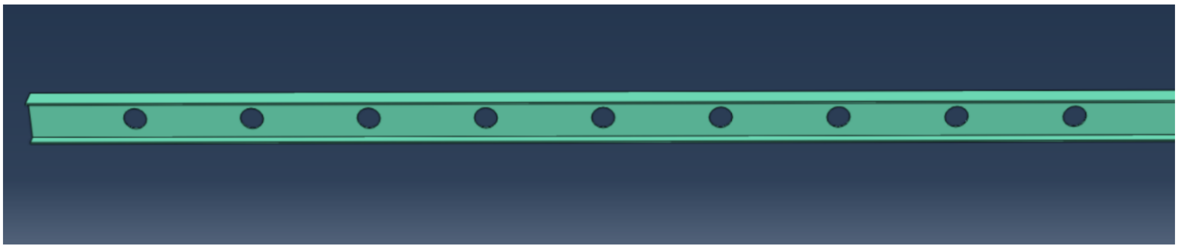


Figure 2. Castela steel circular body opening

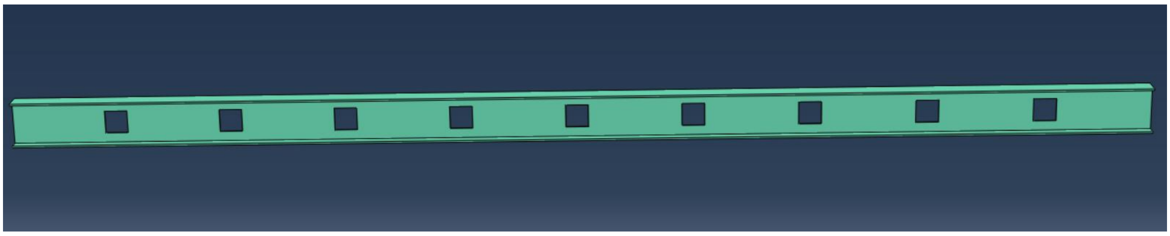


Figure 3. Castela steel square body opening

From Table 2 and Figure 1-Figure 3 summarizes the details of the specimens analyzed, consisting of one solid beam as a control and eight castellated beams with variations in circular (MC) and square (MR) openings at four different spacing distances. These variations were selected to identify the influence of the geometry and distribution of the openings on the beams' dynamic response. The differences in spacing were designed to evaluate the extent to which the interaction between the openings affects the energy dissipation mechanism and, ultimately, the structure's damping ratio.

3. Analysis

Previous studies have emphasized that the dynamic characteristics of building structures, particularly the damping ratio, are strongly influenced by vibration amplitude (Tamura & Suganuma, 1996). As buildings become taller and more complex, the role of damping in maintaining stability and minimizing excessive vibrations has received increasing attention in modern structural design (Li et al., 2000), The damping ratio (ξ), a dimensionless parameter, is widely recognized as one of the most reliable indicators for evaluating the energy dissipation capacity of structural elements (Miranda et al., 2024).

In this study, the damping ratio was determined numerically by analyzing the decay of displacement amplitude over time. The displacement–time response curve was obtained for each specimen, and the gradual reduction in amplitude was used to quantify the damping ratio. An example of the displacement response curve generated by the Abaqus simulation is presented in Figure 4. The curve forms the basis for the calculation of the damping ratio, which is determined using Equations (1) and (2).

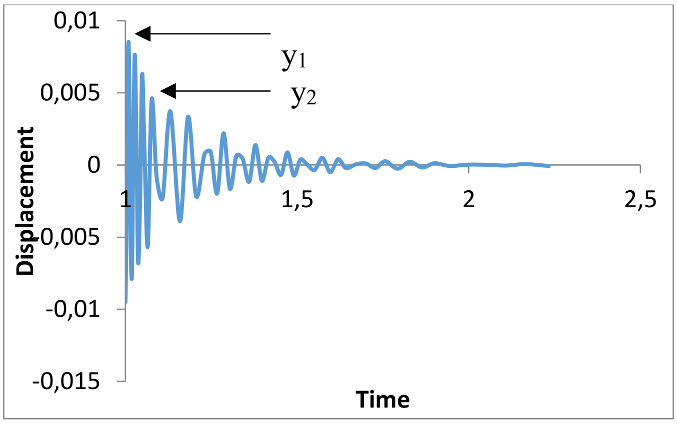


Figure 4. Vibration wave curves

The damping ratio was calculated using the logarithmic decrement method, expressed as follows:

$$\delta = \frac{1}{n} \ln \left(\frac{y1}{yn+1} \right) \quad (1)$$

$$\xi = \frac{\delta}{\sqrt{(2\pi)^2 + \delta^2}} \quad (2)$$

δ is the Logarithmic Decrement, n is the number of waves, y1 is the first wave, yn is the second wave, and ξ is the damping ratio.

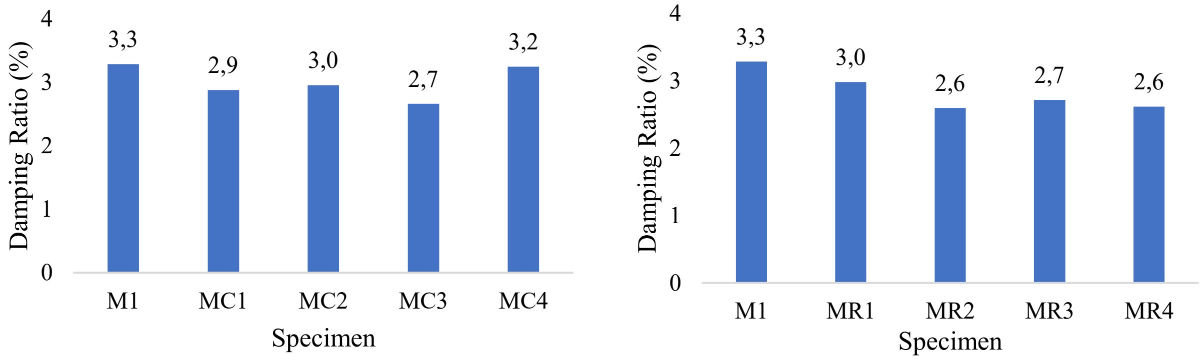
C. Result and Discussion

The damping ratio was analyzed numerically using Abaqus CAE, involving three types of test specimens: one IWF steel beam without openings and two castellated steel beams with circular and square openings. The simulation results for each opening configuration are shown in Table 3, Figure 4, and Figure 5, which compare the damping ratio as the shape and distance between openings vary.

Table 3. Damping ratio analysis results

Model	Opening Type	Distance Between Openings (mm)	Damping Ratio (%)
M1	Without Openings	-	3,3
MC1	Circle	410	2,9
MC2		325	3,0
MC3		200	2,7

MC4		155	3,2
MR1		410	3,0
MR2	Square	325	2,6
MR3		200	2,7
MR4		155	2,6



(a) (b)

Figure 5. (a) Damping ratio with circle body opening and (b) damping ratio with square body opening

In the configuration with circular openings (MC), the damping ratios decreased to 2.9% in MC1, 3% in MC2, and 2.7% in MC3, respectively. This decrease indicates that the presence of openings initially reduces the system's damping capacity, possibly due to disruption of internal force flow and a decrease in local stiffness. However, the trend of damping values increased again at MC4: 3.2% as the spacing between the openings became denser. This phenomenon indicates the significant role of the spatial configuration of the openings in the energy dissipation mechanism. Although openings reduce the damping capability, a denser spacing of openings can re-optimize the structure's damping capacity, approaching or matching the condition without openings.

In the configuration with square openings (MR), the damping response tends to yield lower damping ratios than the circular type. The value of the damping ratio in the square opening has decreased significantly. In the MR1 model, the value decreases by 3%, in the MR2 model, it has a value of 2.6%. However, in MR3, the damping ratio value slightly increased by 2.7%. In the MR4 model, the damping ratio value has decreased again by 2.6%. In the circle opening, most body openings, namely 19 holes, have a high damping ratio of 3.2%. Among the square body openings, the smallest opening, namely 9 body openings, has the highest damping ratio of 3%.

Figure 5 shows the variation of damping ratio (ζ) for castellated beams with circular and square openings compared to the solid reference beam. The solid beam exhibits a baseline damping ratio of 3.3%, while beams with circular openings present values in the range of 2.9–3.1%, depending on the spacing ratio. In contrast, square openings lead to a more pronounced reduction, with ζ decreasing to 2.6–2.8%. This finding indicates that the opening geometry directly affects the beam's energy dissipation capacity. Circular openings tend to distribute stress more evenly around the edges, reducing localized concentrations and thus maintaining a relatively stable damping performance. Conversely, square openings create sharp corners that act as stress risers, which accelerate local stiffness degradation and consequently lower the effective damping. A comparison of the damping ratio values of circular and square opening castellated beams can be seen in Figure 6.

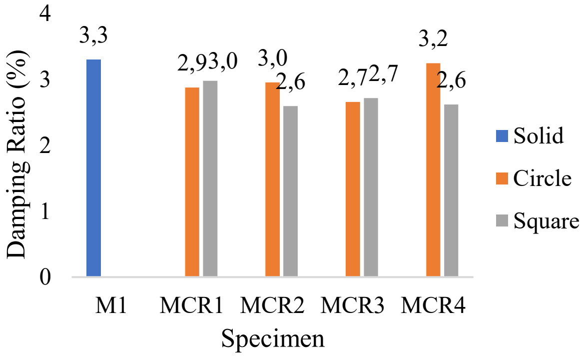


Figure 6. Damping ratio values of steel beams without openings, circular openings, and square openings

The results show that the damping ratio is strongly influenced by variations in the shape and spacing of openings in castellated steel beams. The configuration of circular openings has been proven to maintain the energy dissipation capacity, resulting in a damping value relatively close to that of a solid beam. In contrast, the use of square openings tends to reduce the damping capacity more significantly, indicating stress concentration and uneven energy distribution around the corners of the openings.

A summary of the analysis results is presented in Figure 6, which compares the damping ratio values of solid beams, castellated steel beams with circular openings, and castellated steel beams with square openings. The damping ratio (ζ) obtained from free-decay responses for the solid beam and eight castellated configurations. The spacing ratio was computed from Table 2 as s/d = spacing/100 mm, yielding 4.10, 3.25, 2.00, and 1.55 for both opening types. The solid beam (M1) provides the baseline with $\zeta = 3.3\%$. For vibration-sensitive members (e.g., long-span floors), circular castellations with s/d ≈ 1.55 provide the most favorable damping without substantial loss relative to the solid reference (−3%). Square openings should be avoided at tight spacing, as ζ may drop relative to the solid beam. When square openings are required by functional constraints, wider spacing (s/d ≥ 3.25) is preferable to mitigate damping loss. These results suggest that opening geometry plays a dominant role in determining the damping characteristics. Circular openings are more effective at retaining the beam's energy-dissipation capacity, likely because their smoother geometry reduces stress concentration compared with the sharp corners of square openings. This result is also consistent with the research of Mezher et al. (2023), which showed that opening shapes with smoother geometries, such as circles, produce a more uniform stress distribution, leading to more stable dynamic performance of the beam compared to square, pentagonal, and hexagonal openings (Mezher et al., 2023).

In terms of spacing effect, the data reveal that intermediate to close spacing (MC4 and MR4, s/d ≈ 1.55) enhances damping compared to wider spacing (MC1 and MR1, s/d ≈ 410). When openings are too far apart, the discontinuities act in isolation, reducing the overall interaction and damping capacity. Conversely, closer spacing allows more uniform redistribution of stress and inertia, thus increasing energy dissipation. However, the benefit is less pronounced for square openings, where stress concentration at corners limits the damping improvement. These findings highlight that opening spacing is a critical design parameter for optimizing vibration control in castellated beams. The fact that circular openings consistently outperform square ones further confirms the importance of geometry in controlling energy dissipation. From a practical standpoint, adopting an intermediate spacing ratio can enhance structural comfort and serviceability, particularly in long-span applications where damping plays a key role in mitigating vibration-induced discomfort. Based on analysis theory, the damping ratio is influenced by stiffness, mass distribution, and support conditions. Stiffer structures generally exhibit better damping. The results of this study are consistent with the theory that the solid beam at the fixed-fixed support has the highest damping ratio, while the pined-pined support has the lowest. However, the gap identified in this study shows that leaving it in place does not always reduce the damping ratio in some configurations, it can even increase the structure's damping capability.

D. Conclusion

This study examined how different hole shapes and arrangements in castellated steel beams affect their damping ratio and natural frequency. Based on the numerical analysis conducted, Body openings in castellated steel beams can affect the damping ratio value. In the steel beam model without openings (M1), the damping ratio value is 3.3%. The highest value closest to the reference value (M1) in the circular opening is 3.2% for the MC4 model, and in the square opening it is 3% for the MR1 model. The presence of openings in the castella steel beam body has been shown to reduce the damping ratio compared to beams without openings. Beams with circular openings (MC1-MC4) show more stable damping performance and are close to the damping value of beams without openings, with the highest value at MC4 of 3.2%. Meanwhile, the beams with square openings exhibit lower, stable damping values in the 2.6-3.0% range, with no increase across any model. The decrease in damping values is more pronounced for square openings, indicating that circular openings are preferable in castellated steel beams to maintain good damping characteristics, especially when the structure operates as a dynamic system subject to vibration. The more openings there are and the tighter the spacing, the greater the damping tends to decrease. So, it is important to carefully consider the configuration of openings in the design of dynamic structures.

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