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Vulnerability Assessment of Reinforced Concrete Columns under Varying Axial Loads Using the Park–Ang Damage Index

Authors:

Masoumeh Afagh[1], Fatemeh Z. Dokhanian[1], Mahmoud R. Shiravand[1,*]

Abstract

Reinforced concrete (RC) columns are critical load-bearing components of structural systems, and their cyclic behavior is strongly influenced by the axial load ratio. Variations in the axial load ratio affect the stiffness, strength, ductility, energy dissipation capacity, and damage accumulation of RC columns. Therefore, evaluating the effect of axial load ratio is essential for accurate seismic performance assessment. In this study, the influence of different axial load ratios on the damage evolution of RC columns under cyclic loading was investigated using a nonlinear finite element model validated against experimental data. The Park–Ang damage index was used to evaluate damage evolution. The results showed that increasing the axial load ratio enhanced the initial stiffness and load-bearing capacity but reduced the deformation and energy dissipation capacities, resulting in faster damage accumulation. The maximum cumulative hysteretic energy and the highest Park–Ang damage index were observed at an axial load ratio of 0.20, highlighting the significant influence of axial load ratio on damage evolution. Comparison with experimental observations showed that although the Park–Ang damage index captures the overall trend of damage evolution, its values cannot accurately represent the actual damage states without calibration.

Keywords: Reinforced Concrete Columns; Axial Load Ratio; Cyclic Loading; Damage Evolution; Park–Ang Damage Index

1. Faculty of Civil, Water and Environmental Engineering, Shahid Beheshti University, Tehran, Iran

*Corresponding Author: m_shiravand@sbu.ac.ir

1. Introduction

The seismic performance of structural systems is governed by the strength, ductility, and energy dissipation capacity of their critical members. RC columns are essential structural members that support gravity and lateral loads and ensure the safety and stability of structures. Any damage or capacity degradation of members substantially decreases the stiffness and strength of the structure, induces undesired failure modes, and eventually results in collapse of structures. Post-earthquake reconnaissance following recent major seismic events, including the earthquake that occurred in 2023 in Southern Turkey, has demonstrated that damage to RC columns is one of the causes of failures of bridges (Gundogan et al., 2025; Tra et al., 2026). Consequently, developing accurate methods to assess damage severity and influencing factors is considered one of the major challenges for the performance-based design and evaluation of RC structures.

The axial load ratio constitutes a critical parameter affecting the nonlinear hysteretic response of RC columns. The combined effect of axial and lateral loads governs the stress state, cracking behavior, load-carrying capacity, stiffness, ductility, and energy dissipation capacity of RC columns. It also significantly influences damage accumulation and failure modes. The axial load ratio is generally defined as the ratio of the applied axial force to the nominal compressive strength of the section (Cao et al., 2019; Rodrigues et al., 2016), and can be expressed as:

$$n = \frac{P}{A_g f_c'} \qquad (1)$$

where n represents the axial load ratio, P is the applied axial load, A_g denotes the gross cross-sectional area of the column, and f_c' is the concrete compressive strength.

Previous studies have shown that increasing the axial load improves the initial stiffness and peak strength of RC columns but reduces their displacement capacity, ductility, residual strength, and energy dissipation capacity. This results in a pinching effect, stiffness degradation, and brittle behavior in the hysteresis loops (Rodrigues et al., 2016; Xu et al., 2018; Gundogan et al., 2025). Recent experimental studies have confirmed that, even under constant axial loading, the extent of ductility reduction and strength degradation is strongly governed by the axial load ratio. In particular, Li et al. (2023) reported that increasing the axial load ratio leads to more rapid strength degradation and reduced ductility, thereby affecting the overall seismic performance of RC columns. Similarly, Aydemir et al. (2023) found that increasing the axial load ratio improves the initial stiffness and strength but reduces the deformation capacity and accelerates stiffness degradation. In addition, changes in axial load during seismic loading may cause asymmetrical hysteretic behavior (Chen et al., 2024; Tra et al., 2026; Li et al. 2023).

Several damage indices have been developed to evaluate the damage of structural members under seismic loading. These indices are developed based on different mechanical parameters, including displacement, strength deterioration, stiffness degradation, and hysteretic energy dissipation. Damage indices are not limited to individual response parameters but also account for the progressive accumulation of damage under cyclic loading conditions. Therefore, they are widely used for seismic damage assessment, structural performance evaluation, and performance-based design (Kappos, 1997; Zameeruddin & Sangle, 2016).

A damage index is a dimensionless parameter that represents the degree of structural damage. It can be used to compare the behavior of structural members under different loading conditions and seismic performance levels (Kappos, 1997). Damage indices are generally classified into non-cumulative and cumulative categories. While non-cumulative indices are dependent only on the peak structural response, cumulative indices consider the loading history and hysteretic energy dissipation in determining the damage. Therefore, cumulative indices provide a more realistic representation of the seismic behavior of RC members under cyclic loading (Bassam et al., 2011; Ghobarah et al., 1999).

The Park–Ang damage index is considered one of the most widely used cumulative damage indices for the seismic assessment of RC members. This index combines the effects of maximum deformation and hysteretic energy dissipation to quantify structural damage under cyclic loading. By considering both deformation demand and cumulative energy dissipation, the Park–Ang damage index effectively describes damage progression and has been widely applied in experimental and numerical studies to evaluate the seismic performance of RC members (Park & Ang, 1985; Cao et al., 2019; Chen et al., 2024). Although the cyclic behavior of RC columns under different axial load ratios has been widely studied, the effect of axial load ratio on damage evolution based on the Park–Ang damage index has not been fully investigated. Therefore, this study aims to investigate the effects of different axial load ratios on the damage evolution of RC columns using a validated nonlinear numerical model subjected to quasi-static cyclic loading. The Park–Ang damage index is used to evaluate damage progression and examine the effect of axial load ratio on the seismic performance of RC columns.

A validated nonlinear numerical model was developed in OpenSees to investigate the influence of different axial load ratios on the damage evolution of RC columns subjected to quasi-static cyclic loading. The Park–Ang damage index was used to evaluate the evolution of damage throughout the loading history. The results provide a better understanding of the relationship between axial load ratio and damage evolution and contribute to the seismic performance assessment of RC columns.

2. Theoretical Background of the Park–Ang Damage Index

The Park–Ang damage index is adopted in this study to evaluate the damage evolution of reinforced concrete (RC) columns subjected to varying axial load ratios. Among the cumulative damage indices proposed for the seismic assessment of RC members, it is one of the most widely used and well-established approaches (Bassam et al., 2011; Turchetti et al., 2023; Izhar et al., 2024). The index was developed to overcome the limitations of single-parameter damage indices by considering both maximum deformation and cumulative hysteretic energy dissipation. As a result, it also accounts for the effects of loading history on damage evolution. Because of this, the Park–Ang index has been widely used in both experimental and numerical studies of RC members. The theoretical background and governing equations of the Park–Ang index are presented below. The Park–Ang damage index can be expressed as Eq. (2) (Park & Ang, 1985):

$$DI_{PA} = \frac{\delta_m}{\delta_u} + \beta \frac{E_h}{Q_y \delta_u} \quad (2)$$

Where δ_m is the maximum displacement, δ_u represents the ultimate displacement under monotonic loading, Q_y signifies the yield strength, E_h denotes the cumulative hysteretic energy dissipation, and β is an empirical coefficient that represents the contribution of hysteretic energy dissipation to the damage index.

Park and Ang (1985) and Ang (1987) formulated the empirical β coefficient on experimental results and expressed it as a function of the shear span ratio, axial load ratio, longitudinal reinforcement ratio, and transverse reinforcement ratio. This empirical relationship is given by Eq. (3) (Ang, 1987; Park & Ang, 1985):

$$\beta = \left(-0.447 + 0.073\frac{l}{d} + 0.24n_0 + 0.314\rho_t\right) \times 0.7^{\rho_w} \quad (3)$$

In this equation, l/d represents the shear span ratio, n_0 denotes the axial load ratio, ρ_t is the longitudinal reinforcement ratio, and ρ_w is the transverse reinforcement ratio.

The Park–Ang damage index also enables the damage state of reinforced concrete (RC) members to be classified into different performance levels. Based on experimental observations, Park and Ang (1985) classified the damage state of RC members into five performance levels, ranging from no damage to complete collapse. These performance levels have been widely adopted in seismic damage assessment because they provide a practical interpretation of the calculated damage index values. In this study, these performance levels are used to interpret the calculated Park–Ang damage index values for RC columns subjected to different axial load ratios. Table 1 summarizes the performance levels of the Park–Ang damage index and the corresponding damage descriptions proposed by Park and Ang (1985).

Table 1. Performance levels based on the Park–Ang damage index (Park & Ang, 1985).

Damage Index (DI)	Performance Level	Description
DI < 0.10	No damage	No damage and minor cracking
0.10 ≤ DI < 0.25	Minor damage	Minordamage, light cracks
0.25 ≤ DI < 0.40	Moderate damage	Moderate damage, severe cracking, and spalling
0.40 ≤ DI < 1.00	Severe damage	Severe damage, crushing of concrete, and rebars expose
DI ≥ 1.00	Collapse	Total collapse

While the Park–Ang index is widely employed in seismic damage assessment, its reliability depends on accurate determination of the β factor and the ultimate member capacity. Subsequent studies have shown that the axial load ratio and longitudinal reinforcement ratio have the greatest influence on this coefficient. Therefore, several modified formulations have been proposed to improve the index's accuracy (Chen et al., 2024; Cao et al., 2019; Shen et al., 2024).

Despite its limitations, such as dependence on empirical coefficients, sensitivity to the determination of ultimate capacity, and inability to account for the sequence of plastic cycles (Kappos, 1997; Bassam et al., 2011; Cao et al., 2011; Benavent-Climent, 2007; Amirchoupani et al., 2021), the Park–Ang index is recognized as a reference index in seismic damage assessment.

3. Numerical Modeling

3.1. Geometry and Reinforcement Details

The geometric dimensions, cross-sectional characteristics, reinforcement details, and loading arrangement of the reference specimen are shown in Figure 1.

The geometric configuration of the RC column was adopted from the reference experimental specimen reported by (Sun et al., 2016). The reference column had a circular cross-section with a diameter of 300 mm and was rigidly connected to an RC footing. The effective height of the column, measured from the footing interface to the point of lateral load application, was 1100 mm, resulting in an aspect ratio of approximately 3.67. This aspect ratio ensured that the column experienced a flexure-dominated failure mechanism while minimizing the effect of shear deformations on the overall response.

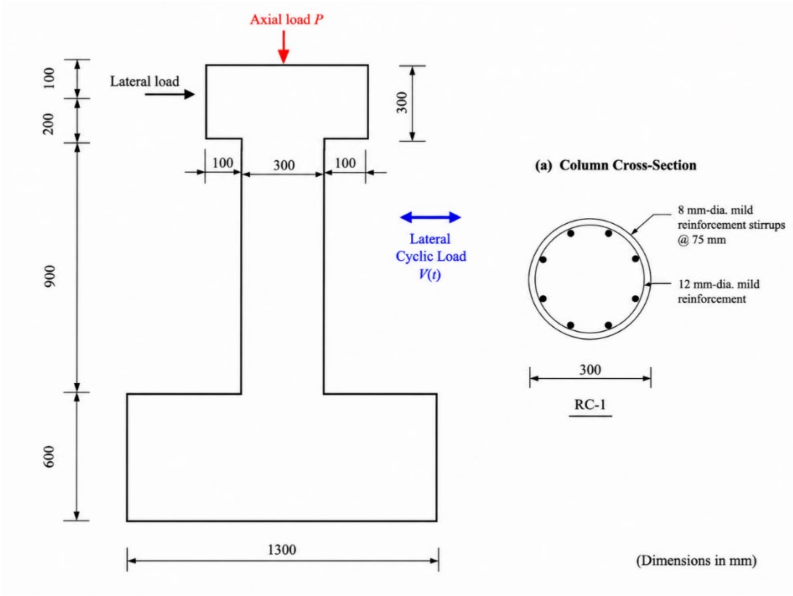

Figure 1. Geometry, reinforcement details, and loading configuration of the reference specimen.

The reinforcement layout was adopted directly from that of the reference specimen. The longitudinal reinforcement, consisting of eight 12-mm-diameter deformed bars, was uniformly distributed around the circular cross-section, while the transverse reinforcement was provided at a constant spacing of 75 mm along the height of the column. This reinforcement configuration provided sufficient flexural capacity while ensuring effective confinement of the concrete core.

3.2. Numerical Modeling Details

A two-dimensional numerical model was established using OpenSees. The 1.1-m-high column was modeled using displacement-based nonlinear beam-column elements (dispBeamColumn), which accurately represent distributed plasticity and the distribution of inelastic deformation along the element length. To consider geometric nonlinearities and second-order effects, the P-Delta geometric transformation was adopted.

The column section was modeled using a fiber-based section approach, with separate modeling of confined concrete in the core region and unconfined concrete in the cover region. This approach enables the confinement provided by the transverse reinforcement to be appropriately considered in the compressive response of concrete. The Concrete02 material model was used to represent the behavior of confined and unconfined concrete using different strength and strain parameters. Longitudinal reinforcements were modeled as steel fibers using the Steel02 material model, which represents kinematic strain hardening and nonlinear cyclic response of steel under cyclic loading conditions. The effects of transverse reinforcement were incorporated indirectly by increasing the strength and ultimate strain of the core concrete according to the confinement model proposed by Mander et al. Figure 2 presents a schematic view of the numerical model geometry, fiber cross-section details, reinforcement arrangement, and material behavior curves.

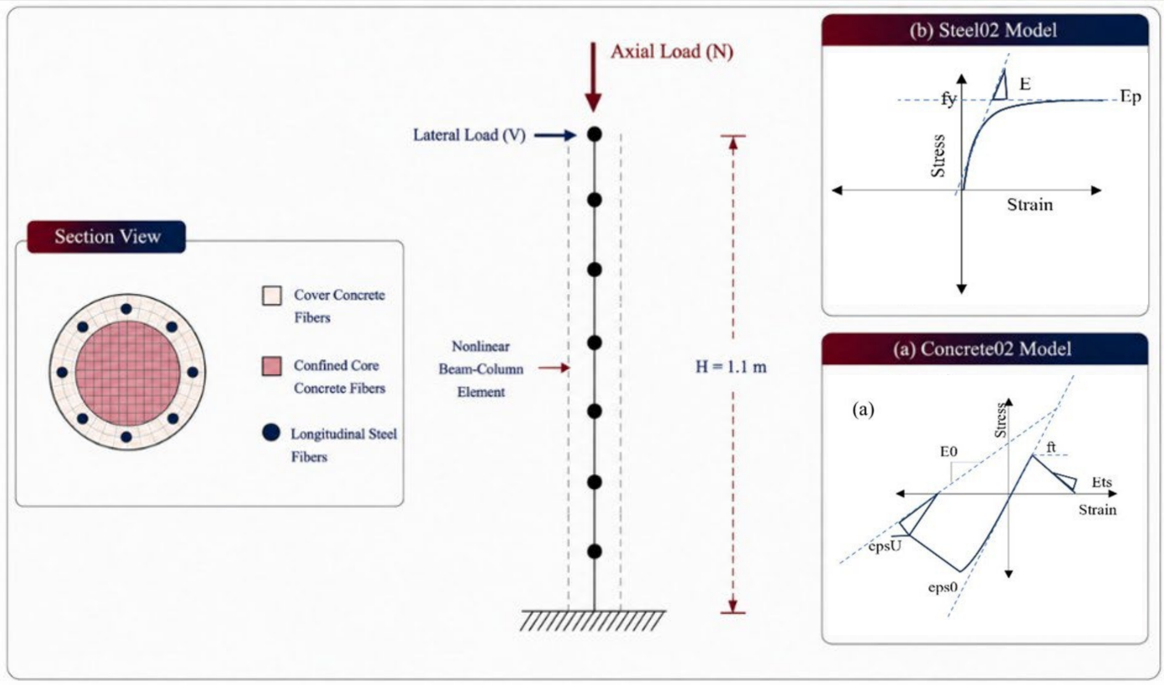

Figure 2. Fiber section details, reinforcement layout, and material constitutive curves.

3.3. Loading Protocol

The loading protocol applied to the RC column consisted of a constant axial load and cyclic lateral displacement. The cyclic lateral loading was applied to evaluate the structural response and damage evolution of the column under reversed loading conditions, whereas the axial load was maintained constant throughout the analysis to represent the sustained gravity load acting on the member.

The lateral displacement was applied at the top of the column, and the displacement-controlled loading protocol is illustrated in Figure 3. The loading history consisted of progressively increasing displacement amplitudes, with three complete loading–unloading cycles performed at each prescribed displacement level. Repeating three cycles at each displacement amplitude was intended to stabilize the structural response, minimize path-dependent effects, and provide a more accurate representation of stiffness degradation, hysteretic behavior, and cumulative damage evolution during successive loading cycles.

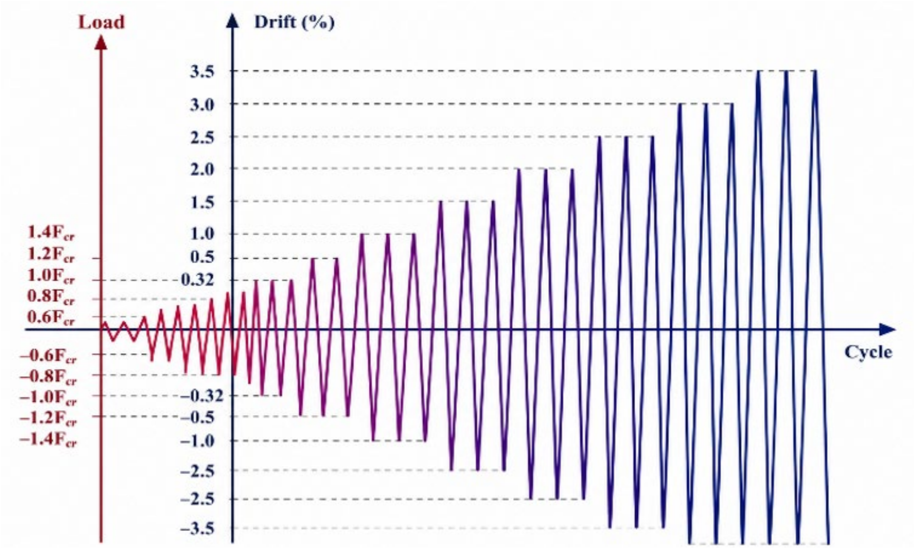

Figure 3. Cyclic loading protocol.

3.4. Model Validation

The numerical model was validated against the experimental response of the reference specimen by comparing the simulated and measured cyclic force–displacement hysteresis curves, as shown in Figure 4. The comparison indicates that the numerical model successfully captures the overall cyclic response of the column, including the initial stiffness, lateral load-carrying capacity, progressive stiffness degradation, strength deterioration during successive loading cycles, and the overall shape and width of the hysteresis loops.

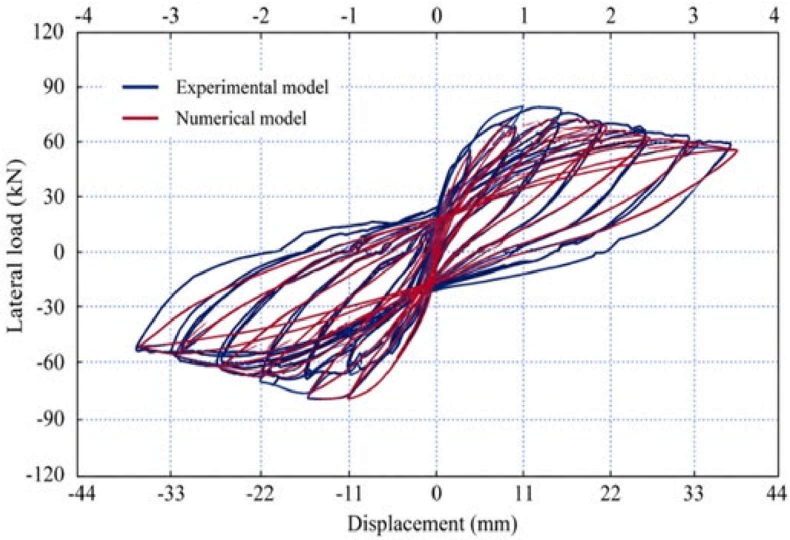

Figure 4. Experimental and numerical hysteresis curves for model validation.

Because reproducing the shape and enclosed area of the hysteresis loops is essential for damage assessment and energy-based analyses, the close agreement between the numerical and experimental results demonstrates that the proposed numerical model is capable of reliably simulating the cyclic behavior of the column. Therefore, the validated model was subsequently used to investigate the influence of different axial load ratios and to evaluate the damage evolution using the adopted damage indices.

4. Results and Discussion

This section investigates the influence of different axial load ratios on the cyclic response and damage behavior of the reinforced concrete column. First, the hysteretic response of the column under different axial load levels is examined by focusing on the changes in strength, stiffness, and deformation capacity. Subsequently, the progression of structural damage is quantitatively assessed using the Park–Ang damage index to clarify the influence of axial compression on the seismic performance of reinforced concrete columns.

4.1. Hysteretic Behavior under Different Axial Load Ratios

Figure 5 shows the force–displacement hysteresis curves of the reinforced concrete column subjected to six axial load ratios ranging from 0.10 to 0.35. The comparison of these curves shows that axial load ratio has an important influence on the cyclic behavior of the column, influencing lateral strength, initial stiffness, deformation capacity, and hysteretic characteristics.

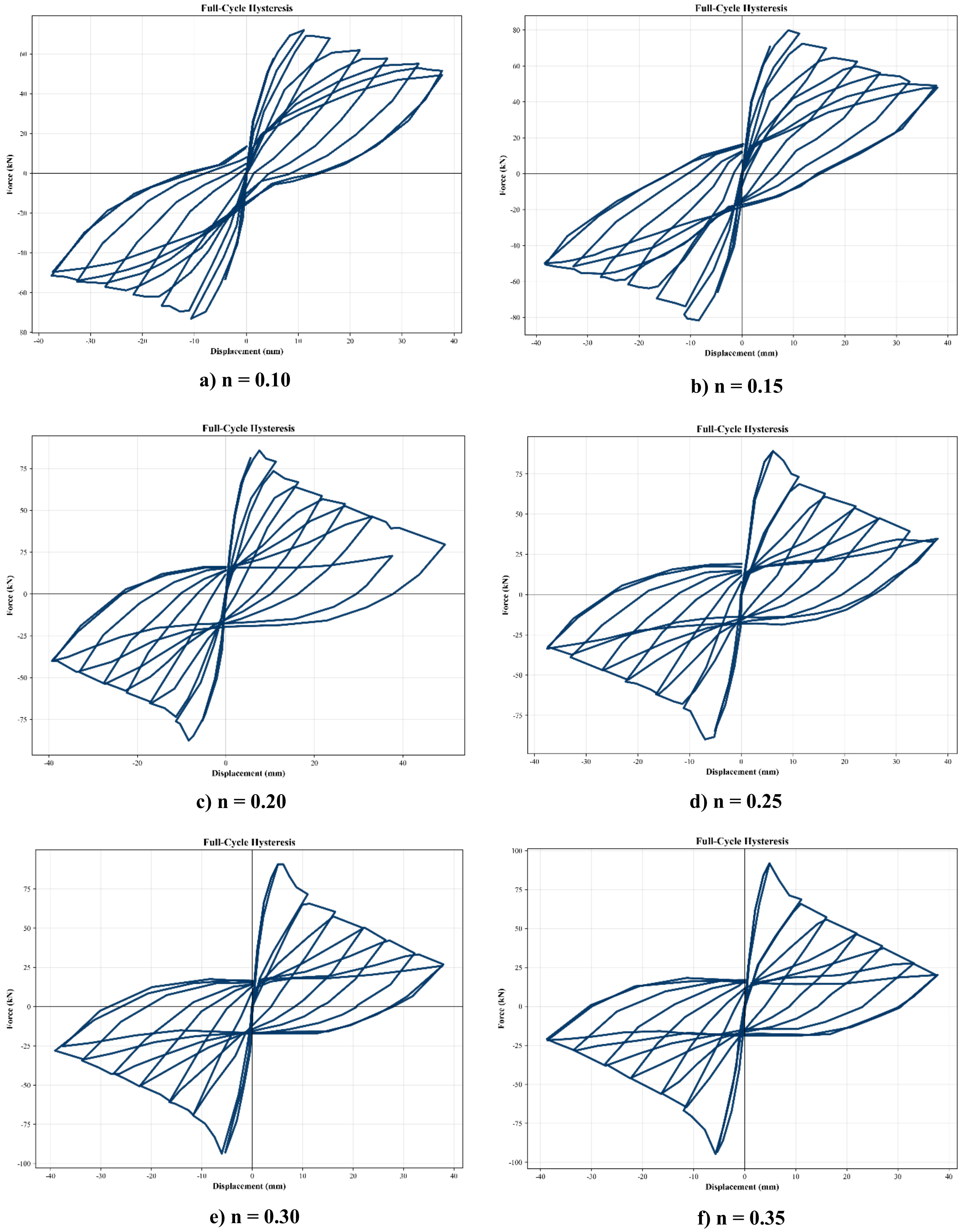

Figure 5. Force–displacement hysteresis curves of the RC column subjected to six different axial load ratios.

At lower axial load ratios (0.10 and 0.15), the hysteresis loops remain relatively wide and stable throughout the loading history. The gradual reduction in strength and the ability of the column to sustain further loading cycles indicate a higher deformation capacity and a more stable cyclic response. In contrast, increasing the axial load ratio, particularly to 0.30 and 0.35, results in narrower hysteresis loops and faster strength deterioration in the later cycles. These changes indicate reduced deformation capacity and a tendency toward a more brittle cyclic response under higher axial compression levels.

The hysteresis curves also show that increasing the axial load ratio enhances the initial stiffness and lateral strength of the column during the early loading cycles. However, this increase is accompanied by narrower hysteresis loops, indicating a reduction in deformation capacity. Similar trends have been reported by Rodrigues et al. (2016) and Gundogan et al. (2025).

Among the analyzed cases, the column with an axial load ratio of 0.20 exhibited high lateral resistance while maintaining relatively stable hysteretic loops during the early and intermediate loading cycles. However, further increases in the axial load ratio to 0.30 and 0.35 resulted in more pronounced deterioration of the cyclic response.

At higher axial load ratios, especially 0.30 and 0.35, a more pronounced pinching response and faster stiffness degradation are observed during the large displacement cycles. The reduction in load-carrying capacity in the final cycles indicates accelerated deterioration of cyclic behavior, which agrees with the findings reported by Xu et al. (2018), Chen et al. (2024), and Tra et al. (2026).

Generally, Figure 5 shows that while an increase in axial load ratio improves the stiffness and lateral strength of the column, excessive axial compression reduces its deformation capacity and accelerates the degradation of cyclic response. This illustrates the considerable effect of axial load ratio on the damage development of reinforced concrete columns. This is further elaborated using the Park–Ang damage index in the next section.

4.2. Evolution of the Park–Ang Damage Index under Different Axial Load Ratios

To better understand the evolution of the Park–Ang damage index, the cumulative hysteretic energy dissipated during cyclic loading is first presented. Since the Park–Ang damage model considers both the maximum deformation demand and the cumulative effect of inelastic energy dissipation, the cumulative hysteretic energy provides useful insight into the predicted damage evolution. The cumulative hysteretic energy values at the end of each loading cycle for all investigated axial load ratios are summarized in Table 2.

Table 2. Cumulative hysteretic energy (Sum_Eh) for different axial load ratios.

Cycle	n = 0.10	n = 0.15	n = 0.20	n = 0.25	n = 0.30	n = 0.35
1	6.38	7.71	12.14	24.99	26.27	31.10
2	91.42	135.27	211.04	340.63	394.23	418.53
3	416.34	576.76	764.13	1137.13	1194.29	1270.49
4	1084.77	1397.91	1824.30	2167.71	2269.53	2325.83

5	2122.51	2502.36	3218.65	3421.26	3610.37	3658.09
6	3585.96	3982.36	4921.24	5140.57	5246.42	5323.79
7	5517.75	5807.68	7578.01	7100.20	7297.14	7299.04
8	7624.29	8093.97	9931.31	9071.33	9367.49	9413.21

As shown in Table 2, the cumulative hysteretic energy increases continuously with the loading cycles for all axial load ratios, indicating the progressive accumulation of inelastic deformation and energy dissipation throughout the cyclic loading history. Among the investigated cases, the specimen with an axial load ratio of 0.20 exhibits the highest cumulative hysteretic energy, reaching 9931.31 kN·mm at the end of the analysis. For axial load ratios greater than 0.20, the cumulative hysteretic energy decreases despite the increase in axial compression, suggesting that excessive axial load limits the energy dissipation capacity of the column during the later loading cycles.

Figure 6 presents the evolution of the Park–Ang damage index for the reinforced concrete column subjected to six axial load ratios ranging from 0.10 to 0.35. The damage index was calculated at the end of each loading cycle to evaluate the influence of the axial load ratio on the progression of structural damage under cyclic loading.

As shown in Figure 6, the Park–Ang damage index increases continuously with the loading cycles for all axial load ratios, indicating the progressive accumulation of damage during cyclic loading. During the early loading cycles, the differences among the damage index values are relatively small. For example, the damage index varies from 0.1534 to 0.1827 in the first loading cycle for all investigated axial load ratios. As loading continues, the differences become more noticeable, particularly after the fourth loading cycle, where the damage index increases more rapidly.

The results also show that the axial load ratio influences the evolution of the damage index. Among the investigated cases, the column subjected to an axial load ratio of 0.20 exhibits the highest damage index during the final loading cycles, reaching a value of 1.97 at the end of the analysis. In comparison, the final damage index values for the remaining axial load ratios range between approximately 1.52 and 1.64.

A comparison of Figure 6 and Table 2 indicates that the specimen with an axial load ratio of 0.20 exhibits both the highest cumulative hysteretic energy (9931.31 kN·mm) and the largest Park–Ang damage index at the end of the analysis. Within the numerical results obtained in this study, these two observations show a similar trend.

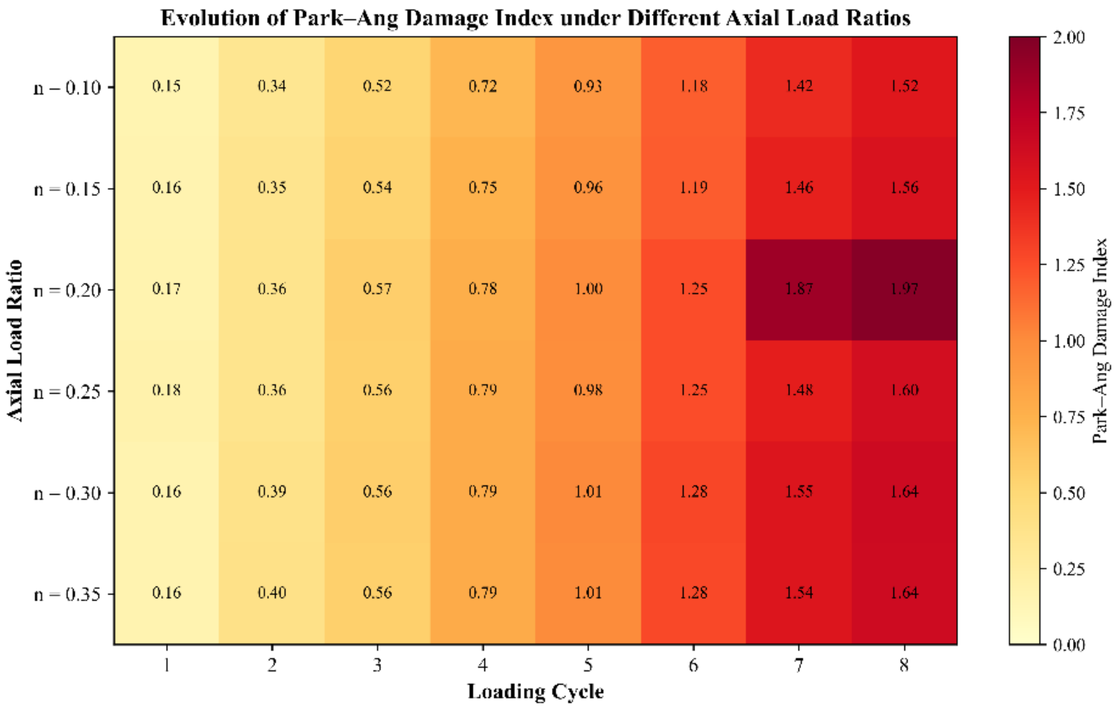

Figure 6. Evolution of the Park–Ang damage index under different axial load ratios.

For the higher axial load ratios (0.25–0.35), although the initial lateral strength and stiffness increase, the cumulative hysteretic energy does not continue to increase. As discussed in the previous section, higher axial compression leads to narrower hysteresis loops, more pronounced pinching, and faster stiffness degradation, which reduce the energy dissipation capacity during the later loading cycles. Correspondingly, the final Park–Ang damage index for these cases remains lower than that predicted for the specimen with an axial load ratio of 0.20.

Overall, the results indicate that the evolution of the Park–Ang damage index is affected by the axial load ratio throughout the loading history. Within the investigated range, the numerical model predicts the highest Park–Ang damage index for the specimen with an axial load ratio of 0.20, which also corresponds to the largest cumulative hysteretic energy observed in the analysis.

4.3. Discussion on the Limitations of the Park–Ang Damage Index

To investigate the capability of the Park–Ang damage index in evaluating the damage progression of reinforced concrete columns, the calculated damage index values were compared with the experimental observations reported by Sun et al. (2016). The results indicate that the Park–Ang index can appropriately represent the general trend of damage accumulation and the increase in nonlinear response intensity of the member. However, the absolute values of the damage index did not show complete agreement with the experimentally observed damage states at all stages of loading.

According to the results presented in Table 3, at a drift level of 2%, where the initiation of concrete cover spalling was reported in the experimental study, the calculated Park–Ang damage index reached 1.185. However, at this stage, the specimen only exhibited the initiation of concrete cover spalling and had not yet reached the final failure mechanisms, such as longitudinal bar buckling and concrete core crushing. Furthermore, during the early loading stages, the calculated damage index values predicted higher damage levels compared with the experimentally observed damage states.

Table 3. Comparison of Park–Ang damage index values with experimental damage observations reported by Sun et al. (2016) for n = 0.10.

Loading Cycle	Drift Level	Park–Ang DI	Damage Classification	Experimental Observation (Sun et al., 2016)
1	Load control	0.153	Minor damage	Formation of horizontal flexural cracks in the plastic hinge region; maximum crack width reached 0.09 mm and residual crack width was approximately 0.01 mm.
2	0.32%	0.341	Moderate damage	Maximum crack width increased to 0.25 mm, with a residual crack width of 0.02 mm.
4	1.00%	0.718	Severe damage	Maximum crack width increased to 0.9 mm.
6	2.00%	1.185	Collapse	Concrete cover spalling initiated, and the specimen reached its maximum lateral load capacity.
7	2.50%	1.422	Collapse	Concrete cover peeled off, and spiral and longitudinal reinforcement bars became exposed.
8	3.00%	1.520	Collapse	Longitudinal bar buckling and concrete core crushing occurred progressively during the subsequent loading cycles.

This discrepancy indicates that the Park–Ang index tends to provide a more conservative estimation of damage severity in the present numerical model. The main reason for this behavior can be attributed to the combined formulation of the Park–Ang index, which considers both cumulative hysteretic energy and maximum inelastic deformation demand in the damage calculation. Therefore, as nonlinear deformations increase, the damage index may increase at a faster rate than the actual development of physical damage in the structural member.

Consequently, although the Park–Ang damage index is suitable for describing the general trend of damage accumulation in reinforced concrete columns, the direct application of its proposed damage thresholds for accurately identifying damage states may lead to an overestimation of damage severity. Therefore, for more reliable application of this index in evaluating reinforced concrete columns subjected to different axial load ratios, calibration based on experimental observations and the specific characteristics of the investigated structural members is recommended.

5. Conclusion

In this study, the influence of different axial load ratios on the damage evolution of reinforced concrete (RC) columns subjected to quasi-static cyclic loading was investigated using the Park–Ang damage index. For this purpose, the nonlinear response of the columns, variations in cumulative hysteretic energy, and the evolution of the damage index under axial load ratios ranging from 0.10 to 0.35 were evaluated. The main findings are summarized as follows:

- Increasing the axial load ratio enhanced the initial stiffness and lateral load-carrying capacity of the column during the early loading stages; however, excessive axial compression reduced the inelastic deformation capacity, ductility, and energy dissipation capability of the member. This behavior was accompanied by more pronounced pinching effects in the hysteresis loops and faster stiffness degradation during the final loading cycles.
- The cumulative hysteretic energy results indicated that the axial load ratio of 0.20 provided the highest energy dissipation capacity. With further increases in axial load ratio, the reduction in deformation capacity and the intensification of nonlinear damage mechanisms limited the energy absorption and dissipation capability of the member.
- The Park–Ang damage index exhibited an increasing trend with the number of loading cycles for all axial load ratios and successfully represented the general accumulation of damage associated with increasing inelastic deformation and hysteretic energy dissipation. Moreover, increasing the axial load ratio generally accelerated the damage evolution process during most loading stages.
- The highest final value of the Park–Ang damage index was obtained for the specimen with an axial load ratio of 0.20, which was consistent with the maximum cumulative hysteretic energy observed for this specimen. This result indicates that the enhanced energy dissipation capacity at this axial load level was accompanied by greater inelastic deformation development and damage accumulation.
- The comparison of the Park–Ang damage index with experimental observations for the specimen with an axial load ratio of 0.10 showed that, although this index can appropriately represent the overall trend of damage progression, its absolute values do not always fully correspond to the actual damage states observed experimentally.
- Based on the obtained results, the direct application of the Park–Ang damage index without calibration according to the specific characteristics of the member and experimental data may lead to discrepancies between the calculated damage index and the actual damage level. Therefore, accurate evaluation of damage levels and performance states of RC columns requires calibration of the model parameters or the use of complementary assessment criteria.

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