Numerical Analysis of Seismic Response of Circular and Square Tubular Steel Columns under Seismic Loading

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DOI: 10.29322/IJSRP.14.10.2024.p15429

Paper Received Date: 15th September 2024
Paper Acceptance Date: 16th October 2024
Paper Publication Date: 22nd October 2024

Abstract- This study presents a numerical analysis of the seismic response of tubular steel columns with circular and square cross-sections. The analysis focuses on three dimensional models for each cross-sectional type: 300 mm, 400 mm, and 500 mm in diameter or width, with corresponding wall thicknesses of 6 mm, 8 mm, and 10 mm, respectively. Using Finite Element Analysis (FEA) seismostruct, the study investigates the behaviour of these columns under seismic loading, examining the impact of cross-sectional shape, dimensions, and boundary conditions on their structural performance. The results highlight critical factors affecting seismic resilience and provide recommendations for optimizing the design of tubular steel columns.

Index Terms- Tubular steel columns, circular cross-section, square cross-section, seismic response, numerical analysis

I. INTRODUCTION

Numerical analysis of steel columns using Finite Element Analysis (FEA) has become an indispensable tool in modern structural engineering research, especially in understanding the performance of columns under various loading conditions, including seismic forces. FEA provides engineers and researchers with the ability to simulate complex loading scenarios, including those induced by earthquakes, and to examine detailed insights into stress distribution, deformation patterns, and potential failure modes within structural elements. The ability of FEA to model both linear and nonlinear behaviors makes it a critical asset in evaluating the overall stability and resilience of steel columns [1]. While previous studies have explored the behavior of steel columns subjected to axial, bending, and torsional loads, with a particular focus on their buckling behavior and ultimate load capacity, there remains a need for more focused research on the seismic response of tubular columns with varying cross-sectional geometries, particularly circular and square cross-sections. This is especially true when considering different dimensional configurations and boundary conditions, which significantly influence seismic performance [2,3].

The shape and geometry of a column's cross-section play a critical role in determining its response to seismic forces. Circular cross-sections are generally favored for their ability to distribute stress more uniformly and resist torsional effects, which enhances their performance under dynamic loading [4]. Circular columns are less prone to stress concentrations, allowing for smoother stress flow and making them ideal for resisting multi-directional forces during earthquakes. On the other hand, square cross-sections often exhibit higher stress concentrations, particularly at the corners, which increases their susceptibility to local buckling and deformation under seismic loads [5, 6]. Research has shown that circular tubular columns typically outperform square columns under combined loading conditions such as axial, bending, and seismic forces. However, with proper design adjustments, such as increasing wall thickness or incorporating reinforcement, square columns can provide sufficient seismic stability, albeit with careful design considerations to mitigate the risks of buckling and material failure [3,7].

Tubular steel columns, characterized by their high strength-to-weight ratio and efficient load distribution, are widely used in a variety of structural applications, including bridges, high-rise buildings, and industrial structures. Their hollow cross-sections provide significant structural advantages, making them an attractive choice in engineering designs that prioritize both strength and material efficiency. Their ability to resist buckling and maintain load-carrying capacity under dynamic loads, particularly in earthquake-prone regions, underscores their importance in structural engineering [2,6]. Given the increasing frequency and intensity of seismic events in certain parts of the world, it is crucial to understand how tubular columns, especially those with circular and square cross-sections, perform under seismic loading conditions. This knowledge is essential for ensuring the safety and resilience of critical infrastructure during seismic events [5, 4].

In this study, Finite Element Analysis is employed to simulate the seismic response of tubular steel columns. FEA allows for detailed simulations of stress distributions, deformation patterns, and the identification of potential failure modes under dynamic seismic loading. One of the key advantages of FEA is its ability to model both material nonlinearity and geometric nonlinearity, making it ideal for studying how structural elements behave under complex loading scenarios such as earthquake-induced ground motions [1, 7]. The study utilizes FEA to assess the seismic performance of tubular steel columns with circular and square cross-sections, providing valuable insights into the effects of cross-sectional shape, size, and wall thickness on seismic behavior. The findings of this research can inform the development of improved design practices that enhance the seismic resilience of tubular steel columns in critical infrastructure.

The main objective of this study is to conduct a detailed numerical analysis of tubular steel columns with circular and square cross-sections, focusing on their seismic performance under fixed-free boundary conditions. Three different dimensional models were developed for each cross-sectional type, with outer dimensions of 300 mm, 400 mm, and 500 mm and corresponding wall thicknesses of 6 mm, 8 mm, and 10 mm. The fixed-free boundary condition, in which the column's base is fixed and the top is free to move and rotate, was chosen to reflect real-world applications such as cantilevered structures commonly found in bridges and towers [6, 8]. The study aims to evaluate how cross-sectional geometry and dimensions influence the columns' seismic performance, particularly in terms of displacement, base moment, and shear force. Ultimately, the goal is to provide practical recommendations for optimizing the design of tubular columns to improve their performance during seismic events.

II. NUMERICAL MODELING APPROACH

The seismic response of tubular steel columns is a critical consideration in the design of structures located in earthquake-prone regions. The hollow cross-section of these columns, available in both circular and square configurations, offers distinct advantages, including high strength-to-weight ratios, efficient use of materials, and enhanced resistance to buckling and lateral loads [6, 9]. These characteristics make tubular columns a preferred choice for many modern infrastructure projects. However, the seismic performance of tubular steel columns is heavily influenced by various factors, including cross-sectional geometry, column dimensions, wall thickness, and boundary conditions [10].

In this study, Finite Element Analysis (FEA) was employed to simulate the seismic response of tubular steel columns with both circular and square cross-sections. Numerical analysis through FEA allows for detailed insights into the behavior of structures under dynamic loading, making it an indispensable tool in structural engineering [7]. The simulation considered three different dimensional models for each cross-sectional type, varying in both outer dimensions (300 mm, 400 mm, and 500 mm) and wall thicknesses (6 mm, 8 mm, and 10 mm). The selected dimensions and thicknesses reflect a range of practical applications, from smaller-scale structures to more massive load-bearing components [6]. By subjecting the columns to seismic loading conditions, the study replicates the effects of severe earthquake motions, as represented by standard ground motion records, particularly those associated with real earthquake events like the Chi-Chi earthquake [9].

The boundary condition applied in this study is fixed-free, where the base of the column is fully constrained, while the top is free, allowing both movement and rotation [10]. This boundary condition is commonly found in cantilevered structures, such as bridge piers and towers, and it plays a significant role in the column's dynamic response [7, 10]. Under such conditions, the free end experiences large lateral displacements and rotations, making the column highly susceptible to bending moments and buckling under seismic loading. The fixed-free boundary condition has been widely studied in the literature, with research by Zhao & Grzebieta (1999) and Shanmugam & Lakshmi (2001) emphasizing its influence on stress concentrations and structural stability under earthquake-induced forces [9, 10].

To conduct the seismic structural analysis, this study utilized Seismostruct, a sophisticated finite element software known for its ability to model nonlinear static and dynamic structural behavior. Seismostruct is particularly effective in capturing the complex inelastic behaviors of materials under seismic loads, including material degradation, yielding, and plasticity [6, 7]. The software is capable of incorporating advanced material models and handling geometric nonlinearity, allowing for highly accurate simulations of seismic responses in structures. Its ability to perform time-history analysis—applying real-time ground motion data such as that from the Chi-Chi earthquake—provides a realistic representation of the forces and deformations that a structure endures during an earthquake. Time-history analysis is widely regarded as one of the most precise methods for simulating seismic loading, as it considers the entire duration and intensity of ground shaking, rather than relying on simplified static load approximations [6, 10].

Through the application of Seismostruct, this paper focuses on evaluating several key performance metrics, including displacement, base moment, and shear forces. These metrics were analyzed across different column geometries and dimensions to understand how various factors influence the overall seismic resilience of tubular steel columns [7]. The precision of Seismostruct in capturing the inelastic behavior of materials was critical in this analysis, as it enabled the simulation of realistic structural responses under the harsh loading conditions associated with significant seismic events. The circular and square cross-sections analyzed in this study offer different advantages in terms of structural performance, and this research aims to provide a comprehensive comparison of their behavior under dynamic seismic forces [9, 10]. Furthermore, the inclusion of nonlinear behavior in the analysis offers valuable insights into potential failure modes, such as local buckling and excessive deformation, which are essential for developing more resilient structural designs [6, 10].

Table 1 presents the dimensions of the three models for circular and square cross-sections. Each model varies in outer dimension (D for circular sections or W for square sections) and wall thickness (t).

Table 1: Dimensional Models

Model No.	*Cross-section shape*	*Outer dimension (D or W)*	*Wall thickness t*
1	Square	300 mm	6 mm
2	Square	400 mm	8 mm
3	Square	500 mm	10 mm

4	Circle	300 mm	6 mm
5	Circle	400 mm	8 mm
6	Circle	500 mm	10 mm

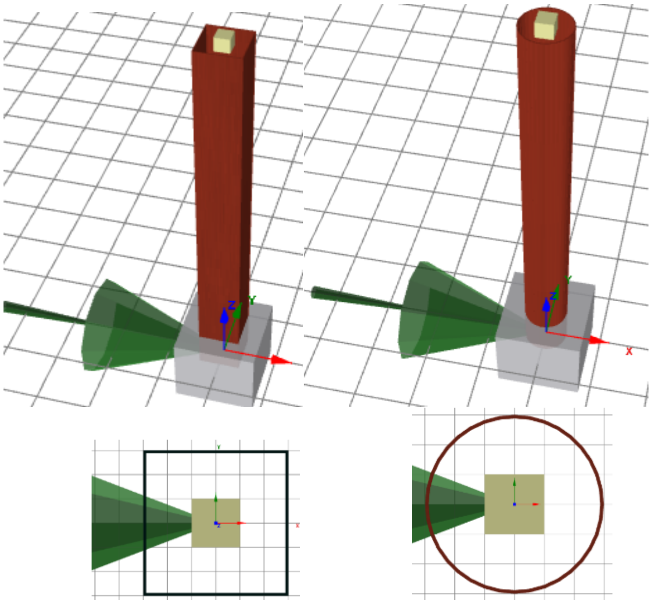


Figure 1: Column Models

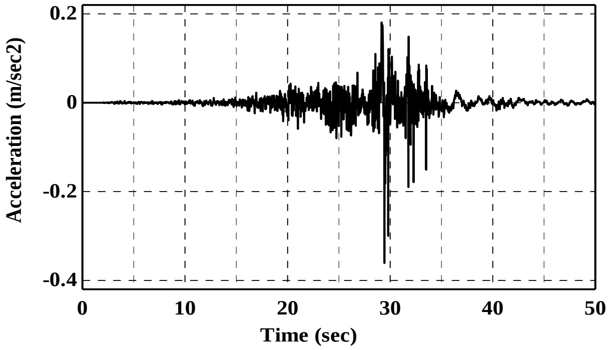


Figure 2: Input waves

III. INPUT GROUND MOTIONS

The acceleration-time history of the Chi-Chi earthquake presents a seismic event lasting 50 seconds, with the most intense ground motion occurring between 20 and 30 seconds, where acceleration peaks range from 0.2 m/sec² to -0.4 m/sec². This period represents the most critical phase of the earthquake, where columns will experience the highest dynamic forces. Before and after this phase, the accelerations are smaller, with the motion tapering off after 35 seconds. This earthquake motion will be used as input ground motion at the base of steel columns to evaluate their seismic response, particularly their stability, displacement, and resistance to dynamic forces under severe seismic loading [11]. The input wave characteristics can be shown in **Fig. 2**.

IV. RESULTS AND DISCUSSION

The dynamic time history analysis conducted in this study compares the seismic performance of six tubular steel column models under seismic loading, specifically examining three square cross-section models and three circular cross-section models. The analysis is visualized in **Fig. 3(a)** for the square models and **Fig. 3(b)** for the circular models. The models were evaluated in terms of their lateral displacement, which serves as a key indicator of their flexibility and resistance to seismic forces. Each model varied in cross-sectional geometry, outer dimensions, and wall thickness, providing a comprehensive comparison of how these factors influence the columns' dynamic behavior under earthquake-induced loading.

For the square cross-section models, the results show a clear relationship between cross-sectional size, wall thickness, and seismic performance. Model 1 (300 mm side length, 6 mm wall thickness) exhibited the highest lateral displacement of 0.19 mm among the square models, indicating that it was the most flexible and, consequently, the least resistant to seismic forces. The smaller cross-sectional area and thinner walls contribute to lower stiffness, making the column more susceptible to lateral movement during the seismic event. This flexibility, while beneficial in absorbing energy, also increases the risk of local buckling or excessive deformation, especially under prolonged or intense seismic loading.

As the dimensions and wall thickness increased, the models displayed significantly improved seismic resistance. Model 2 (400 mm side length, 8 mm wall thickness) exhibited a reduced displacement of 0.08 mm, representing a 58% decrease in flexibility compared to Model 1. The larger cross-sectional area and thicker walls provide increased stiffness, which enhances the column's ability to resist lateral forces during seismic events. The reduced displacement in Model 2 highlights the importance of both size and material distribution in improving the dynamic response of square tubular columns.

Model 3 (500 mm side length, 10 mm wall thickness) showed the smallest displacement among the square models, with a value of 0.05 mm, reflecting its superior stiffness and highest resistance to seismic forces. The increased size and wall thickness significantly enhance the structural integrity of the column, making it more stable under dynamic loading conditions. Model 3's performance demonstrates that increasing both the cross-sectional dimension and wall thickness results in substantial gains in seismic performance, with the column showing minimal lateral movement and a greater ability to resist bending moments and shear forces. This model's low displacement suggests that it is well-suited for critical structural applications where seismic resilience is a priority, such as in high-rise buildings or bridges.

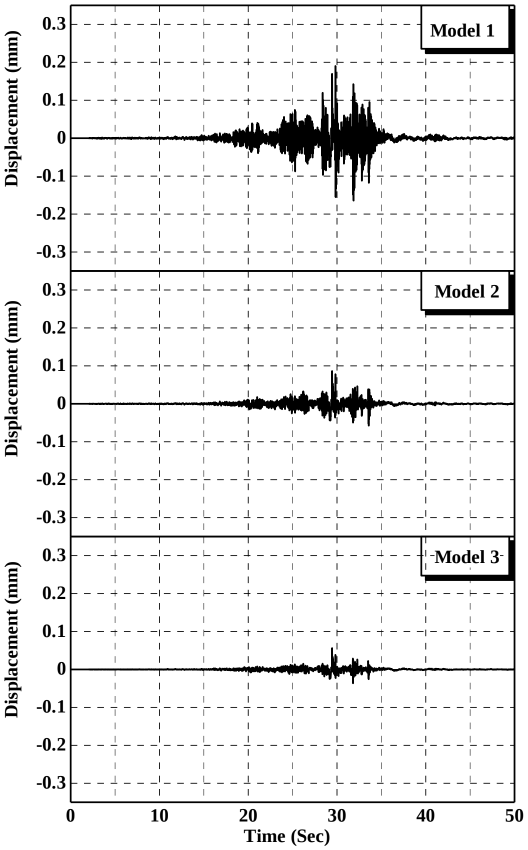
The circular cross-section models followed a similar trend, though with overall higher displacements compared to their square counterparts. Model 4 (300 mm diameter, 6 mm wall thickness) exhibited the largest displacement among all models, with a value of 0.31 mm. This indicates that it was the most flexible and had the lowest seismic resistance. The circular geometry, while providing better stress distribution under static loads, tends to offer less lateral stiffness compared to square cross-sections during seismic events. This flexibility can result in higher deformations, making circular columns, particularly smaller ones with thinner walls, more vulnerable to seismic forces.

As with the square models, increasing the diameter and wall thickness led to improved seismic performance in the circular models. Model 5 (400 mm diameter, 8 mm wall thickness) showed a reduced displacement of 0.12 mm, representing a 61% decrease in displacement compared to Model 4. The larger diameter and thicker walls contributed to greater stiffness, though it remained more flexible than the equivalent square model. The improved performance of Model 5 suggests that increasing the size and wall thickness of circular columns is effective in enhancing their resistance to seismic loading, though not to the same extent as square columns.

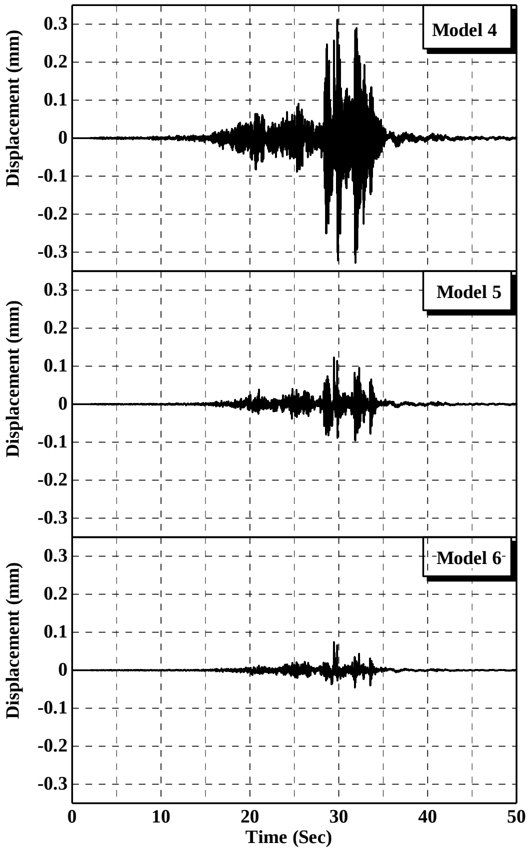
Model 6 (500 mm diameter, 10 mm wall thickness) exhibited a displacement of 0.074 mm, the lowest among the circular models, but still higher than the square models. While the increased size and wall thickness improved the stiffness of the column, making it more resistant to lateral forces, the circular cross-section inherently provides less lateral rigidity than the square cross-section, which explains the higher displacement compared to the similarly sized Model 3 (square, 500 mm, 10 mm). Nevertheless, Model 6's performance indicates that larger circular columns with thicker walls can still offer satisfactory seismic performance, particularly in applications where torsional resistance and flexibility are desired.

The comparative analysis between the square and circular cross-section models highlights the significant impact of cross-sectional geometry on seismic performance. Square cross-sections consistently exhibited lower displacements, indicating greater stiffness and better resistance to seismic forces compared to circular cross-sections of similar dimensions. Model 3 (square, 500 mm side length, 10 mm wall thickness) was the best performer, showing the least displacement of 0.05 mm, making it the most resilient to seismic loading. In contrast, Model 4 (circular, 300 mm diameter, 6 mm wall thickness) was the least resistant, with a displacement of 0.31 mm.

The superior performance of square cross-sections in structural applications, particularly under seismic loading, is largely due to their ability to resist bending moments and shear forces more effectively than circular cross-sections. The corners of square columns provide additional stiffness, reducing lateral deformations during dynamic loading and making them ideal for high-rise buildings and bridge piers in earthquake-prone areas. In contrast, circular columns, while more flexible and prone to larger displacements due to their lack of corners, offer advantages in torsional resistance and uniform stress distribution, making them suitable for structures like towers and chimneys. However, their lower lateral stiffness requires more precise design considerations, such as increased wall thickness or reinforcement, to ensure seismic resilience, especially in regions with high seismic activity. Ultimately, the choice between square and circular cross-sections depends on the specific structural requirements, with square sections excelling in lateral stability and circular sections in torsional strength.

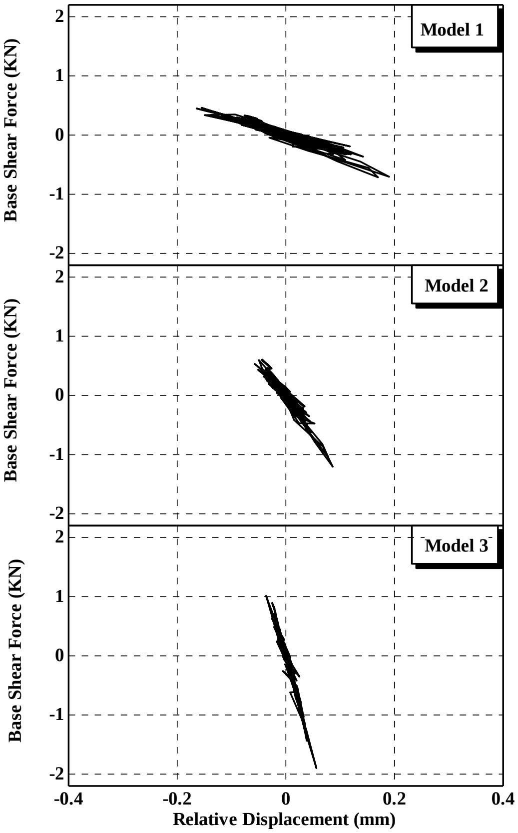


(a) Square Cross-sections

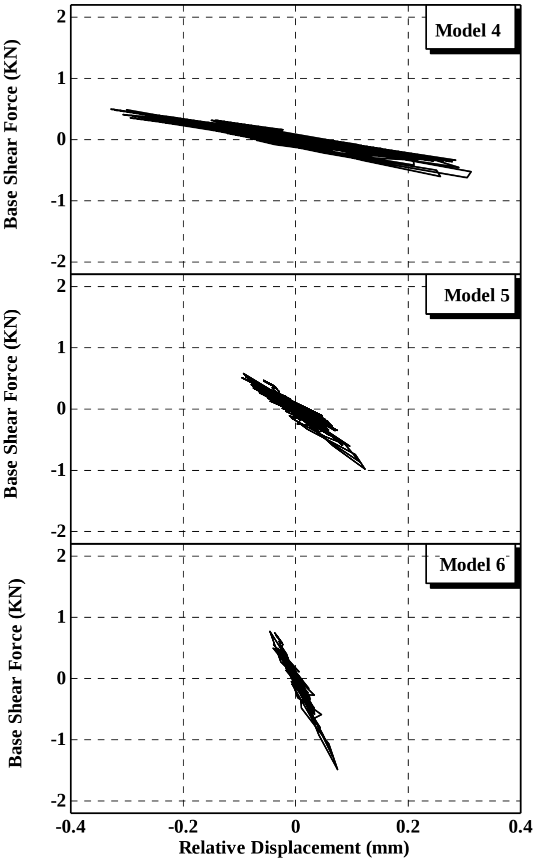


(b) Circular Cross-sections

Figure 3: Displacement time-history



(a) Square Cross-sections



(b) Circular Cross-sections

Figure 4: Hysteric Displacement Force Relationship

The hysteresis curves for six tubular steel column models three with square cross-sections, **Fig. 4(a)** and three with circular cross-sections, **Fig. 4(b)** reveal the relationship between relative displacement and base shear force under cyclic loading, an essential aspect of seismic performance. The hysteresis loops provide valuable insights into energy dissipation, stiffness, and ductility of the columns during seismic events.

In **Fig. 4(a)**, the square cross-section models demonstrate a clear trend where increasing cross-sectional dimensions and wall thicknesses lead to improved seismic performance. Model 1 (300 mm side length, 6 mm thickness) exhibits the smallest base shear force of 0.714 KN and the narrowest hysteresis loop, reflecting its limited ability to dissipate energy and lower overall stiffness. The narrow hysteresis loop indicates that Model 1 experiences higher levels of inelastic deformation without efficiently absorbing seismic energy, making it more susceptible to local buckling and excessive displacement under dynamic loading.

As the dimensions and wall thickness increase, both Model 2 (400 mm side length, 8 mm thickness) and Model 3 (500 mm side length, 10 mm thickness) show significant improvement in performance. Model 2 demonstrates a larger hysteresis loop and a higher base shear force of 1.205 KN, indicating greater energy dissipation and increased stiffness. Model 3 performs the best among the square cross-section models, with the largest hysteresis loop and the highest base shear force of 1.901 KN. The wider hysteresis loop for Model 3 suggests its superior ability to absorb and dissipate seismic energy, which enhances its resistance to seismic forces. The increased wall thickness and cross-sectional size also contribute to better resistance to bending moments and shear forces, making Model 3 the most resilient to dynamic loading conditions.

In **Fig. 4(b)**, the circular cross-section models exhibit similar behavior, but their overall performance lags behind the square models in terms of stiffness and energy dissipation. Model 4 (300 mm diameter, 6 mm thickness) has the smallest base shear force of 0.622 KN and the narrowest hysteresis loop, indicating that it is the most flexible and least resistant to seismic forces. The limited energy dissipation in Model 4 results in higher lateral displacement and a lower capacity to resist inelastic deformations, making it more vulnerable to buckling under seismic loading.

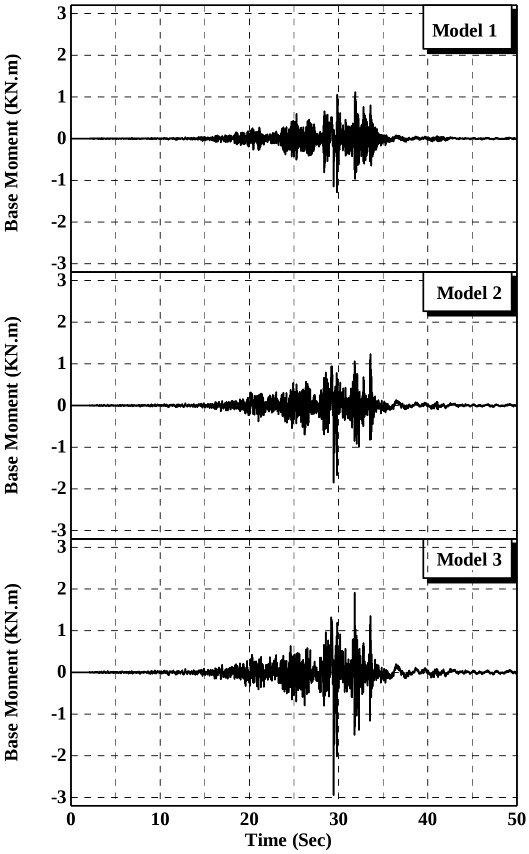
As the dimensions and thickness increase, Model 5 (400 mm diameter, 8 mm thickness) and Model 6 (500 mm diameter, 10 mm thickness) show improved seismic resistance, with base shear forces of 0.98 KN and 1.49 KN, respectively. While these values represent better performance than Model 4, they are still lower than their square counterparts. The circular models exhibit narrower hysteresis loops, suggesting that while the increase in size and thickness improves performance, circular columns are inherently more flexible and less efficient at dissipating seismic energy compared to square columns. Model 6, despite having a larger size and wall thickness, still trails behind Model 3 (square, 500 mm side length, 10 mm thickness) in terms of energy absorption and overall stiffness.

The dynamic time history analysis further evaluates the seismic performance of the columns by analyzing the base moments under seismic loading. Figure 5(a) displays the results for the square cross-sections, with Model 1 (300 mm side length, 6 mm thickness) showing the smallest base moment of 0.013 KN.m, indicating that it has the lowest resistance to bending moments. As the dimensions and thickness increase, Model 2 (400 mm, 8 mm thickness) and Model 3 (500 mm, 10 mm thickness) show progressively higher base moments of 0.019 KN.m and 0.029 KN.m, respectively. This demonstrates that larger dimensions and thicker walls significantly improve the columns' resistance to seismic-induced bending forces, making them more stable under dynamic loading. The higher base moment in Model 3 indicates superior moment resistance, making it the most stable and rigid under seismic conditions.

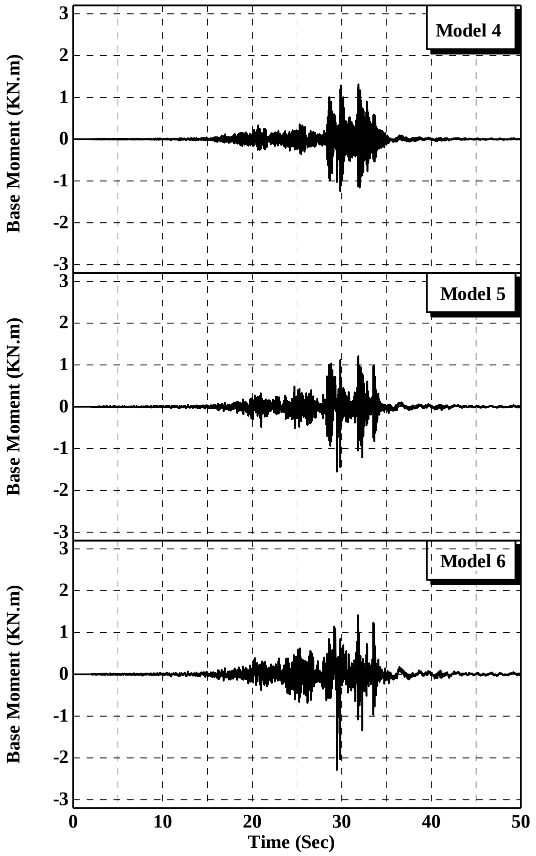
In **Fig. 5(b)**, which represents the circular cross-section models, Model 4 (300 mm diameter, 6 mm thickness) also shows a low base moment of 0.013 KN.m, similar to Model 1 (square). As the dimensions and thickness increase, Model 5 (400 mm diameter, 8 mm thickness) and Model 6 (500 mm diameter, 10 mm thickness) display higher base moments of 0.016 KN.m and 0.023 KN.m, respectively. Although Model 6 performs better than the other circular models, it still exhibits a lower base moment than Model 3 (square), indicating that circular cross-sections are less effective at resisting bending forces than square cross-sections of comparable dimensions and thicknesses.

Square cross-sections provide better moment resistance compared to circular cross-sections of similar dimensions and thicknesses. Model 3 (square, 500 mm, 10 mm thickness) performs the best, with the highest base moment of 0.029 KN.m, indicating superior stability and resistance to dynamic forces. In contrast, both Model 4 (circular, 300 mm, 6 mm thickness) and Model 1 (square, 300 mm, 6 mm thickness) exhibit the lowest base moments of 0.013 KN.m, suggesting that smaller columns, regardless of their cross-sectional shape, are more flexible and less resistant to seismic forces. However, the square cross-sections consistently show greater moment resistance across all models, indicating that they are better suited for seismic applications where stiffness and moment resistance are critical.

Based on the findings from the numerical analysis, several design recommendations are proposed to enhance the seismic performance of tubular steel columns:
1. Circular Cross-Sections: These are preferred for applications where torsional resistance is critical, but they require increased wall thickness or additional reinforcement to improve their resistance to bending moments and reduce the risk of buckling.
2. Square Cross-Sections: While square columns offer better seismic resistance, they are prone to local buckling at the corners. To mitigate this risk, square sections should be designed with increased wall thickness or corner reinforcement to ensure stability under seismic loading.
3. Boundary Conditions: For columns with fixed-free boundary conditions, additional bracing or support measures should be considered to reduce lateral displacement at the free end and delay the onset of buckling, ensuring the column's stability during seismic events.



(a) Square Cross-sections



(b) Circular Cross-sections

Figure 5: Hysteric Displacement Force Relationshi

V. CONCLUSIONS

This study provided a comprehensive numerical analysis of the seismic response of tubular steel columns with circular and square cross-sections under various boundary conditions. The analysis demonstrated that circular cross-sections generally offer superior seismic performance due to their ability to distribute stress more uniformly and resist torsional effects. Square cross-sections, while advantageous in certain design contexts, exhibited higher susceptibility to local buckling.

The findings of this study have significant implications for the structural design of tubular steel columns in seismic regions. Designers and engineers should prioritize the use of circular cross-sections in applications where seismic performance is critical. For square cross-sections, additional design measures, such as increased wall thickness and reinforcement, are necessary to ensure adequate seismic performance. These recommendations aim to enhance the resilience of steel structures against seismic forces and contribute to safer and more reliable infrastructure.

While this study provided valuable insights into the seismic performance of tubular steel columns, several limitations should be acknowledged. The numerical analysis was based on idealized models and may not fully capture the complexities of real-world conditions, such as material imperfections or construction variability. Future research should explore these factors in more detail, as well as investigate the performance of other cross-sectional shapes, such as elliptical or hexagonal sections. Additionally, further studies should examine the impact of different types of seismic loading and explore advanced design and retrofit techniques for improving the seismic resilience of tubular steel columns.

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