

Journal of Materials and Engineering Structures

Research Paper

Comparative Numerical Study of Reinforcement Buckling in Square vs. Circular RC Bridge Piers under Seismic Loading

H. Bouazza^a, M. Djelil^{a,b}, M. Matallah^{a,*}

^a Risk Assessment and Management Laboratory, University of Tlemcen, B.P.119, Tlemcen, 13000, Algeria.

^b Smart Structures Laboratory, University of Ain-Témouchent, B.P. 248, Ain-Témouchent, 46000, Algeria.

ARTICLE INFO

Article history:

Received : 25 November 2025

Revised : 10 December 2025

Accepted : 10 December 2025

Keywords:

Reinforced concrete (RC) bridge piers

Cross-sectional geometry

Reinforcement buckling

Seismic performance

OpenSees simulations

ABSTRACT

A series of nonlinear simulations is conducted using fiber-based beam-column elements in OpenSees, where square and circular piers are modeled under identical axial load ratios, flexural stiffness, and material properties. Longitudinal reinforcement behavior is captured using an advanced phenomenological hysteretic steel model that accounts for inelastic bar buckling, while the effective buckling length is determined through analytical formulations. Cross-section discretization is performed in accordance with best practices, and the circular pier configuration is calibrated against benchmark experimental data.

Results highlight distinct differences in bar stability, stiffness degradation, and energy dissipation between the two geometries. The findings emphasize the importance of geometric confinement in delaying bar instability and sustaining seismic performance. This study contributes to a more accurate understanding of reinforcement buckling mechanisms and provides guidance for the seismic design of ductile RC bridge piers.

1 Introduction

Reinforced concrete (RC) columns are fundamental structural elements that ensure the vertical and lateral stability of bridges, especially under seismic loading. Over the past decades, devastating earthquakes have highlighted the vulnerability of RC columns, particularly when they are exposed to large inelastic deformations. One of the most critical local failure mechanisms that affect their seismic performance is the **buckling of longitudinal reinforcement**. This phenomenon typically leads to a rapid loss of stiffness, reduced energy dissipation capacity, and, in severe cases, premature collapse. To better understand and mitigate these failure modes, numerous experimental and numerical studies have been undertaken. However, a majority of them have focused on uniaxial loading scenarios, which do not fully reflect the multidirectional nature of real

* Corresponding author.

E-mail address: mohammed.matallah@gmail.com

earthquake ground motions. Recent works underline the importance of considering reinforcement detailing, cross-sectional geometry, and local instability simultaneously. For example, biaxial dynamic analyses have shown that circular RC columns, thanks to their spiral reinforcement, provide more uniform confinement and therefore achieve higher ductility and stability [1]. Other studies confirm these findings, reporting that circular columns present a lower collapse risk and improved seismic performance under bidirectional excitations, mainly due to the uniform confinement of spiral reinforcement [2].

The role of reinforcement buckling as a dominant degradation mechanism has been extensively investigated. It was shown in [3] that accounting for inelastic bar buckling in nonlinear models significantly influences the predicted seismic capacity and failure modes of RC columns. This conclusion was further supported in [4], where fiber-based damage analysis revealed that neglecting bar instability can lead to non-conservative estimates of column strength and ductility, particularly at high drift levels.

To capture such degradation mechanisms with greater accuracy, an advanced hysteretic steel material model that accounts for bar buckling and low-cycle fatigue degradation. This model has since been widely adopted for the seismic simulation of RC columns and bridge piers. In the same line, [5] emphasized the need to explicitly incorporate bar buckling, slip, and fatigue in seismic fragility assessments. Their study on circular RC bridge piers showed that omitting these effects results in non-conservative estimates of failure probability. They therefore advocate for more detailed simulations of steel instability to ensure the reliability of performance-based design approaches.

Despite extensive research on the seismic behavior of RC columns, a key research gap persists concerning the isolated role of cross-sectional shape—particularly square versus circular sections—in influencing inelastic buckling and fatigue degradation of longitudinal reinforcement. Most existing studies assess cross-sectional effects in conjunction with other parameters such as bidirectional loading, varying axial load levels, or cumulative fatigue, which complicates the interpretation of geometric influence alone. As a result, it remains unclear to what extent the observed structural degradation is driven by shape-induced variations in confinement effectiveness and the susceptibility of longitudinal reinforcement to inelastic bar buckling.

To address this gap, the present study conducts a controlled numerical comparison of square and circular RC bridge piers subjected to cyclic seismic loading, focusing on their differential susceptibility to reinforcement buckling and post-yield degradation. Using nonlinear fiber beam-column elements in OpenSees, both column types are modeled with identical axial load ratios, flexural stiffness, and material properties to ensure comparability. Reinforcement behavior is captured using the phenomenological hysteretic steel model [4], which accounts for inelastic bar buckling effects. The effective buckling length is calculated following the formulation in [6], while the fiber section discretization follows the guidelines in [7]. To ensure realism, the circular column geometry is further calibrated against experimental data from [8].

This study contributes to closing a critical gap by systematically evaluating the influence of cross-sectional shape on reinforcement instability mechanisms, offering new insight into the design and detailing of ductile RC bridge piers under seismic demands.

Table1- Details of the hypothetical columns.

Cross section shape	L (mm)	L/D	L_{eff}/d	$\rho_l(\%)$	$\rho_s(\%)$	$N_u/(f_c A_g)$	T(s)
Square	2438.4	4	10	1.49	0.7	0.04	0.27
Circular	2438.4	4.5	10	1.72	0.8	0.04	0.24

Column height (L), shear span to depth ratio (L/D), the ratio of effective buckling length of longitudinal bar to its diameter (L_{eff}/d), The longitudinal bars ratio (ρ_l), volumetric ratio of transverse reinforcements (ρ_s), axial force ratio $N_u/(f_c A_g)$ and fundamental period of each column (T).

2 Modelling Approach and Methodology

The finite element model is developed in OpenSees [9], an open-source platform for earthquake engineering simulation. Reinforced concrete (RC) bridge piers are modeled using nonlinear beam-column elements with fiber-defined cross-sections, allowing the nonlinear behavior to be captured along the member length. Each section is divided into fibers, and each fiber follows a uniaxial nonlinear material law representing steel, unconfined concrete, or confined concrete. The nonlinear

response is simulated using a distributed plasticity approach with force-based elements, which requires few elements while accurately capturing the spread of plasticity along the column.

Force-based elements were integrated using the Gauss-Lobatto scheme, with three and five integration points for the first and second elements, respectively. Fiber discretization followed Berry and Eberhard's recommendations. A zero-length section element was added to capture bar slip at the column base. The fiber beam-column model is illustrated in Figure 1.

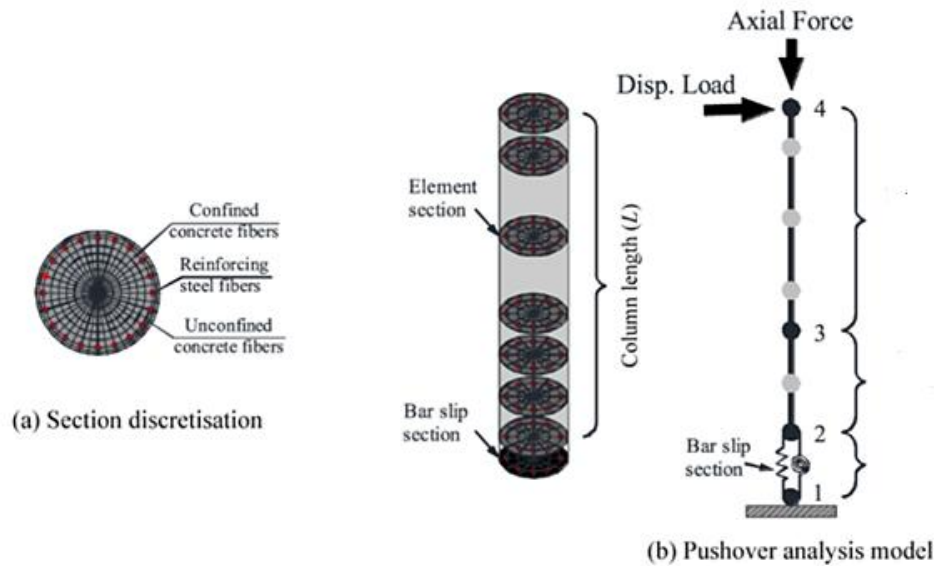


Fig. 1 - Section discretisation (a) and finite element model of RC bridge piers under (b) monotonic and cyclic loading.

In this study, the uniaxial Concrete04 material model is adopted to simulate the behavior of concrete. This model considers both confined and unconfined concrete, employing the Popovics curve [10] for compression and a linear–exponential softening relationship for tension. The cyclic response is captured through predefined unloading and reloading rules. For the longitudinal reinforcement, the uniaxial steel material model developed by Kunnath et al. [11] is implemented. This model accurately reproduces the nonlinear stress–strain behavior of reinforcing bars, including critical phenomena such as inelastic buckling, low-cycle fatigue, and tensile fracture [12]. The mechanical properties of longitudinal and transverse reinforcing bars are tabulated in **Table 2**. The compressive strength of concrete is 30 MPa.

Table 2 - Mechanical properties of reinforcing bars.

Bar type	Transverse bars	Longitudinal bars
Yield strain ϵ_y	0.0028	0.00236
Yield stress $f_y(\text{MPa})$	497	497
Elastic Modulus $E_s(\text{MPa})$	210000	210000
Maximum stress $\epsilon_u(\text{MPa})$	0.0566	0.13
Strain at maximum $f_u(\text{MPa})$	645	662
Fracture strain ϵ_r	0.16	0.195

To further account for the additional rotation at the pier-to-footing interface induced by strain penetration of longitudinal bars, a nonlinear rotational spring element is introduced at the base of the column, as shown in Figure 2. This spring is modeled with a zero-length element defined using the bond_sp01 material [13], which represents an independent fiber section composed of special reinforcement and concrete fibers.

The structural geometry consisted of two cantilever piers with different cross-sectional shapes: square (540×540 mm²) and circular (diameter 609.6 mm), as shown in Table 1, both designed to exhibit identical gross area and initial flexural

stiffness. Reinforcement ratios and detailing were kept constant across both configurations to isolate the influence of geometry. The circular pier model was calibrated using experimental data from Lehman et al. (2004) [8], ensuring realistic confinement and hysteretic response.

Both models were subjected to a constant axial load and cyclic lateral displacements with increasing drift levels. Reinforcement buckling was modeled using the Kashani steel material, with effective buckling length estimated following Dhakal and Maekawa. Bar slip at the column base was simulated using a zero-length section element with the Zhao et al. [13] stress–slip model. The model was validated against experimental results for the circular pier, showing good agreement in strength, stiffness degradation, and energy dissipation. The validated framework was then used to compare the seismic response of square and circular piers.

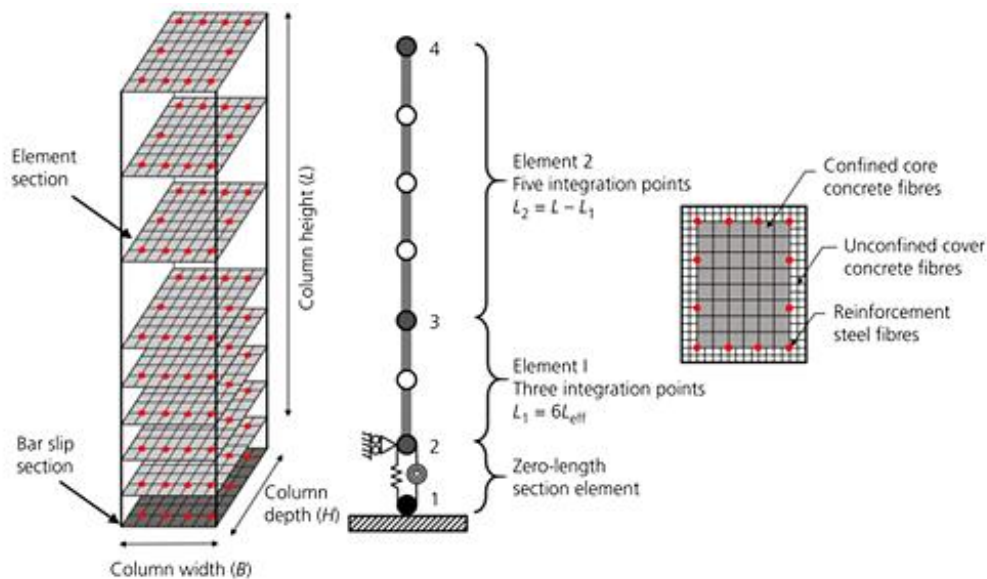


Fig. 2 - Proposed FE model using forced-base non-linear fiber beam-column element.

3 Results and discussions

3.1 Nonlinear static monotonic pushover analyses

The nonlinear pushover analysis shows that the square section exhibits a higher initial stiffness, reflecting greater resistance at small displacements. The circular section, although slightly less stiff at the beginning, reaches a comparable lateral strength and maintains this capacity without showing any post-peak drop. This behavior indicates that both sections preserve good stability beyond yielding, with the circular section demonstrating higher ductility due to its uniform confinement. Consequently, while the square section stands out for its initial rigidity, the circular section proves to be more capable of sustaining large displacements while retaining its strength, which is a significant advantage under seismic loading.

3.2 Global Hysteretic Response

The simulated lateral force–displacement ($F-\Delta$) hysteresis loops revealed clear differences in global seismic response between the square and circular RC piers. Both models initially exhibited stable energy-dissipative behavior at low drift levels; however, beyond 2% drift, the square column began to show pinched loops and a reduction in unloading stiffness, indicating earlier onset of damage. In contrast, the circular column maintained fuller, more stable loops with greater hysteretic energy dissipation even at higher drift amplitudes.

This superior performance of the circular section can be attributed to its more uniform transverse confinement provided by spiral reinforcement, which delays the onset of concrete cover spalling and reinforcement buckling. These results confirm previous experimental findings and highlight the critical role of cross-sectional geometry in controlling post-yield behavior.

3.3 Comparative Performance Summary

As shown in **Figure 3**, the initial stiffness (K_{initial}) of both square- and circular-section columns is nearly identical, reflecting their comparable elastic properties and flexural stiffness. Based on the early linear portion of the pushover curve, the estimated initial stiffness is on the order of 1.2×10^4 kN/m. Differences emerge in the post-yield phase: the square-section column develops a higher maximum lateral bearing capacity, reaching approximately 320 kN at a displacement of 0.10–0.11 m, whereas the circular-section column attains a slightly lower peak of about 290 kN at a similar displacement level. However, the circular column sustains larger deformations, with a gradual strength decay extending up to nearly 0.18 m, in contrast to the shorter plateau and more abrupt strength degradation of the square column.

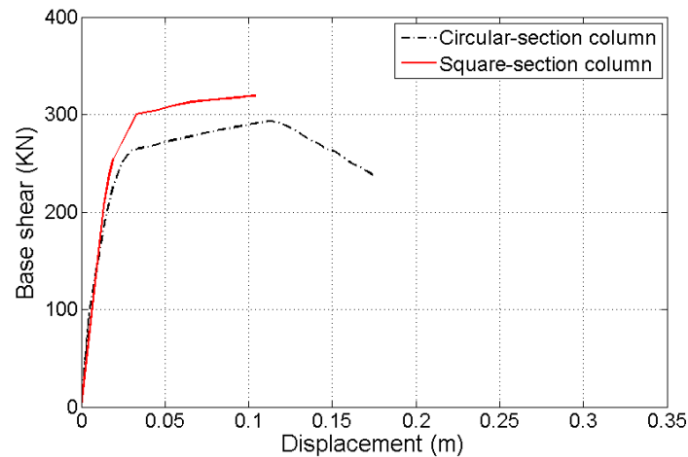


Fig. 3 - Pushover comparison: Base shear vs. displacement capacity for square- and circular-section RC columns.

These results indicate that the square-section column provides greater over strength but limited ductility, while the circular-section column offers enhanced deformation capacity and more stable post-peak behavior. From a seismic design perspective, this highlights a strength–ductility trade-off, where square sections may maximize peak resistance, but circular sections are more effective in sustaining energy dissipation and ensuring reliable performance under large seismic demands.

The key takeaway is that cross-sectional shape has a profound impact on seismic performance as shown in **figure 4 and 5**.

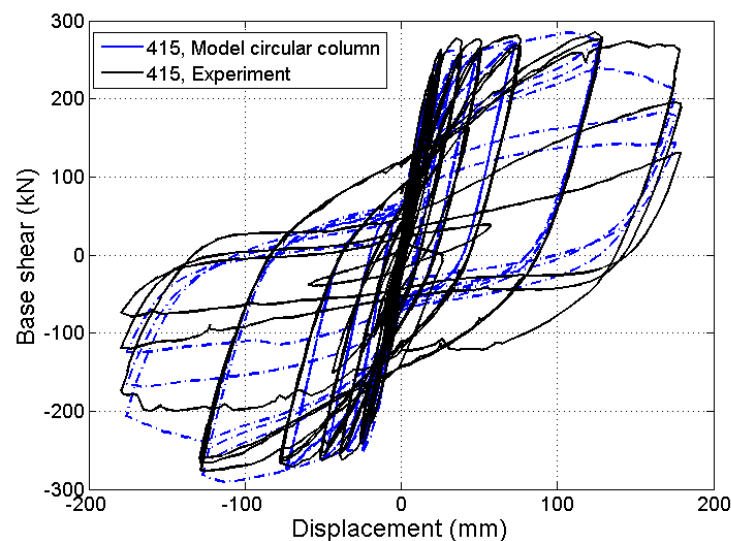


Fig. 4 - Effect of Reinforcement Buckling and Low-Cycle Fatigue on the Hysteretic Response: Comparison between Square and Circular Sections

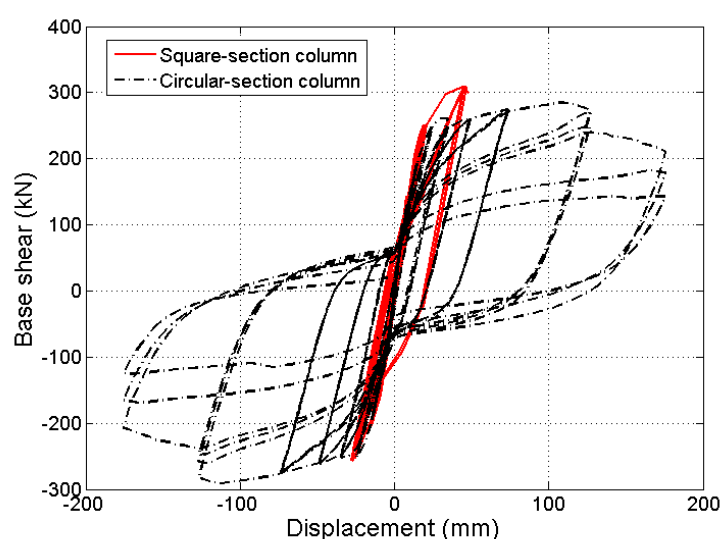


Fig. 5 - Effect of Reinforcement Buckling and Low-Cycle Fatigue on the Hysteretic Response: Comparison between Square and Circular Sections

The **circular column** is the superior seismic performer. Its shape allows for more effective confinement of the concrete core (typically with spiral reinforcement), which prevents brittle crushing and enables the stable, ductile behavior seen in the pushover curve. This confirms a well-established principle in seismic design. The **square column**, despite being equally strong, performs poorly under cyclic loads. Its straight reinforcement bars (ties) provide less effective confinement, especially at the mid-sides, leading to concrete crushing, bar buckling, and the pinched, degraded hysteresis loops observed.

4 Conclusion

This study investigates the influence of cross-sectional shape on the behavior of reinforced concrete columns. Two column types — square and circular — with equivalent stiffness and dynamic characteristics were modeled. An advanced structural modeling technique, capable of capturing longitudinal rebar buckling and low-cycle fatigue effects, was implemented.

The main findings of this research are as follows:

Square columns are more sensitive and prone to damage in comparison to circular columns with similar dynamic characteristics. This is particularly true for the reinforcements located at the corners, which are highly affected by stress concentrations.

Despite having comparable initial stiffness, circular columns demonstrate superior overall performance due to more effective confinement of the concrete core, which provides greater ductility and limits damage progression.

This preliminary study was conducted using single values for column height, reinforcement ratio, buckling length, and axial load ratio. Future research will expand this work by systematically investigating the impact of these variable parameters combined with different structural geometries. The objective will be to develop fragility curves for each case to provide a more comprehensive understanding of seismic vulnerability.

REFERENCES

- [1]- M.R. Salami, E.A. Dizaj, M.M. Kashani, The behavior of rectangular and circular reinforced concrete columns under biaxial multiple excitation. *Comput. Model. Eng. Sci.*, 120(3) (2019) 677–691. <https://doi.org/10.32604/cmes.2019.05666>
- [2]- M.R. Salami, E.A. Dizaj, M.M. Kashani, Fragility analysis of rectangular and circular reinforced concrete columns under bidirectional multiple excitations. *Eng. Struct.*, 233 (2021) 111887. <https://doi.org/10.1016/j.engstruct.2021.111887>

-
- [3]- J. Su, J. Wang, Z. Bai, W. Wang, D. Zhao, Influence of reinforcement buckling on the seismic performance of reinforced concrete columns. *Eng. Struct.*, 103 (2015) 174–188. <https://doi.org/10.1016/j.engstruct.2015.09.007>
- [4]- J. Su, R.P. Dhakal, J. Wang, Fiber-based damage analysis of reinforced concrete bridge piers. *Soil Dyn. Earthq. Eng.*, 96 (2017) 13–34. <https://doi.org/10.1016/j.soildyn.2017.01.029>
- [5]- H. Bouazza, M. Djelil, M. Matallah, On the relevance of incorporating bar slip, bar buckling and low-cycle fatigue effects in seismic fragility assessment of RC bridge piers. *Eng. Struct.*, 256 (2022) 114032. <https://doi.org/10.1016/j.engstruct.2022.114032>
- [6]- R.P. Dhakal, K. Maekawa, Modeling for postyield buckling of reinforcement. *J. Struct. Eng.*, 128(9) (2002) 1139–1147. [https://doi.org/10.1061/\(asce\)0733-9445\(2002\)128:9\(1139](https://doi.org/10.1061/(asce)0733-9445(2002)128:9(1139)
- [7]- M.P. Berry, M.O. Eberhard, Performance Modeling Strategies for Modern Reinforced Concrete Bridge Columns - PEER 2007/07. Pacific Earthquake Engineering Research Center, University of California, Berkeley (2008).
- [8]- D. Lehman, J. Moehle, S. Mahin, A. Calderone, L. Henry, Experimental Evaluation of the Seismic Performance of Reinforced Concrete Bridge Columns. *J. Struct. Eng.*, 130(6) (2004) 869–879.
- [9]- OpenSees: Open System for earthquake engineering simulation, version 3.0.3. Pacific Earthquake Engineering Research Center (2019). <https://opensees.berkeley.edu/>
- [10]- S. Popovics, A numerical approach to the complete stress-strain curve of concrete. *Cem. Concr. Res.*, 3(5) (1973) 583–599. [https://doi.org/10.1016/0008-8846\(73\)90096-3](https://doi.org/10.1016/0008-8846(73)90096-3)
- [11]- S.K. Kunnath, Y. Heo, J.P. Moehle, Nonlinear Uniaxial Material Model for Reinforcing Steel Bars. *J. Struct. Eng.*, 135(4) (2009) 335–343. [https://doi.org/10.1061/\(ASCE\)0733-9445\(2009\)135:4\(335](https://doi.org/10.1061/(ASCE)0733-9445(2009)135:4(335)
- [12]- Y. Ding, D. Wu, J. Su, Z. Li, L. Zong, K. Feng, Experimental and numerical investigations on seismic performance of RC bridge piers considering buckling and low-cycle fatigue of high-strength steel bars. *Eng. Struct.*, 227 (2021) 111464. <https://doi.org/10.1016/j.engstruct.2020.111464>
- [13]- J. Zhao, S. Sritharan, Modeling of strain penetration effects in fiber-based analysis of reinforced concrete structures. *ACI Struct. J.*, 104(2) (2007) 133–141. <https://doi.org/10.14359/18525>