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UNDAMPED FORCED VIBRATION ANALYSIS OF CASTELLATED STEEL BEAM WITH CIRCULAR, SQUARE AND PENTAGONAL WEB OPENINGS

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ABSTRACT

This study conducts a comprehensive investigation into the influence of web opening shapes on the forced vibration response of castellated steel beams, particularly emphasizing the temporal aspects of the dynamics. These beams are widely employed in practice due to their enhanced structural efficiency and reduced weight, but the incorporation of web openings may potentially impair their shear and bending strength capacities. Three types of web opening shapes are considered. Finite element methodology is employed using ANSYS. The investigation encompasses the forced vibration behavior of castellated steel beams subjected to varying loads. Additionally, the impact of various parameters, including the beam's geometry, and boundary conditions, on the dynamic behavior of castellated beams are analyzed. The obtained results demonstrate that the web opening shape has significant influence on the vibration amplitudes and oscillation periods of castellated steel beams.

Keywords: *Castellated steel beam, finite element analysis, forced vibration, dynamic behavior, web opening shapes*

GÖVDESİNDE DAİRESEL, KARE VE BEŞGEN BOŞLUK BULUNDURAN PETEK KİRİŞLERİN SÖNÜMSÜZ ZORLANMIŞ TİTREŞİM ANALİZİ

ÖZET

Bu çalışma, dinamik yüklerin zaman bağlı özelliğini vurgulayarak gövde boşluk tiplerinin çelik petek kirişlerin zorlanmış titreşim davranışına etkisini ele almaktadır. Bu kirişler, gelişmiş yapısal özellikleri ve azaltılmış ağırlıkları nedeniyle pratikte yaygın olarak kullanılmaktadır. Ancak, gövde boşluklarının bulundurması, bu kirişlerin kesme ve burulma mukavemeti kapasitelerini potansiyel olarak azaltmaktadır. Bu çalışmada, üç farklı boşluk tipi dikkate alınmıştır. Petek kirişlerin zamana bağlı yükler etkisinde zorlanmış titreşimini incelemek için sonlu elemanlar yöntemine dayalı ANSYS programı kullanılmıştır. Ayrıca, kirişin geometrisi, sınır koşulları gibi parametrelerin petek kirişlerin dinamik davranışına etkisi incelenmiştir. Elde edilen sonuçlar, boşluk tiplerinin zorlanmış titreşim genliklerine ve salınım periyotlarına önemli bir etki ettiğini göstermektedir.

Anahtar Kelimeler: *Petek çelik kiriş, sonlu elemanlar analizi, zorlanmış titreşim, dinamik davranış, gövde boşluk şekli*

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1. Introduction

Castellated beams are widely used in civil engineering and construction projects due to their enhanced strength and improved performance. These beams are steel section members with various shapes of web openings and offer several advantages over traditional solid beams. The web openings are created to facilitate the installation of services, minimize weight, or improve architectural design. The structural performance of these elements is critical to ensure safety and durability. To evaluate the behavior of these elements under various loads, static and dynamic analyses are performed. Static analysis involves assessing the load distribution, stress analysis, shear capacity, and flexural capacity of the element. The dynamic analysis examines the natural frequencies, mode shapes, vibration damping, resonance, and dynamic response of the element. Their resistance is particularly affected by the shear stress around the web opening. Therefore, the presence of web openings reduces the shear strength of the beam and can lead to various failure modes. Various failure modes have been identified in castellated beams, including the formation of the Vierendeel mechanisms, rupture of welded joints, and shear buckling in web posts. With these factors in mind, engineers can design castellated beams with optimal deflection, stress distribution, shear capacity, and harmonic response. When evaluating the stresses in castellated beams ANSYS can be utilized. It provides a comprehensive analysis of stress distribution within the beam, considering important factors and aspects like geometry, loading conditions, and material properties. This method offers a higher level of accuracy and can reveal valuable insights into the behavior of the structure under different loadings. On the other hand, performing manual design calculations for an initial estimate is a simpler and quicker approach to perform, but it may not capture all the complexities of the beam's behavior. These calculations are based on established formulas and assumptions, which can lead to reasonable results for basic designs but may not be sufficient for more intricate or demanding structures. Nevertheless, they can still be useful for ensuring compliance with building codes and standards, especially when used in conjunction with the more advanced ANSYS analysis [1]. The load-bearing capacity of castellated beams can be increased by using vertical stiffeners around the opening and at the beginning of the web opening [2]. The use of stiffeners in the web area of castellated beams has proven effective in increasing strength and minimizing deflection. Proper selection of the stiffener’s dimensions is essential to ensuring optimal performance and structural integrity of the beam [3]. A comparison was made using a circular and octagonal ring stiffener around an octagonal web opening, and it was found that the circular stiffener was more efficient in strengthening the beam [4]. The specific properties and performance of castellated beams can vary depending on design, materials used, and construction methods [5]. The ultimate strength capacity of composite castellated beam is a composite action of both steel section and concrete element which creates an efficient combination of tensile and compressive strength [6]. By conducting static and dynamic analysis of castellated beams, engineers can determine their ability to withstand various loads and forces [7]. The deflection behavior of castellated beams under uniformly distributed transverse loading depends on factors such as beam dimensions, material properties, and support conditions [8]. The specific behavior of castellated columns under axial compression buckling at elevated temperatures depends on factors such as the column's geometry, material properties, fire protection measures, and design considerations, which highlights the need for careful consideration [9]. Assessing the dynamic behavior of castellated beams under loading conditions is crucial to preventing instability or buckling phenomena [10]. When an external force acts upon beams, causing them to bend, the desired outcome is to attain maximum shear strength first, followed by maximum bending moment, and finally maximum deflection [11]. While larger spacing of openings has minimal impact on mechanical properties, careful consideration must be given to the design and placement of openings to maintain adequate strength and stability [12]. Different types of web openings (hexagonal, circular, rectangular, etc.) exhibit varying degrees of fatigue life, with circular castellated steel beams demonstrating the best performance [13]. The frequency of the curved castellated beams can be affected by the shape of the web openings [14]. Throughout an analysis that was carried out in ABAQUS, it was observed that castellated beams provide increased strength by increasing cross-sectional depth without adding significant weight [15]. Designers and engineers can develop optimized guidelines and recommendations for enhancing the shear resistance and overall performance of castellated beam chassis in real-world applications [16].

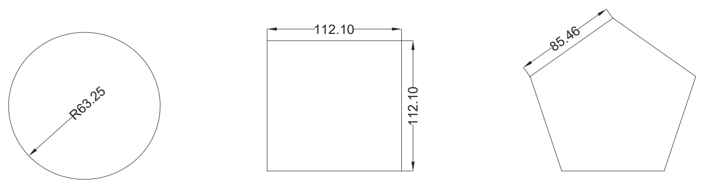
Several researchers have focused their studies on different aspects of castellated beam behavior. These studies investigated the optimization of stress concentration, deflection, shear strength, and web opening using the (FEM) and advanced software tools such as ABAQUS and ANSYS. The results of these studies have provided valuable insight into the design and performance of castellated beams [17]. Deepa et al. [18] analyzed the nonlinear behavior of a castellated beam using the (FEM). It was found that the provision of fillets on the corners of the web openings decreases the stress concentration of the castellated beam. Using the (FEM) a castellated beam optimization study was done by Shendge and Shinde [19]. The conclusion of their study states that castellated beams with fillets in their web openings have greater load-bearing capacity than castellated beams with rectangular or hexagonal-shape web openings when they have the same opening height. Jamadar and Kumbhar [20] used ABAQUS software to study a castellated beam with a hexagonal web opening, and it was observed that the lack of shear transfer area played a key role in the local failure of the beam. A simply supported beam with a hexagonal web opening under a uniformly distributed transverse load was investigated by Elaiwi et al. [21] using the potential energy method. They have found that the shear effect should be considered in the deflection of the castellated beams, specifically for those beams that have wide or narrow sections and short or medium span lengths. Doori and Noori [22] investigated the bending analysis of six castellated beams having different web openings using the (FEM). The effect of web opening on the flexural behavior of hybrid beams was studied analytically by Morkhade et al. [23]. They have found out through that castellated beams with circular openings have the best performance amongst other shapes of openings.

The utilization of diverse materials in structural beams has been a crucial aspect of modern engineering, particularly with the increasing popularity of lightweight and high-performance materials. Among these materials, aluminum stands out as a "wonder metal" owing to its exceptional physical properties and corrosion resistance. In welded aluminum alloy box castellated beams, the versatility of Alloy 6061-T6 allows engineers to carefully weigh the tradeoffs between performance and cost, thereby tailoring their designs to meet specific requirements [24]. Ertürkmen and Noori [25] investigated the static behavior of curved castellated beams using (FEM), and focused on the effect of the web opening geometry on the displacement and stress values of castellated beams. From the obtained results, the maximum total displacement values occur in the square web opening type, while the smallest maximum total displacement values occur when the circular web opening type is used. ANSYS Workbench software was used for static and dynamic analysis of castellated beams for four types of web opening shapes in [26]. The (FEM) stands as a proficient numerical procedure that has been effectively deployed in addressing various structural mechanics problems. [27-30].

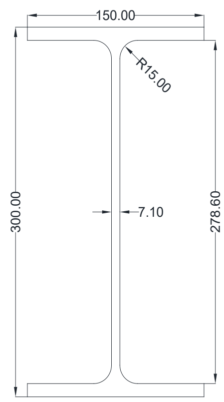
To the best of authors' knowledge, the review of literature suggests a dearth of published papers examining the influence of web opening geometry on the forced vibration behavior of castellated steel beams. The novelty of the present research lies in its endeavor to address this gap in knowledge, thereby furnishing a benchmark solution that may serve as a reference point for subsequent investigations within this field. This study investigates the transient response of castellated steel beams. The material of the beam is assumed to be isotropic homogenous. Fixed-fixed supported type of boundary conditions is considered in this study. three distinct web openings (circular, square and pentagonal) are examined and the results are compared for several time steps, such as 32, 64, 126, 256, 512 and 1024. Through extensive research and analysis, engineers can optimize castellated steel beams to meet specific design needs and improve overall performance under the dynamic loads.

2. Materials and Method

This study aims to analyze the undamped forced vibration response of steel castellated beams with three different shapes of web openings. The transient response of the considered beams is carried out by using step by step time integration method (Newmark-β) for (32, 64, 128, 256, 512, and 1024 time steps). First, analysis of (15 periods) has been done to identify the convergence of time steps and then results of web opening shapes are compared for (6 periods). Three IPE300 profiles are used with circular, square, and pentagonal web openings. The span length of all the beams is (3 m), and each beam has (15) openings in its web. The length between the center of the opening and the support is considered to be (α =240 mm), the distance between the center of the opening and the flange is (β =124.3 mm), and each opening is (γ = 180 mm) apart. Web opening geometries and profile dimensions are given in Fig.1. The material properties of castellated beams are presented in Table 1. Three models are used in this study, the geometric properties of web opening shapes for these models are given in Table 2.



(a) Web opening geometries



(b) Profile dimensions (mm)

Figure 1. Geometric properties of castellated steel beam

Table 1. Material properties

Young's Modulus (GPa)	Poisson's Ratio	Mass Density (Kg/m^3)	Shear Modulus (GPa)
200	0.3	7850	76.923

Table 2. Geometric properties of web openings

Model	Profile	Web opening shape	Area of the openings (mm^2)	α (mm)	β (mm)	γ (mm)	Number of openings in web
1	IPE300	Circular	12561.76	240	124.3	180	15
2	IPE300	Square	12566.41	240	124.3	180	15
3	IPE300	Pentagon	12565.35	240	124.3	180	15

Using (FEM) for solving the problem with the aid of ANSYS [31], a spatial element SOLID187 (Fig.2.) is used. This element is defined by 10 nodes with each node having three degrees of freedom. SOLID187 has a quadratic shifting behavior and is suitable for modeling the finite element irregular mesh. The degrees of freedom in the elements consist of translations in the x-axis, y-axis, and z-axis. The element has plasticity, hyper elasticity, creep, stress stiffening, large deflection, and large strain capabilities. It also possesses mixed formulation capability for the simulation of deformations exhibited by materials with properties ranging from nearly incompressible elasto-plasticity to fully incompressible hyper-elasticity. This element has proven efficacious in the application of several structural mechanical quandaries [32-33]. For a comprehensive exposition concerning the theoretical underpinnings, assumptions, constraints, and formulation of this element, refer to reference [34]. In this research, the finite element mesh of the system is done with the default mesh setting of the software. The mesh properties of the elements and nodes for three types of modules are given in Table 3. Castellated steel beam with circular web openings meshed by software's default mesh setting is shown in Fig. 3.

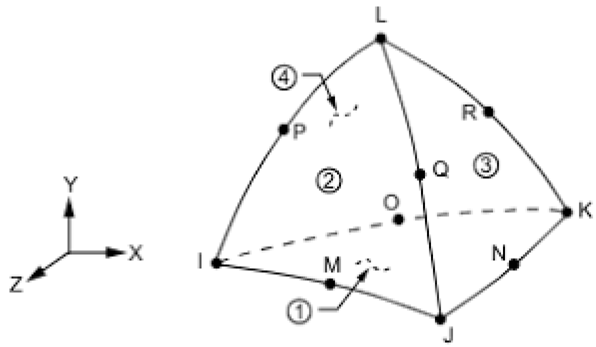


Figure 2. Geometry of SOLID187

Table 3. FEM meshing properties

Model	Web opening shape	Number of elements	Number of nodes
1	Circular	3554	8000
2	Square	3323	7515
3	Pentagonal	3626	8251

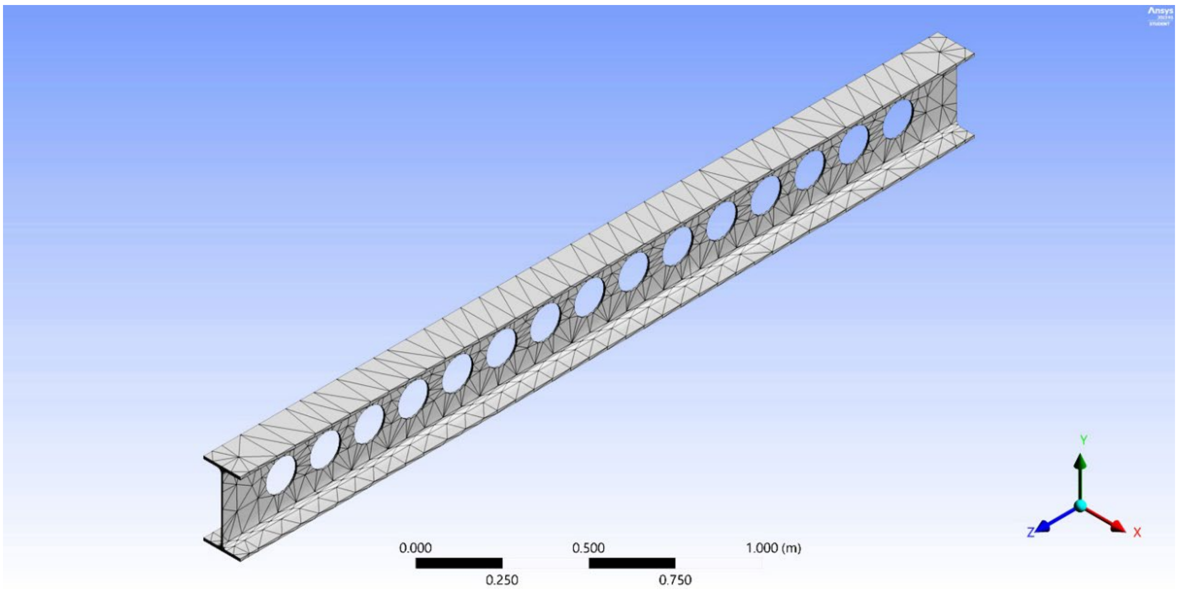


Figure 3. Meshed castellated steel beam with circular web openings

3. Numerical results and discussion

In this study, the forced vibration analysis of castellated steel beam subjected to step-load is carried out. The effect of the web opening shape and time steps on the forced vibration response of the castellated beam is investigated in details. The pressure is applied on the top of the beam, and its magnitude is deemed to be (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 time steps and the effect of web opening shape on the dynamic response of the castellated beams. For all the cases throughout this study, the IPE300 profile with fixed-fixed boundary condition is used. In this context, only the web opening shape is changed by keeping the length of the beam, the web opening area, and the distance between the openings constant in all cases for each profile. Different models are generated and analyzed using the (FEM). To outline the effect of web opening shape on the dynamic response and discuss the effect of the time step numbers on the accuracy of the transient analysis, a parametric study is carried out for (32, 64, 128, 256, 512, and 1024) time steps. The maximum total displacement results of fixed–fixed supported castellated beams of n = 1024 time steps results for circular web openings are given in Fig.(4-8).

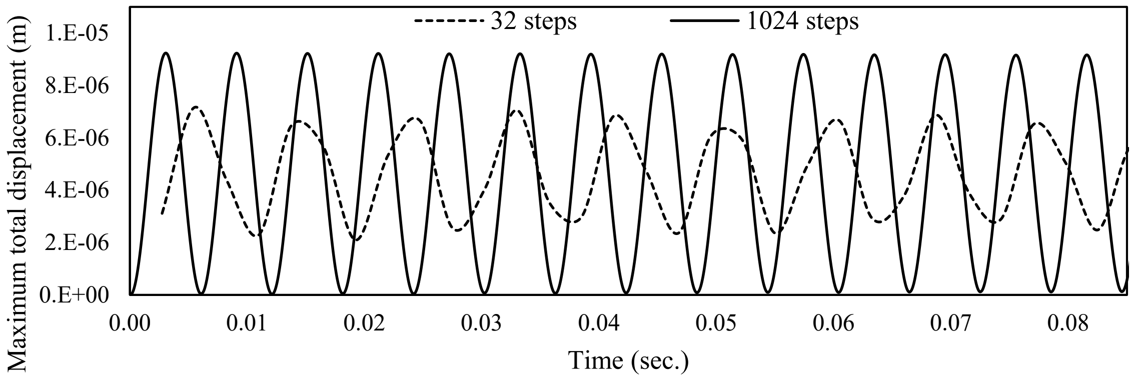


Figure 4. The maximum total displacement of fixed – fixed supported castellated beam with circular web openings for n = 32 and n = 1024

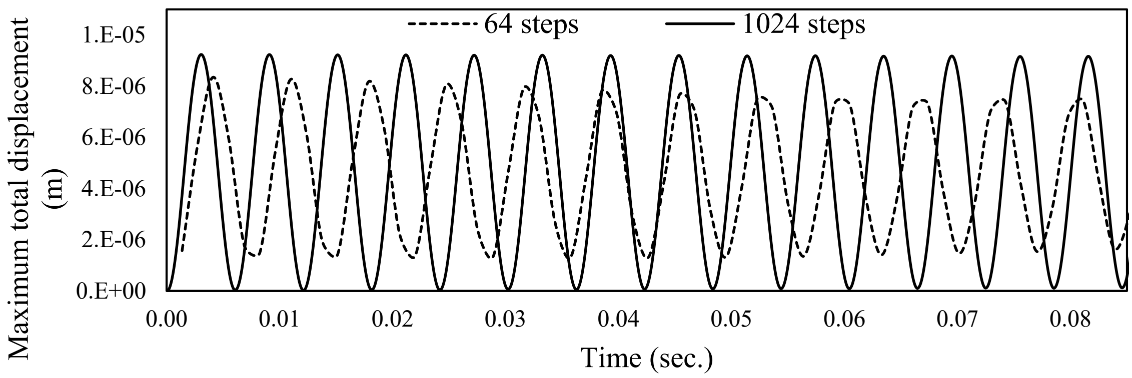


Figure 5. The maximum total displacement of fixed – fixed supported castellated beam with circular web openings for n = 64 and n = 1024

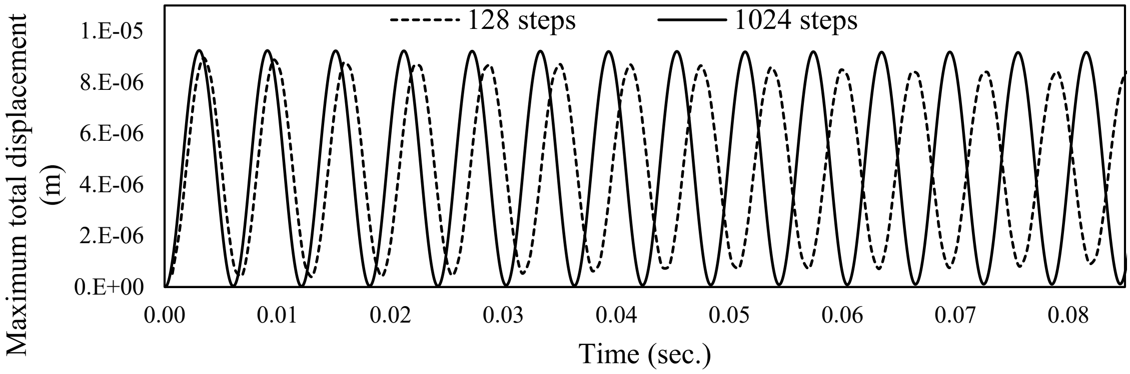


Figure 6. The maximum total displacement of fixed – fixed supported castellated beam with circular web openings for n = 128 and n = 1024

As shown in Fig. 4, there is a discernible divergence in periodic outcomes conducted with (32) and (1024) time steps. With temporal increment, the amplitude values are diverging by a significant amount. This trend is evident across Fig. 4 through Fig. 6, wherein an augmentation in the time steps yields a convergence of amplitude values.

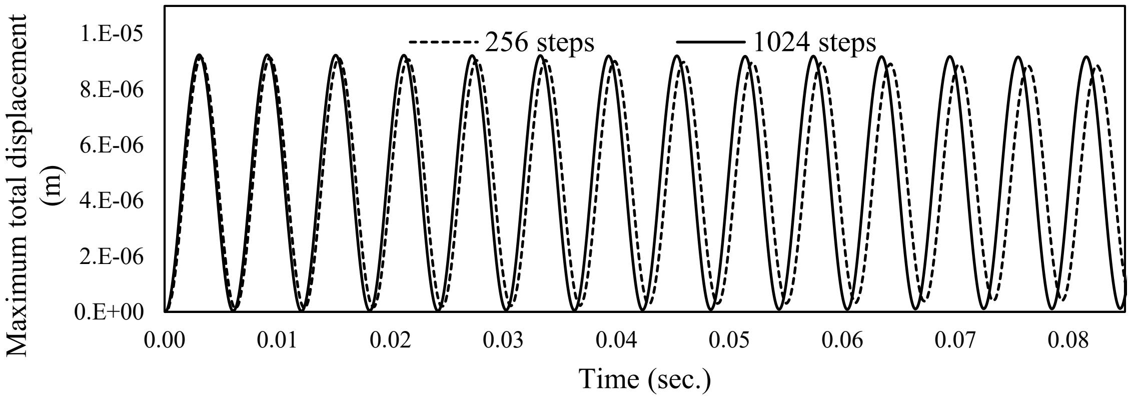


Figure 7. The maximum total displacement of fixed – fixed supported castellated beam with circular web openings for n = 256 and n = 1024

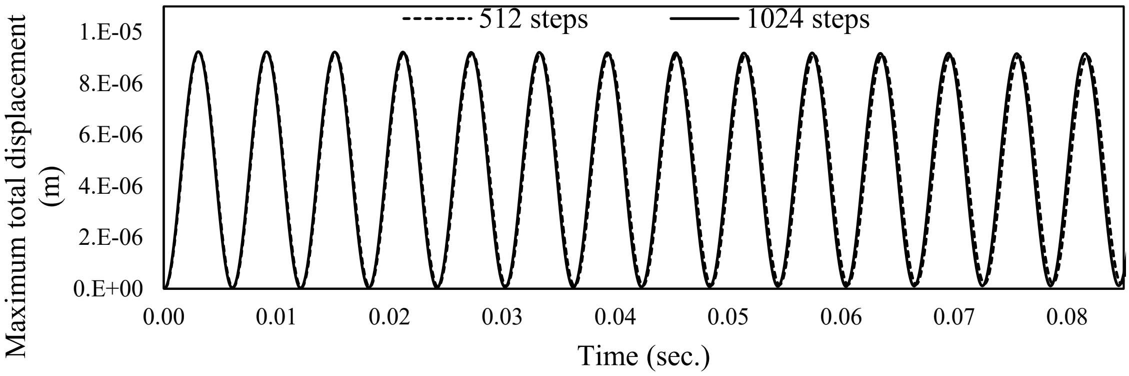


Figure 8. The maximum total displacement of fixed – fixed supported castellated beam with circular web openings for n = 512 and n = 1024

From Fig. 4, it can be seen that the frequency of the periodic results of (32) and (1024) time steps diverges from each other, and by increasing the number of time steps, results are approaching to each other. As seen in Fig. 8, the results obtained for (512 steps) overlap those of (1024 steps). The maximum total deformation results of fixed–fixed supported castellated beams with circular and square web openings for (32 – 1024) time steps are given in Fig. (9-14).

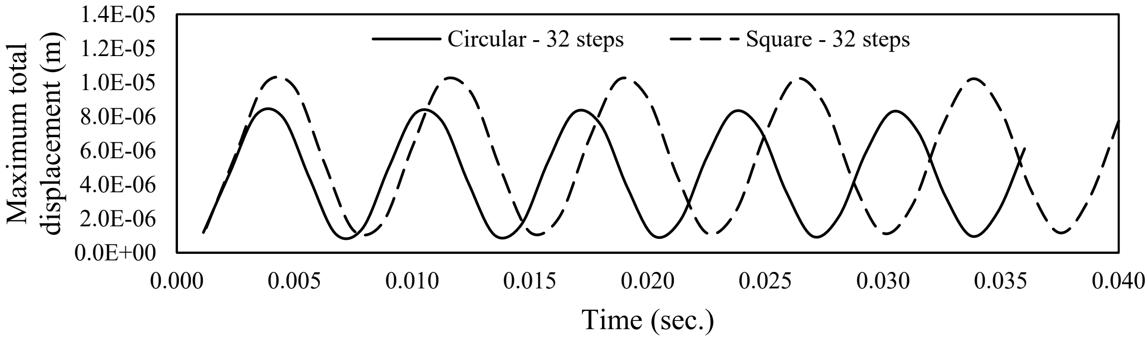


Figure 9. The maximum total displacement of fixed – fixed supported castellated beams with circular and square web openings for n=32

At identical time steps, the total maximum displacement between square and circular web openings is compared. Fig. 9 illustrates the evident discrepancy in frequencies of their periodic results. Notably, the amplitude values associated with square web openings surpass those of circular, with this discrepancy accentuating with temporal progression. At identical time steps, the total maximum displacement between square and circular web openings is compared. Fig. 9 illustrates the evident discrepancy in frequencies of their periodic results. Notably, the amplitude values associated with square web openings surpass those of circular, with this discrepancy accentuating with temporal progression.

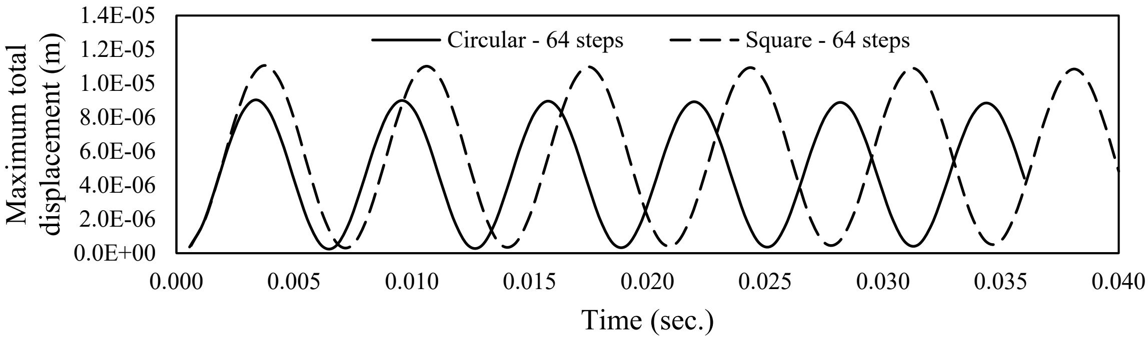


Figure 10. The maximum total displacement of fixed – fixed supported castellated beams with circular and square web openings for n=64

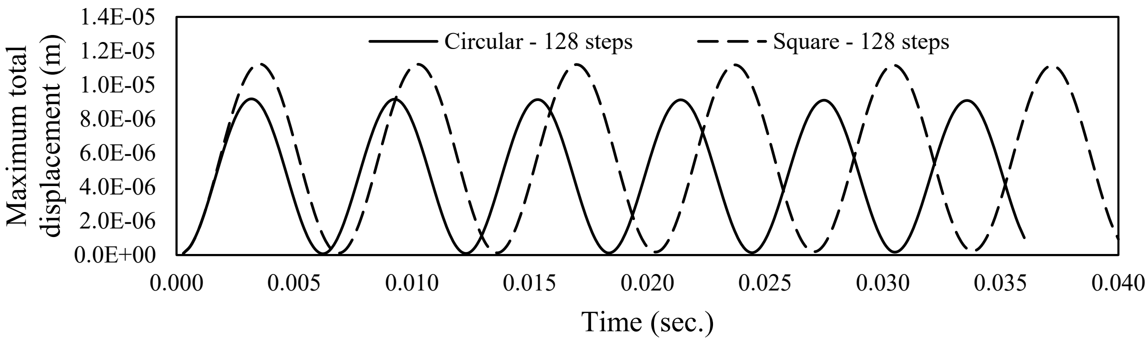


Figure 11. The maximum total displacement of fixed – fixed supported castellated beams with circular and square web openings for n=128

Fig. 10 and Fig. 11 indicate that with escalating time steps, the maximum total displacement values remain relatively stable and maintain proximity to one another, akin to the results observed at 32 time steps. Concurrently, the disparities in periodic results between square and circular web openings remain unaltered.

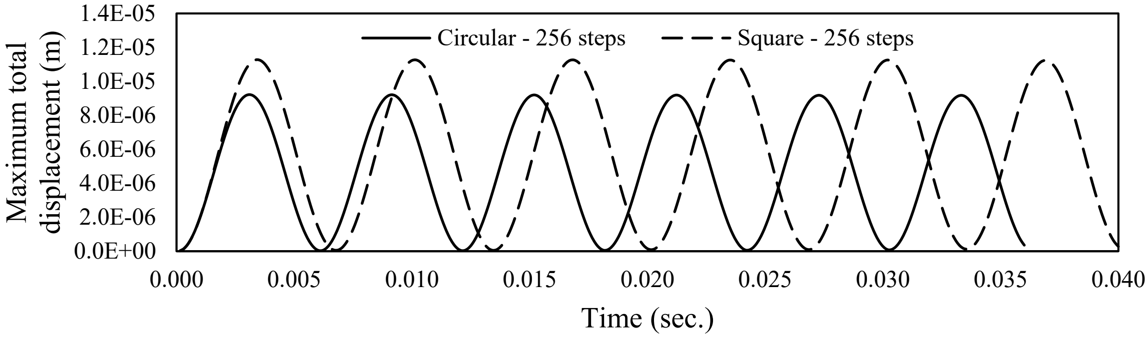


Figure 12. The maximum total displacement of fixed – fixed supported castellated beams with circular and square web openings for n=256

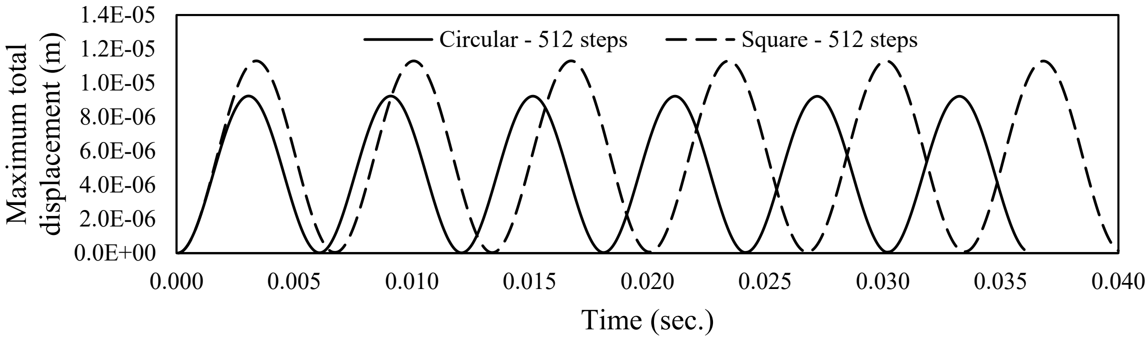


Figure 13. The maximum total displacement of fixed – fixed supported castellated beams with circular and square web openings for n=512

In Fig. (12-13), the maximum total displacement outcomes remained the same when the time step is increased from 256 to 512.

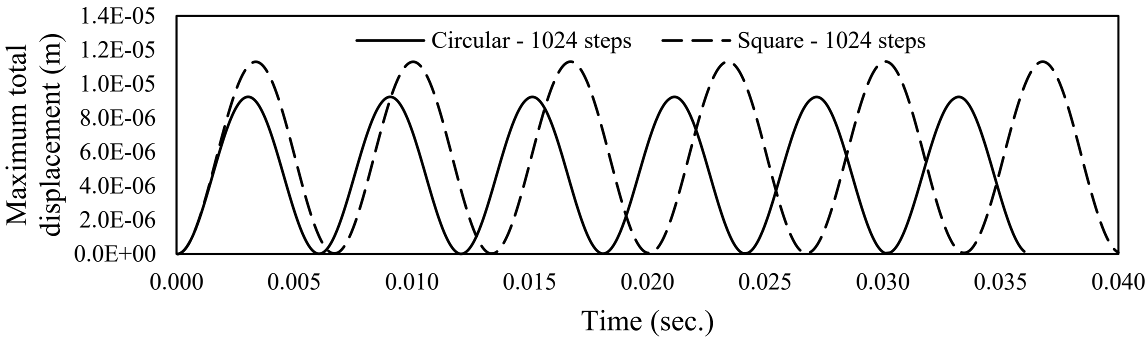


Figure 14. The maximum total displacement of fixed – fixed supported castellated beams with circular and square web openings for n=1024

The comparison between circular and square web openings for various periods indicates that the amplitude values of square web openings are greater than those of circular, and it is observed that by increasing the time steps, the amplitude values of the square web opening are increasing. The comparison of circular and pentagonal web openings for (32-1024 time steps) are given in Fig. (15-20).

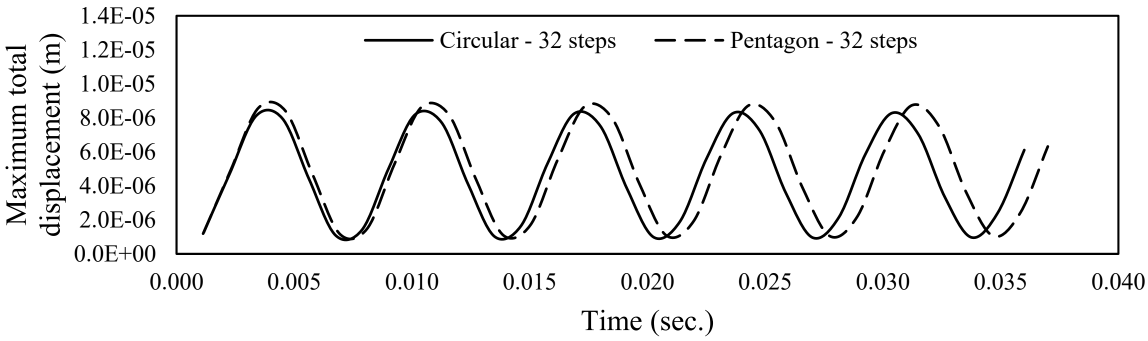


Figure 15. The maximum total displacement of fixed – fixed supported castellated beams with circular and pentagonal web openings for n=32

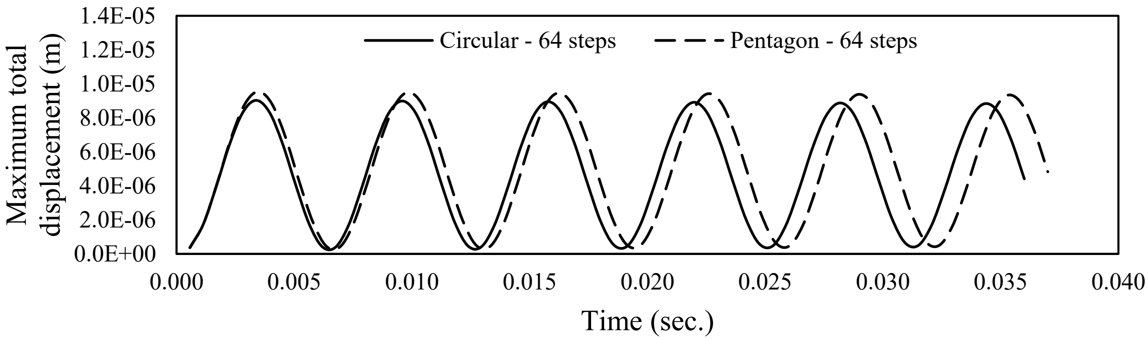


Figure 16. The maximum total displacement of fixed – fixed supported castellated beams with circular and pentagonal web openings for n=64

Pentagonal and circular web openings are compared in Fig. (15-16). It shows, that the amplitude value of the pentagonal web opening is larger than the circular web opening. The comparison between circular and pentagonal web openings for various periods shows that the amplitude values of pentagonal web openings are close to those of circular ones. Especially, in the first period, we can observe that the difference in amplitudes almost disappears. As time increments, there is discernible divergence observed in their amplitudes.

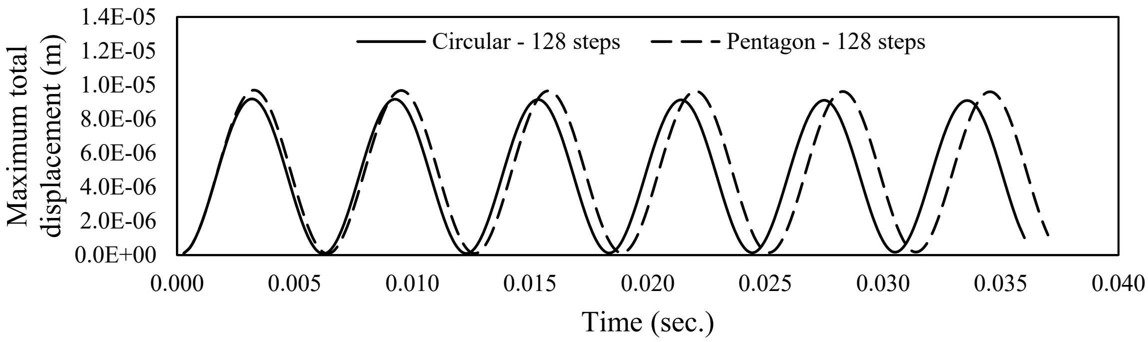


Figure 17. The maximum total displacement of fixed – fixed supported castellated beams with circular and pentagonal web openings for n=128

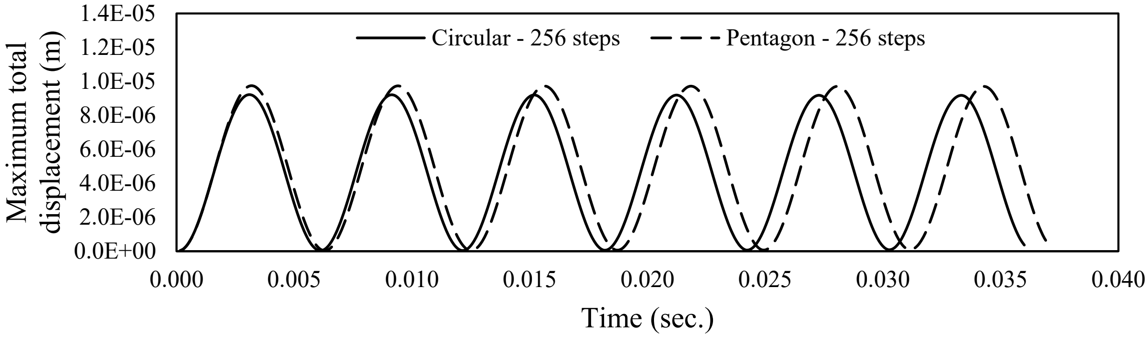


Figure 18. The maximum total displacement of fixed – fixed supported castellated beams with circular and pentagonal web openings for n=256

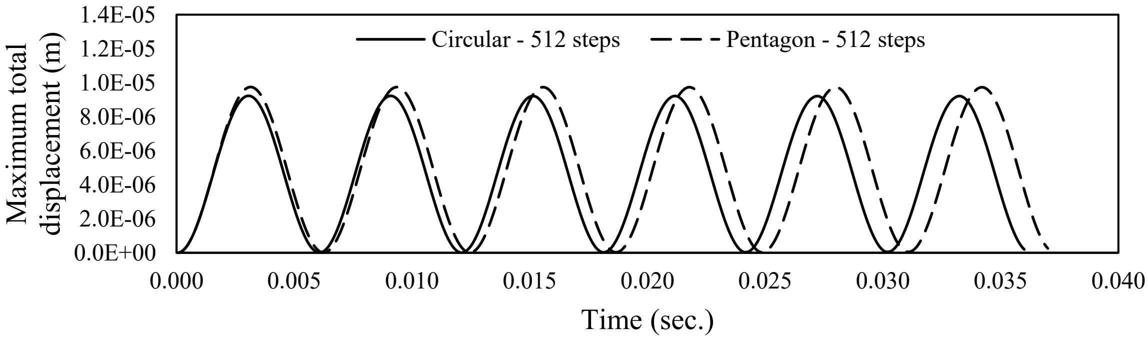


Figure 19. The maximum total displacement of fixed – fixed supported castellated beams with circular and pentagonal web openings for n=512

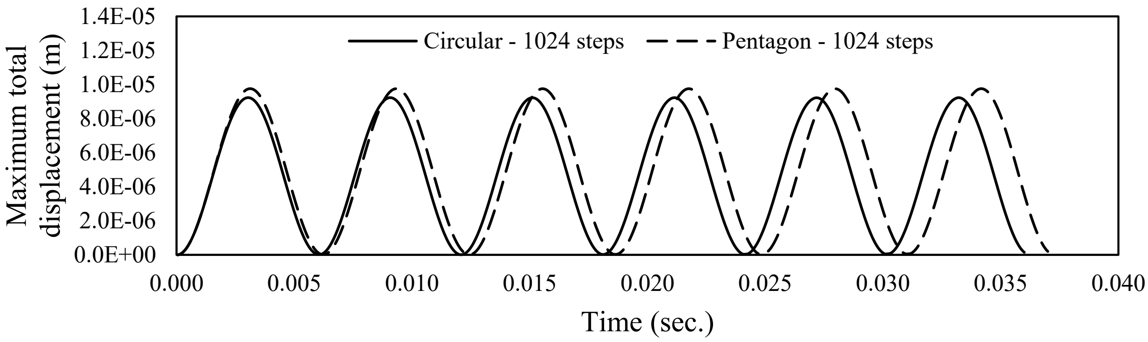


Figure 20. The maximum total displacement of fixed – fixed supported castellated beams with circular and pentagonal web openings for n=1024

The comparison of square and pentagonal web openings for (32-1024 time steps) are given in Fig. (21-26).

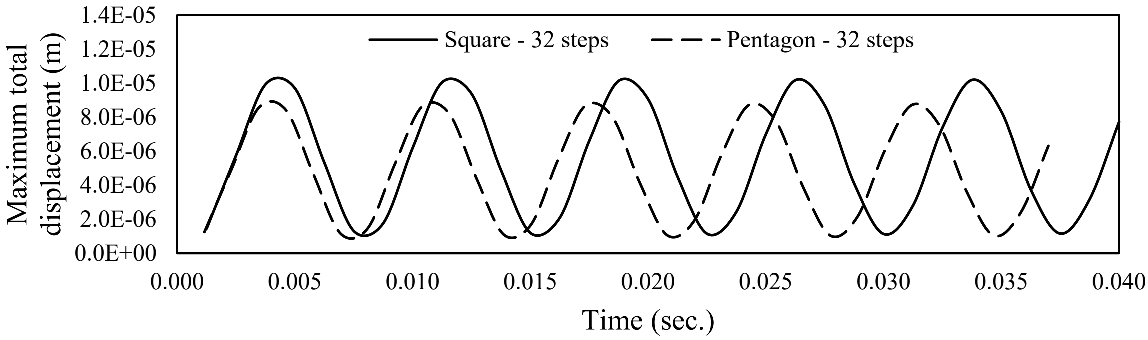


Figure 21. The maximum total displacement of fixed – fixed supported castellated beams with square and pentagonal web openings for n=32

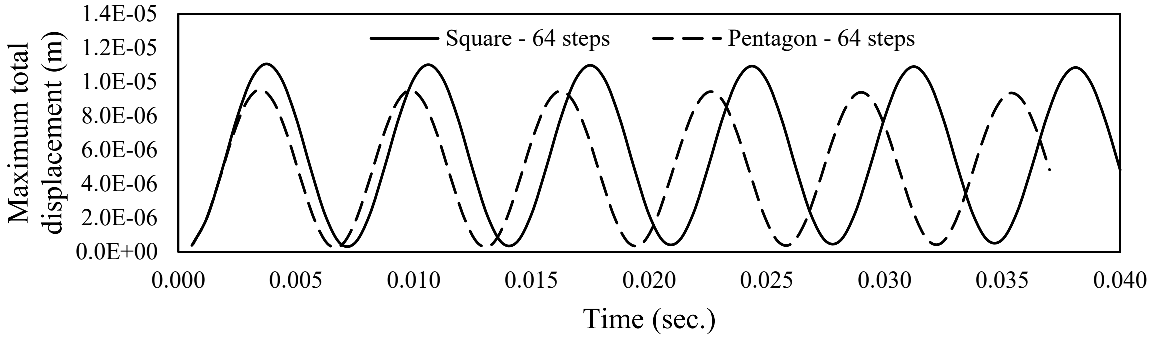


Figure 22. The maximum total displacement of fixed – fixed supported castellated beams with square and pentagonal web openings for n=64

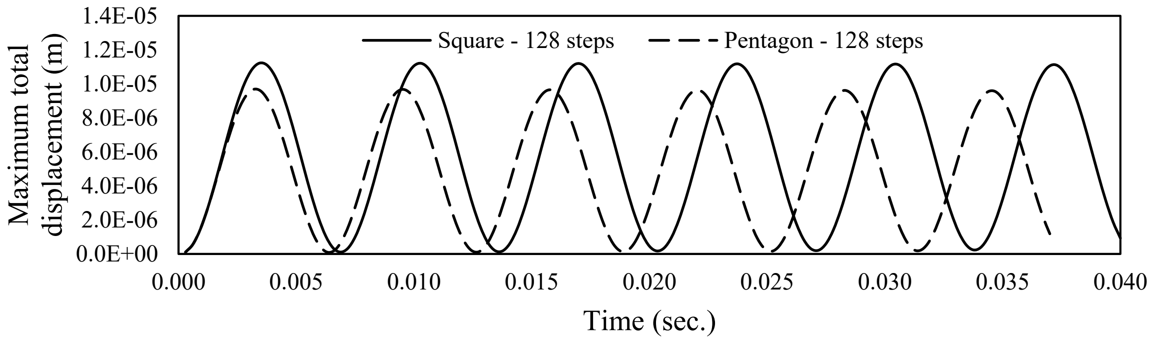


Figure 23. The maximum total displacement of fixed – fixed supported castellated beams with square and pentagonal web openings for n=128

As illustrated in Fig. (21-23), the maximum total displacement results of the square and pentagonal web openings are contrasted.Amplitude values associted with square web openings happens to be larger than those of pentagonal web openings.

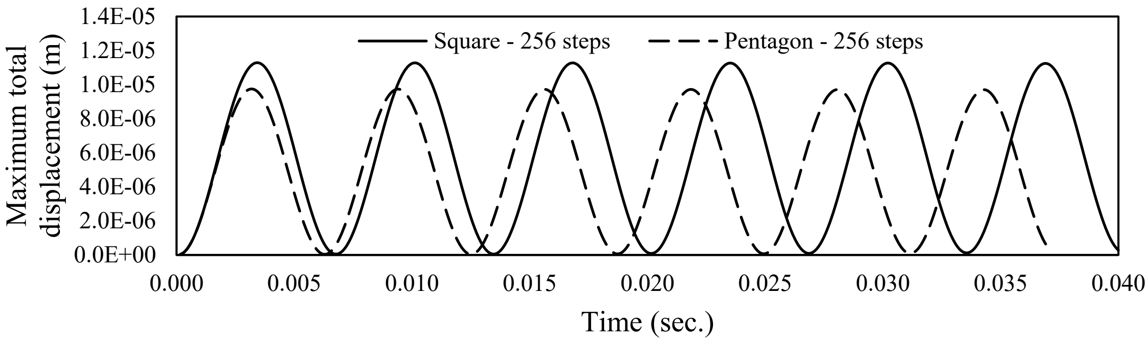


Figure 24. The maximum total displacement of fixed – fixed supported castellated beams with square and pentagonal web openings for n=256

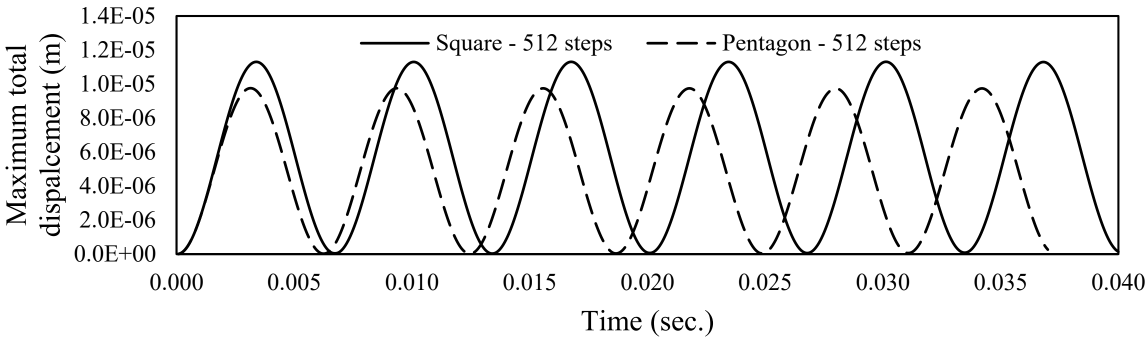


Figure 25. The maximum total displacement of fixed – fixed supported castellated beams with square and pentagonal web openings for n=512

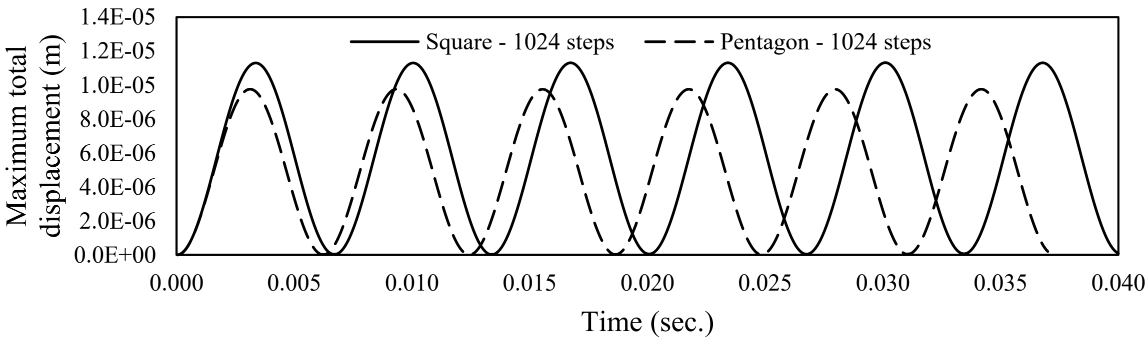


Figure 26. The maximum total displacement of fixed – fixed supported castellated beams with square and pentagonal web openings for n=1024

The comparison between square and pentagonal web openings for various periods indicates that the amplitude values of square web openings are greater than those of pentagonal web openings for all time steps.The comparison of circular, square, and pentagonal web openings for (32-1024 time steps) are shown in Fig.(27-32).

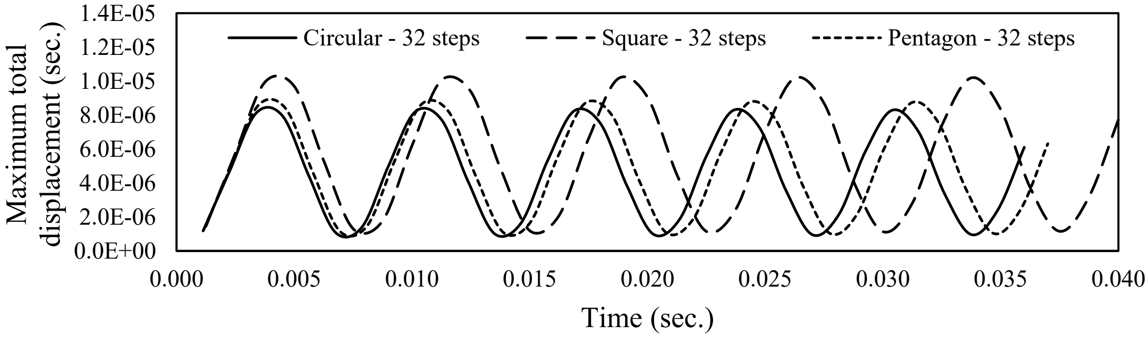


Figure 27. The maximum total displacement of fixed – fixed supported castellated beams with circular, square and pentagonal web openings for n=32

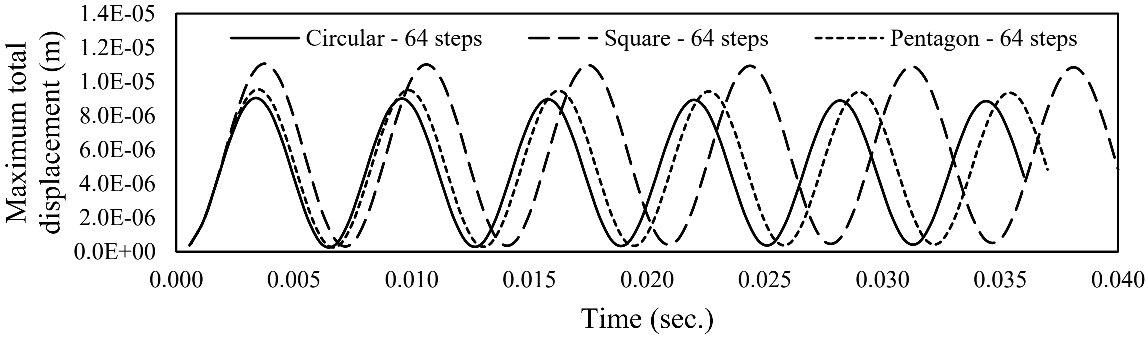


Figure 28. The maximum total displacement of fixed – fixed supported castellated beams with circular, square and pentagonal web openings for n=64

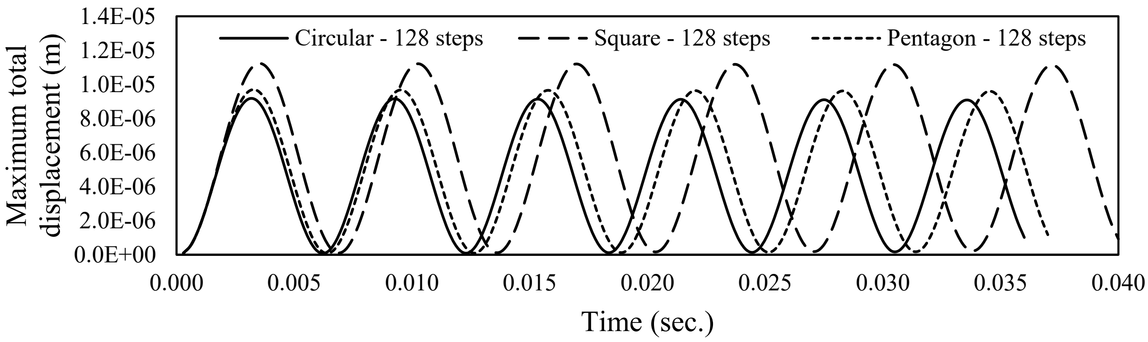


Figure 29. The maximum total displacement of fixed – fixed supported castellated beams with circular, square and pentagonal web openings for n=128

In Fig. (27-30), a comparison of the maximum total displacement values of all three web openings (circular, square, and pentagonal web openings) is conducted. Notably, an increase in temporal increments corresponds to an enlargement of the disparity among the results, concomitant with an increase in the amplitude values. Moreover, it is discerned that square web opening exhibit greater amplitude values compared to pentagonal and circular web openings.

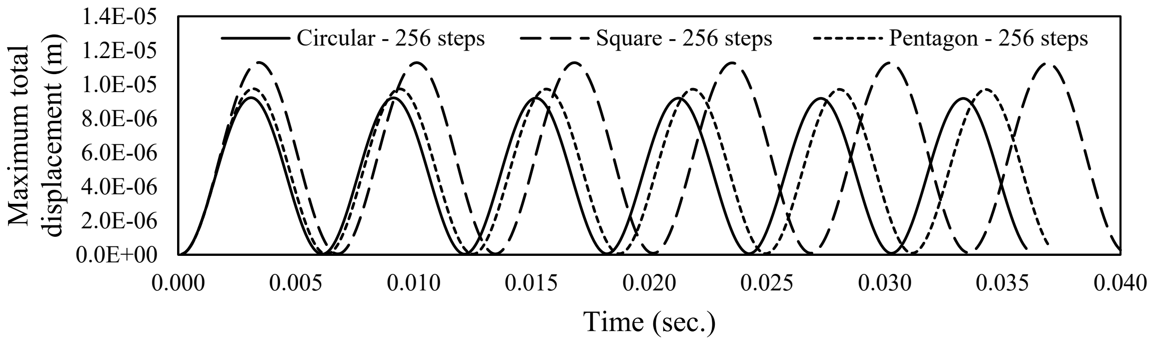


Figure 30. The maximum total displacement of fixed – fixed supported castellated beams with circular, square and pentagonal web openings for n=256

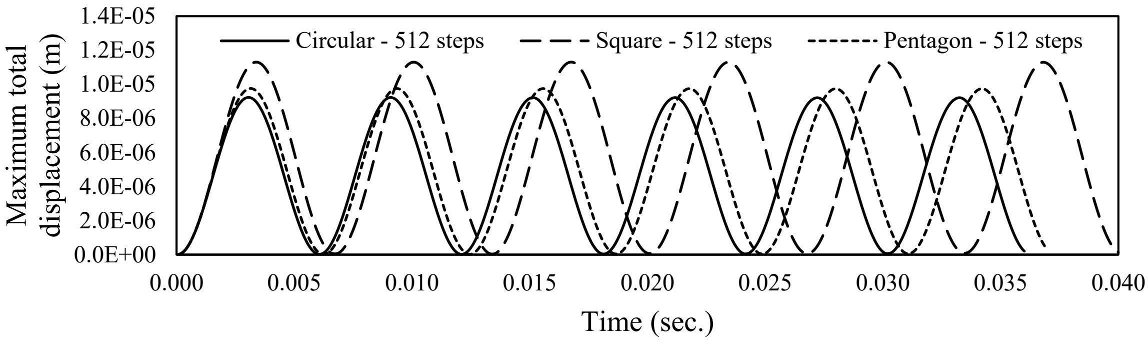


Figure 31. The maximum total displacement of fixed – fixed supported castellated beams with circular, square and pentagonal web openings for n=512

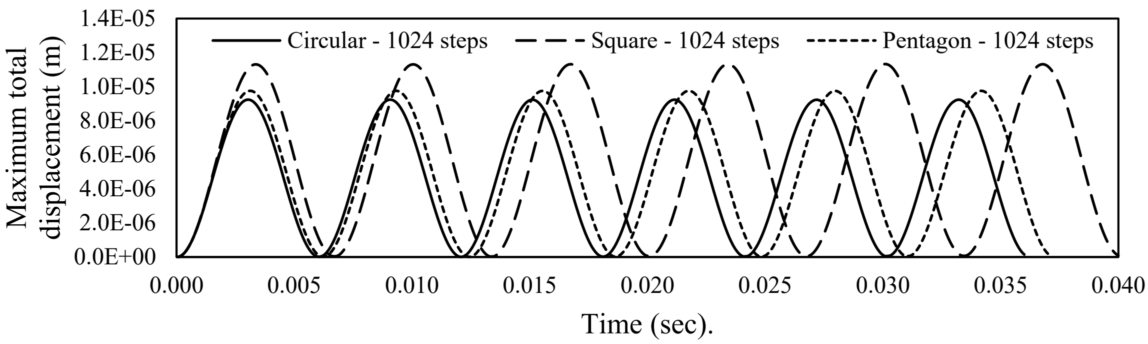


Figure 32. The maximum total displacement of fixed – fixed supported castellated beams with circular, square and pentagonal web openings for n=1024

The comparison between circular, square, and pentagonal web openings for various periods clearly indicates that the amplitude values of square and pentagonal web openings are greater than those of circular web openings. In general, it has shown similar performance for different time steps.

4. Conclusions

This study examined the impact of web opening shape on the dynamic behavior of castellated beam using theoretical analysis. (FEM) implemented through ANSYS Workbench software is employed to create forced vibration models of the studied castellated steel beams. To investigate the effects of various web opening geometries, three different shape configurations are utilized: circular, square, and pentagonal. Boundary conditions of fixed-fixed type are applied to analyze the dynamic behavior of castellated beams manufactured from the IPE300 profile. The results revealed the following outcomes:

- The findings demonstrate that the maximum total displacement within the castellated steel beam occurs when square web openings are present, whereas the least amount of the maximum total displacement is observed when circular web openings are incorporated into the IPE300 profile.
- It is found that the results for castellated steel beams with circular, square, and pentagonal web openings converge at around 512 and 1024 time steps.
- Highly accurate results can be obtained when we use (512 time steps) for six periods and (1024 time steps) for more than ten periods.
- Utilization of an optimal time increment in analysis results in reduced efforts and computational time for castellated beams.
- Accurate results can be obtained when the number of time steps for each period is considered to be 85.
- Evidently, the most favorable results in different time periods are obtained in case of circular web opening configuration.

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