



Displacement component-based modeling of reinforced concrete columns in SAP2000: Validation against experimental and OpenSees results

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Abstract

Accurate estimation of lateral displacement in reinforced concrete (RC) columns is essential for performance-based seismic assessment. Total lateral displacement consists of flexural, bar-slip, and shear deformation components; however, commercial structural analysis platforms such as SAP2000 generally consider only flexural deformation, which may lead to overestimation of stiffness and inaccurate prediction of deformation capacity in non-ductile members. Although advanced nonlinear finite element platforms such as OpenSees explicitly represent these mechanisms, their implementation typically requires considerable modeling expertise and computational effort. This study presents a displacement component-based modeling framework within SAP2000 to represent flexural, bar-slip, and shear deformations through a component-based plastic hinge formulation. Rather than proposing new analytical formulations, the framework provides a practical and reproducible implementation strategy for representing individual deformation mechanisms within a commercial structural analysis platform. The proposed methodology is validated against the cyclic responses of an experimental database comprising 24 RC column specimens and is further compared with fiber-based OpenSees simulations in terms of lateral load–displacement response, stiffness degradation, and hysteretic behavior. The results demonstrate good agreement with the experimental responses, indicating that the proposed framework can effectively represent the nonlinear cyclic response of RC columns while explicitly accounting for the contributions of individual deformation mechanisms. The proposed methodology offers a practical intermediate nonlinear assessment approach between simplified engineering models and computationally demanding distributed-plasticity simulations for the seismic performance evaluation of existing RC structures.

1. Introduction

Reinforced concrete (RC) columns are the primary lateral load-resisting elements of structures, and the inelastic deformation capacities of these elements determine the seismic performance of the structures. In performance-based seismic evaluation, accurately predicting the lateral displacement response is essential to reliably determine the total displacement capacity and governing failure mechanisms. The total lateral displacement of RC columns results from the combination of flexural, bar-slip, and shear deformation mechanisms. However, commercial software such as SAP2000 generally assumes flexural deformation as the sole source of lateral displacement. This simplification

becomes even more critical when estimating the displacement capacity of existing structures designed according to older seismic design provisions.

Numerous studies have investigated the individual displacement components of RC columns in the literature. Flexural deformations have been investigated in detail in [1-7], while bar-slip and shear deformations have been studied in [8-20]. Although deformation behavior in modern ductile columns is predominantly controlled by flexural deformation, experimental studies [10] show that bar-slip and shear deformations contribute significantly to the total displacement capacity of poorly detailed existing RC structures.

1.1. Research gap

Recent studies have further advanced the nonlinear modeling of reinforced concrete columns by addressing individual deformation mechanisms and alternative plasticity formulations. Flexure–shear interaction has been incorporated into numerical and analytical models to improve the representation of the seismic response of RC columns and bridge piers [21–22]. Bond–slip behavior and its influence on the response of RC columns have also been investigated experimentally and numerically, including applications involving deterioration and repair [23–24]. In parallel, recent studies have developed lumped-plasticity models for RC columns and examined the influence of concentrated and distributed plasticity formulations on seismic response assessment [25–26]. Cyclic modeling approaches have also been improved to represent shear deformation and nonlinear load–deformation behavior under repeated loading, including stiffness and strength degradation [27–28].

In research-oriented nonlinear analysis platforms such as OpenSees [29], individual deformation mechanisms can be modeled using separate elements, zero-length springs, or nonlinear material models. Although distributed plasticity and fiber-section-based models enable a detailed evaluation of member response, their implementation requires advanced modeling expertise and greater computational effort.

In contrast, SAP2000 [30], which is widely used in engineering applications, lacks a unified modeling procedure for explicitly representing flexural, bar-slip, and shear deformations within a single model. Existing component-based studies mostly focus on the analytical calculation of a specific deformation mechanism or its implementation in research-oriented analysis platforms. However, systematic and reproducible workflows that convert analytical models reported in the literature into user-defined plastic hinge properties for implementation in commercial finite element software remain limited. This situation creates a significant gap between advanced research-oriented modeling approaches and commercial software used in engineering applications. Therefore, there is a need for a systematic modeling methodology suitable for engineering applications that allows existing analytical models to be directly implemented in commercial analysis software without developing new finite element formulations or creating user-defined elements.

1.2. Objectives and novelty of the study

This study presents a displacement component-based modeling procedure for representing the nonlinear behavior of RC columns in SAP2000. In the proposed methodology, flexural, bar-slip, and shear deformations are represented by independent plastic hinges, allowing the contribution of each deformation mechanism to the total lateral displacement to be explicitly incorporated within a single finite element model. Unlike the conventional single plastic hinge approach (typically restricted to flexural behavior), the proposed

methodology overcomes this limitation by explicitly separating flexural, bar-slip, and shear deformations into distinct plastic hinges while simultaneously capturing their combined effect on the overall column response. As a result, the nonlinear behavior of RC columns in which bar-slip and shear deformations play a significant role can be represented more realistically.

The novelty of this study does not lie in the development of new analytical models for flexural, bar-slip, or shear deformations. Instead, its primary contribution is the development of a systematic and reproducible workflow that transforms existing analytical models from the literature into user-defined plastic hinge properties that can be directly implemented in SAP2000. The proposed procedure consists of: (i) calculating the flexural, bar-slip, and shear deformation components using analytical models; (ii) converting these components into plastic hinge properties; (iii) assigning flexural, bar-slip, and shear behaviors as independent plastic hinges; and (iv) integrating these hinges within a single finite element model to simulate the overall column response.

Through this approach, existing analytical models are transformed into a modeling procedure that can be directly implemented in a commercial finite element software. The proposed methodology does not require developing new finite element formulations, creating user-defined elements, or using advanced programming expertise. Instead, using the existing modeling infrastructure of SAP2000, flexural, bar-slip, and shear deformations are first modeled separately via independent plastic hinges to obtain the load-displacement behavior of each deformation component. The total behavior calculated through the superposition of these components is then verified by comparing it with an integrated model in which the same deformation mechanisms are simultaneously defined within a single SAP2000 finite element model. Consequently, this approach not only enables the individual contribution of each deformation mechanism to be quantified, but also demonstrates that the superposed total response remains consistent with the simultaneously integrated finite element model. Thus, by expanding the scope of the existing plastic hinge approach in a commercial analysis software, a practical, systematic, and reproducible modeling methodology is presented.

The proposed methodology was validated using an experimental database comprising 24 RC column specimens with different geometries, axial load levels, reinforcement details, and failure modes. No specimen-specific parameter calibration was performed during the modeling process; all input parameters were obtained directly from the geometry and material properties reported in the corresponding experimental studies. The analytical results were compared with the experimental load-displacement responses and with fiber-based nonlinear analyses conducted in OpenSees. The purpose of this comparison is not to establish superiority between the two software programs, but rather to assess the ability of the proposed SAP2000 modeling approach to

represent experimental behavior alongside the widely used OpenSees platform. The obtained results demonstrate good agreement between the proposed modeling approach and the experimental responses, offering a practical and reproducible engineering solution that allows multiple deformation components to be modeled both independently and simultaneously in commercial finite element software.

2. Definition of displacement components

The total lateral displacement of an RC column under lateral loading results from the combined contributions of flexural, bar-slip, and shear deformation mechanisms (Fig. 1). In the proposed modeling approach, each deformation component is calculated using widely accepted analytical models from the literature. This enables the contribution of each deformation mechanism to the total lateral displacement to be quantified individually before being incorporated into the proposed component-based SAP2000 model.

These models are adopted not to propose new analytical formulations, but rather to provide the theoretical basis for the SAP2000 modeling procedure. The calculated deformation components are subsequently converted into plastic hinge properties and implemented in the SAP2000 model, as described in the following section.

The empirical relationships presented in this section are adopted directly from the original studies and are therefore expressed in the U.S. customary unit system. Accordingly, lengths are given in inches (in.), forces in kips, and stresses in psi or ksi. For statistical analyses and graphical presentation, all calculated results were converted to the SI unit system.

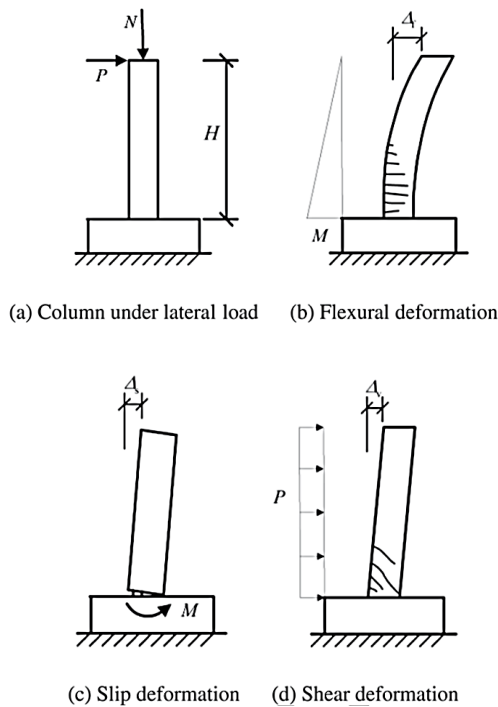


Fig. 1. Lateral deformation mechanisms in RC columns under cyclic loading [11]

2.1. Flexural Displacement

Flexural deformation constitutes the primary component of the lateral displacement response of RC columns. In this study, flexural displacement is determined through cross-sectional analysis based on the moment–curvature relationship by evaluating the corresponding curvature distribution along the column height. The analysis is based on the Bernoulli–Euler hypothesis, which assumes that plane sections remain plane after bending. Although this assumption is not strictly valid for columns in which shear deformations are significant, it is adopted here to isolate the independent contribution of flexural deformation.

Flexural displacement is calculated by integrating the curvature distribution along the column. In the elastic region, the flexural displacement is obtained from the first moment of the curvature distribution using Eq. (1).

$$\Delta_f = \int_0^L \phi(x) x dx \quad (1)$$

After yielding, the plastic curvature is assumed to remain constant over the plastic hinge region, and the corresponding plastic flexural displacement is calculated using Eq. (2).

$$\Delta_f = \Delta_{f,y} + (\phi - \phi_y) L_p \left(a - \frac{L_p}{2} \right) \quad (2)$$

where Δ_f is the flexural displacement of the column (in); L is the column height (in); $\phi(x)$ is the curvature distribution along the column (1/in); $\Delta_{f,y}$ is the flexural displacement at yield (in); ϕ_y is the yield curvature (1/in); L_p is the plastic hinge length (in), and a is the shear span (in).

2.2. Bar slip displacement

Bar slip deformation is calculated using the bi-uniform bond-stress model proposed by Setzler and Sezen [31]. In this model, bond stresses between the reinforcing steel and concrete are idealized as two distinct regions: elastic and inelastic zones (Fig.2). The slip within the anchorage zone is calculated using the strains developed along the reinforcement and is subsequently converted into lateral displacement through rigid-body rotation at the column–foundation interface. Thus, the contribution of the bar-slip mechanism to the total displacement can be determined independently.

The lateral displacement due to bar slip is calculated using Eq. (3), while the bar slip is calculated using Eq. (4), which accounts for both the elastic and post-yield behavior of the reinforcing steel.

$$\Delta_s = \theta_s L, \quad \theta_s = \left(\frac{slip}{d-c} \right) \quad (3)$$

$$slip = \frac{\epsilon_s l_d}{2} \quad \text{for } \epsilon_s < \epsilon_y \quad (4)$$

$$slip = \frac{\epsilon_s l_d}{2} + \frac{(\epsilon_y + \epsilon_s) l_d'}{2} \quad \text{for } \epsilon_y$$

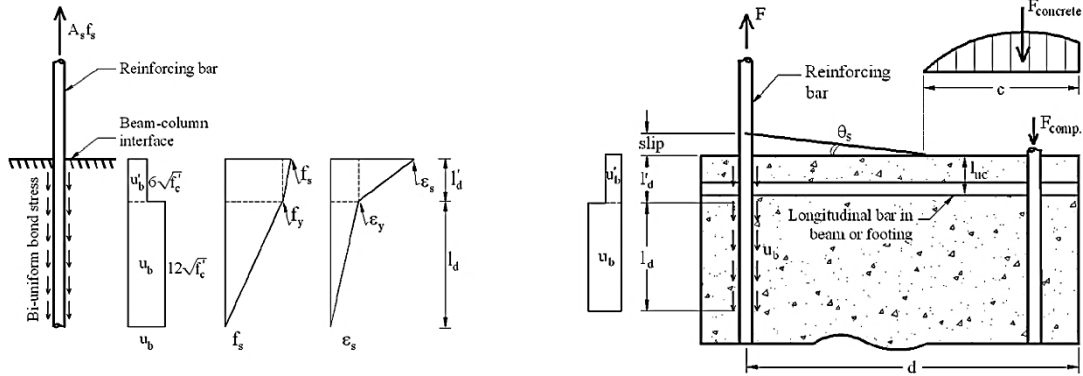


Fig. 2. Moment-slip relationship for an RC column proposed by Setzler and Sezen [31]

In Eqs. (3) and (4) Δ_s is the bar slip displacement of the column (in); θ_s is the slip rotation (rad); *slip* is the reinforcement slip (in); d is the effective depth (in); c is the depth of the compression block (in); l_d and l'_d are the development lengths for the elastic and inelastic portions of the bar (in), respectively; ε_s is the strain of the bar; and ε_y is the steel yield strain.

2.3. Shear displacement

Shear deformation was calculated using the analytical model developed by Patwardhan [32] based on the Modified Compression Field Theory (MCFT) [8] (Fig. 3). The model defines four characteristic behavioral points: shear cracking formation, maximum shear strength, onset of strength degradation, and loss of axial load-carrying capacity. The force and displacement values corresponding to these points are calculated using the analytical relationships given below. Shear cracking points (Point A):

$$V_{cr} = \Delta_{v,cr} \frac{GA}{L}; G = \left(\frac{E_c}{2(1+\mu)} \right) \quad (5)$$

$$\Delta_{v,cr} = \left(\frac{P}{50000} + 0.0062 \right) \quad (6)$$

where V_{cr} is the shear cracking point (kips); $\Delta_{v,cr}$ is the shear displacement corresponding to shear cracking (in); G is the concrete shear modulus (psi); A is the cross-sectional area

(in²); E_c is the modulus of elasticity (psi); μ is Poisson's ratio; and P is the axial load (kips).

Maximum Shear Strength and Corresponding Shear Displacement (Point B):

$$V_n = k (V_c + V_s),$$

$$V_n = k \left(\left(\frac{6\sqrt{f'_c}}{a/d} \sqrt{1 + \frac{P}{6\sqrt{f'_c}A_g}} \right) 0.8A_g + \left(\frac{A_{sp}f_{yw}d}{s} \right) \right) \quad (7)$$

$$\Delta_{v,n} = \gamma_n L,$$

$$\gamma_n = \frac{1}{33000} \frac{f_{yl}\sqrt{\rho_l}}{(a/d) \sqrt{\frac{P}{A_g f'_c}}} - 0.0006 \quad (8)$$

where V_n is the maximum shear strength (kips); V_c is the concrete contribution to shear strength (kips); V_s is the transverse reinforcement contribution to shear strength (kips); k is the displacement ductility factor; f'_c is the concrete compressive strength (psi); A_g is the cross-sectional area (in²); A_{sp} is the transverse reinforcement area (in²); f_{yw} is the yield strength of the transverse reinforcement (ksi); s is the transverse reinforcement spacing (in); $\Delta_{v,n}$ is the shear displacement corresponding to the maximum shear strength (in); f_{yl} is the yield strength of the longitudinal reinforcement (ksi); and ρ_l is the longitudinal reinforcement ratio.

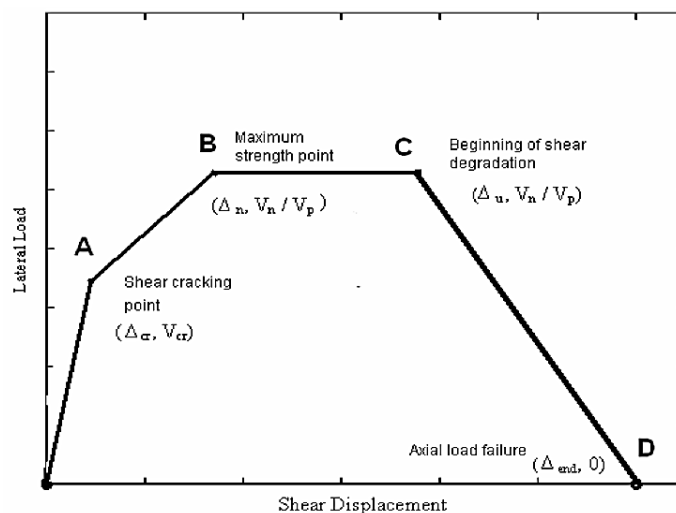


Fig. 3. Shear deformation model developed by Patwardhan [32]

Onset of Shear Strength Degradation (Point C):

$$V_n = k (V_c + V_s)$$

$$V_n = k \left(\left(\frac{6\sqrt{f'_c}}{a/d} \sqrt{1 + \frac{P}{6\sqrt{f'_c}A_g}} \right) 0.8A_g + \left(\frac{A_{sp}f_{yw}d}{s} \right) \right) \quad (9)$$

$$\gamma_u = \left(4 - 12 \frac{v_n}{f'_c} \right) \gamma_n, \quad \Delta_{v,u} = \gamma_u L \quad (10)$$

where γ_u is the ultimate shear strain; v_n is the shear stress at peak strength (V_{peak}/bd); and γ_n is the shear strain at peak strength. Displacement at Axial Load Failure (Point D):

$$\Delta_{v,f} = \Delta_{ALF} - \Delta_{f,f} - \Delta_{s,f} \geq \Delta_{v,u},$$

$$\Delta_{ALF} = \frac{4}{100} \left[\frac{1 + \tan^2\theta}{\tan\theta + P \left(\frac{s}{A_{sp}f_{yw}d_c \tan\theta} \right)} \right] \quad (11)$$

where Δ_{ALF} is the total displacement at axial load failure (in); $\Delta_{f,f}$ is the flexural displacement at axial load failure (in); $\Delta_{s,f}$ is the reinforcement slip displacement at axial load failure (in), and θ is the shear failure angle (65°).

2.4. Combination and behavioral classification

The total lateral displacement of RC columns results from the combined contributions of flexural, bar-slip, and shear deformation components. The behavioral classification proposed by Setzler and Sezen [31] was adopted to determine the post-peak behavior. This classification consists of five behavioral categories based on the relationship between shear strength (V_n), flexural yield strength (V_y), and flexural capacity (V_p) (Fig. 4). The shear strength V_n is calculated using Eq. (7). V_y is the lateral force corresponding to flexural yielding, obtained by dividing the yield moment by the shear span. V_p is the peak lateral force corresponding to flexural capacity, calculated by dividing the maximum moment by the shear span. The classification framework represents the dominant deformation mechanism governing the post-peak behavior and failure mode of each specimen.

- Category I ($V_n < V_y$): Peak strength is governed by shear. The post-peak response is dominated by shear deformation, resulting in rapid strength degradation and limited displacement capacity.
- Category II ($V_y \leq V_n \leq 0.95V_p$): Flexural yielding occurs before the peak lateral strength is reached; however, failure is governed by shear. During the post-peak stage, shear deformation continues to increase, whereas flexural and bar-slip deformations are assumed to remain constant at their peak values.
- Category III ($0.95V_p \leq V_n \leq 1.05V_p$): Shear and flexural strengths are comparable, and the peak capacity is governed by the lower of the two. The post-peak response is characterized by the simultaneous degradation and accumulation of flexural, bar-slip, and shear deformation components.
- Category IV ($1.05V_p \leq V_n \leq 1.4V_p$): Peak behavior is governed by flexural strength. After the peak response, flexural and bar-slip deformations continue to develop, whereas shear deformation is assumed to remain constant after reaching its peak contribution.
- Category V ($V_n > 1.4V_p$): The lateral response is governed primarily by flexural behavior. Shear deformation is considered negligible, and the deformation capacity is controlled by the combined effects of flexural and bar-slip deformations.

The analytical calculations presented in this section are independent of any specific finite element model and form the theoretical basis of the proposed modeling methodology. The calculated flexural, bar-slip, and shear deformation components, along with the behavioral categories, are utilized in the next section to generate nonlinear plastic hinge properties. Thus, the analytically computed deformation components are transformed into applicable plastic hinge properties within the SAP2000 environment through a systematic workflow.

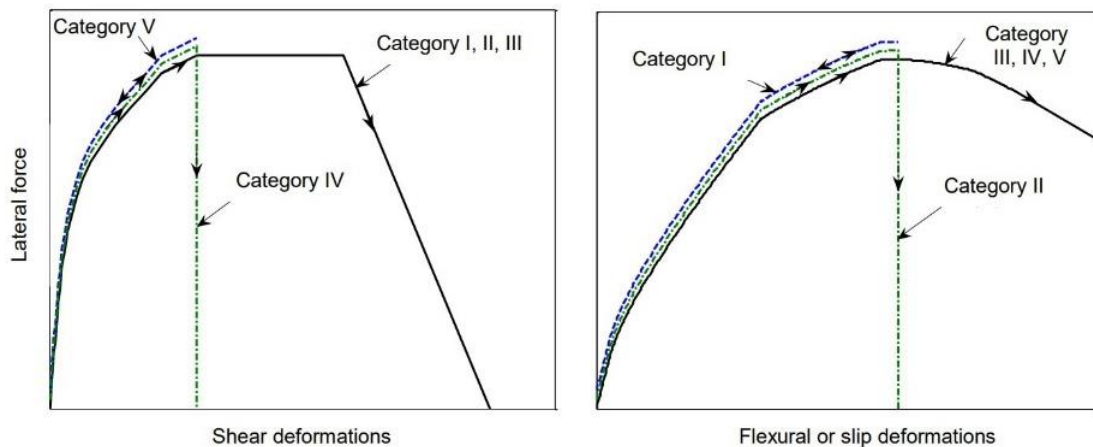


Fig. 4. Classification of RC columns into five behavioral categories [31]

3. Proposed component-based SAP2000 modeling framework

In this study, a component-based modeling framework is proposed within SAP2000 to represent the nonlinear behavior of RC columns subjected to lateral loading. The proposed framework models flexural, bar-slip, and shear deformations as independent components using user-defined plastic hinges within a single finite element model. This enables the explicit representation of multiple deformation mechanisms in a commercial analysis platform without requiring new finite element formulations, user-defined elements, or advanced programming expertise.

3.1. Overall modeling procedure

The proposed modeling methodology begins with the definition of the geometric properties, material parameters, and reinforcement details of the RC column. Based on these parameters, the column cross-section is created in the SAP2000 Section Designer environment, and a moment–curvature analysis is performed under the applied axial load. Flexural, bar-slip, and shear deformations are then calculated independently using the analytical formulations presented in Section 2. Flexural behavior is determined from the moment–curvature relationship, bar-slip behavior is evaluated using the bond-slip model proposed by Setzler and Sezen [31], and shear behavior is determined using the analytical model developed by Patwardhan [32]. Consequently, nonlinear response curves are obtained for each deformation mechanism.

The nonlinear response curves corresponding to the individual deformation components are subsequently idealized as backbone curves and converted into user-defined plastic hinge properties in SAP2000. The idealization procedure is established according to the behavioral category (Cat. I–V) assigned to each column.

Based on the generated backbone curves, user-defined plastic hinges representing the flexural, bar-slip, and shear deformations are created and assigned to their corresponding locations in the model. The proposed component-based numerical model is subsequently established by incorporating these plastic hinges into a single SAP2000 model.

Nonlinear pushover analyses are first performed to obtain the monotonic load–displacement response of the column. For cyclic analysis, the resulting monotonic backbone curves are then assigned to user-defined link elements. Appropriate hysteretic models (Pivot or Takeda) are selected according to the behavioral category of each specimen, and the monotonic backbone curves are used to define the cyclic hysteretic behavior of the link elements. Finally, the loading protocols reported in the corresponding experimental studies are applied, and nonlinear cyclic analyses are carried out.

The overall workflow of the proposed modeling methodology is illustrated in Fig. 5. The generation of nonlinear component response curves, development of backbone curves, definition of user-defined plastic hinge properties, hinge assignment procedure, implementation of the user-defined link elements, and cyclic modeling procedure are described in detail in the following sections.

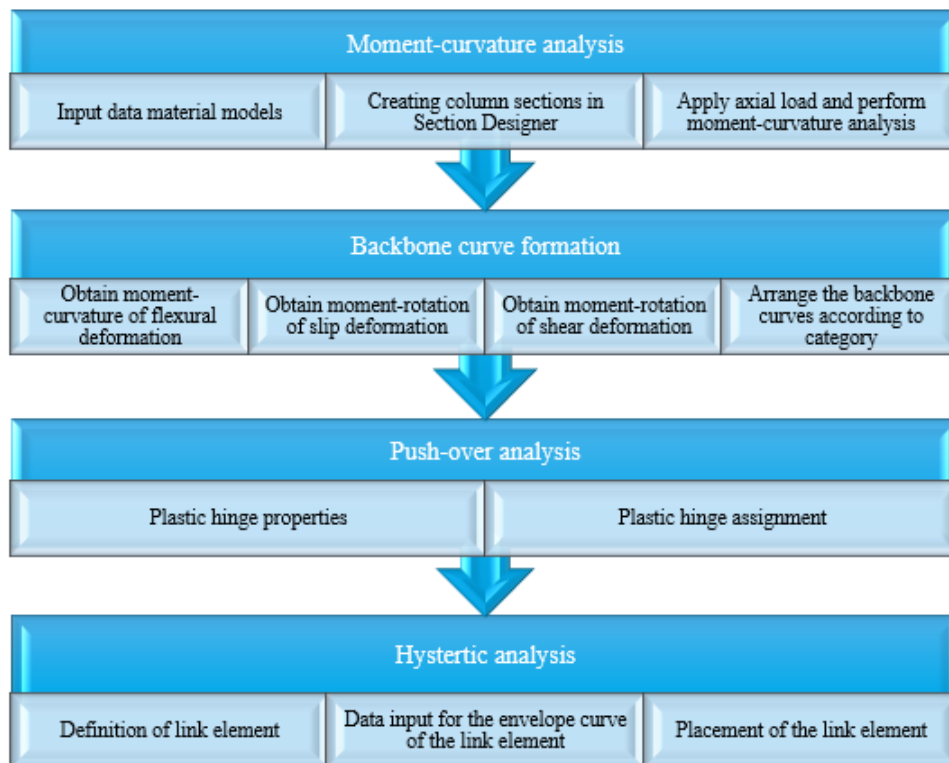


Fig. 5. Workflow of the proposed component-based modeling methodology in SAP2000

3.2. Generation of nonlinear component response curves

Using the analytical formulations presented in Section 2, nonlinear response curves are generated for the flexural, bar-slip, and shear deformation mechanisms.

The nonlinear response curve for flexural behavior is obtained from the moment–curvature analysis performed in the SAP2000 Section Designer module. The column cross-section is defined using the geometry, reinforcement details, and material properties of each specimen, and the analysis is carried out under the corresponding axial load. The resulting moment–curvature ($M-\phi$) relationship is used as the nonlinear response representing flexural behavior.

The nonlinear response curve for bar-slip behavior is established using the analytical bar-slip model proposed by Setzler and Sezen [31]. The calculated bar slip is converted into slip rotation, and the corresponding moment values obtained from the moment–curvature analysis are assigned to these rotation values to construct the moment–rotation ($M-\theta$) relationship for bar-slip behavior.

For shear behavior, the nonlinear response curve is derived using the analytical force–displacement model proposed by Patwardhan [32]. Force and displacement values corresponding to four characteristic limit states—cracking formation, peak shear strength, onset of strength degradation, and loss of axial load-carrying capacity—are calculated using the equations presented in Section 2.3 (Fig. 3; Eq. 5–11). The resulting force–displacement relationship is then converted into an equivalent moment–rotation ($M-\theta$) relationship using the shear span, making it compatible with the plastic hinge formulation adopted in SAP2000. For implementation within the SAP2000 rotational hinge formulation, the resulting shear force–displacement relationship is represented by an equivalent moment–rotation ($M-\theta$) relationship using $M=Va$ and $\theta=\Delta/L$, where a is the shear span, and L is the column height. This transformation is introduced solely as an equivalent numerical representation of the analytical shear response within the SAP2000 hinge framework.

Consequently, three independent nonlinear response curves are established for the individual deformation mechanisms: a moment–curvature ($M-\phi$) relationship for flexural behavior, a moment–rotation ($M-\theta$) relationship for

bar-slip behavior, and an equivalent moment–rotation ($M-\theta$) relationship for shear behavior. These continuous nonlinear response curves are not directly assigned as SAP2000 plastic hinge properties. Instead, they are idealized into backbone curves, as described in the following section, to generate the user-defined plastic hinge properties.

3.3. Development of behavior-dependent SAP2000 backbone curves and hinge properties

The nonlinear response curves developed for the deformation mechanisms are subsequently idealized into backbone curves for defining user-defined plastic hinge properties in the SAP2000. Flexural behavior is represented by the moment–curvature ($M-\phi$) relationship, whereas bar-slip and shear behaviors are represented by equivalent moment–rotation ($M-\theta$) relationships. These curves were idealized to capture the key stages of nonlinear behavior while conforming to the plastic hinge formulation adopted in SAP2000.

The user-defined plastic hinges in SAP2000 are described by five characteristic points (A, B, C, D, E). In the proposed methodology, these points are established directly from the nonlinear response curves presented in Section 3.2. Point A represents the undeformed state, where both moment and curvature/rotation are zero. Point B corresponds to the first characteristic limit state of the respective deformation mechanism (yielding for flexural and bar-slip behavior, and crack formation for shear behavior). Point C denotes the maximum strength, Point D marks the onset of strength degradation, and Point E represents the ultimate deformation capacity.

Although SAP2000 provides five characteristic points for defining user-defined plastic hinges, not all of these points are required for every deformation mechanism. The extent of the backbone curve depends on the governing behavioral category of the RC column. For deformation mechanisms that continue to exhibit post-peak degradation, the complete A–B–C–D–E backbone is adopted. In contrast, when the deformation mechanism is assumed to remain constant after reaching the peak response, the backbone terminates at Point C. Consequently, the characteristic points assigned to the flexural, bar-slip, and shear backbone curves vary according to the governing behavioral category, as summarized in Table 1.

Table 1. Assignment of backbone curve characteristic points for each deformation component according to the behavioral category

Behavioral Category	Flexural Plastic Hinge	Bar-Slip Plastic Hinge	Shear Plastic Hinge
I	Not Assigned	Not Assigned	A–B–C–D–E
II	A–B–C	A–B–C	A–B–C–D–E
III	A–B–C–D–E	A–B–C–D–E	A–B–C–D–E
IV	A–B–C–D–E	A–B–C–D–E	A–B–C
V	A–B–C–D–E	A–B–C–D–E	Not Assigned

The resulting backbone curves are then assigned as user-defined plastic hinge properties in SAP2000, creating independent plastic hinges for the flexural, bar-slip, and shear deformation mechanisms. Through this procedure, the continuous nonlinear response curves obtained from the analytical models are systematically converted into implementable plastic hinge definitions within a commercial finite element platform.

3.4. Hinge assignment procedure

The plastic hinge properties developed in the previous section are assigned to the finite element model to construct the proposed component-based modeling framework.

The RC columns are modeled using two-node, one-dimensional frame elements available in SAP2000. At each node point, two translational and one rotational degree of freedom are defined. In the two-dimensional column model has two translational and one rotational degrees of freedom at each node. All plastic hinges are assigned to the local M3 rotational degree of freedom of the frame element. Consequently, flexural, bar-slip, and shear deformations are represented independently while sharing the same rotational axis within a single finite element model.

The flexural plastic hinge is assigned along the column, whereas the bar-slip and shear plastic hinges are placed at both ends of the RC column. This configuration reflects the locations where the corresponding deformation mechanisms are expected to develop during the structural response.

To verify the proposed modeling strategy, the analyses are performed in two stages. In the first stage, the flexural, bar-slip, and shear plastic hinges are analyzed independently. The lateral displacements obtained from each nonlinear static analysis are then combined through displacement superposition at the same lateral load level to obtain the total column response. This stage provides a reference response by quantifying the contribution of each deformation mechanism separately. In the second stage, the flexural, bar-slip, and shear plastic hinges are incorporated simultaneously into a single column model. The resulting load–displacement response is then compared with the response obtained from the superposition procedure in the first stage. In the integrated model, the three hinges represent distinct deformation components subjected to the same lateral load, and their deformation contributions accumulate within the column response. Therefore, at a given lateral load level, the total displacement is consistent with the sum of the flexural, bar-slip, and shear displacement contributions obtained from the independent analyses. The close agreement between the two responses confirms the consistency of the proposed component-based modeling framework.

To prevent double counting of deformation components, each plastic hinge is assigned to represent only one deformation mechanism (flexural, bar-slip, or shear). The frame segments between adjacent plastic hinges are modeled as rigid, ensuring that deformation is concentrated exclusively

within the corresponding plastic hinge. Consequently, no overlap is introduced among the individual deformation mechanisms.

Displacement compatibility among the deformation mechanisms is enforced through the SAP2000 finite element formulation. The flexural, bar-slip, and shear plastic hinges are incorporated into the same frame model through common nodes and are defined with respect to the same local M3 rotational axis. The nodal kinematic compatibility of the integrated model is therefore maintained directly by the finite element formulation, without requiring additional compatibility equations or constraint definitions.

3.5. Nonlinear static and cyclic modeling procedure

Using the user-defined backbone curves developed in the previous sections, nonlinear static (pushover) analyses are performed to obtain the monotonic load–displacement response of each RC column. The monotonic backbone curves obtained from the pushover analyses are then assigned to the user-defined link elements in SAP2000. Consequently, the nonlinear monotonic response of each deformation mechanism defines the backbone curve governing the cyclic behavior of the corresponding link element.

The cyclic response is modeled using the Pivot and Takeda hysteretic models available in SAP2000. The backbone curves assigned to the user-defined link elements are combined with the selected hysteretic models to represent the nonlinear cyclic behavior of the RC columns. The hysteretic model assigned to each specimen is selected according to its behavioral category and governing failure mechanism. Since the cyclic response of Category I–IV columns is significantly influenced by shear effects, stiffness degradation, and pinching behavior, the Pivot hysteretic model was adopted for these specimens. In contrast, the Takeda hysteretic model is employed for Category V columns, where the response is predominantly governed by flexural behavior.

The cyclic loading histories reported in the corresponding experimental studies are then directly applied to the numerical models. Consequently, the number of loading cycles, loading direction, and displacement amplitudes are identical to those used in the experimental programs. During the cyclic analyses, the user-defined link elements representing the flexural, bar-slip, and shear deformation mechanisms responded simultaneously within the same finite element model, while the interaction among the deformation mechanisms is inherently enforced by the SAP2000 finite element formulation.

3.6. SAP2000 numerical implementation

The proposed component-based modeling framework is implemented in SAP2000. The column geometry, boundary conditions, axial load, and material properties are defined according to the experimental data. Cross-sectional properties are established using the SAP2000 Section Designer module,

where the section geometry and reinforcement details are defined according to the corresponding test specimens.

The nonlinear response curves developed using the analytical procedures described in Section 3.2 are converted into user-defined plastic hinge backbone curves following the idealization procedure presented in Section 3.3. Accordingly, the moment–curvature and moment–rotation relationships representing the flexural, bar-slip, and shear deformation mechanisms are transformed into the characteristic A–B–C–D–E points required for the SAP2000 user-defined plastic hinge formulation (Fig. 7).

The generated plastic hinges are then assigned to the column model according to the proposed component-based modeling procedure described in Section 3.4. The flexural

hinge was assigned along the column, whereas the bar-slip and shear hinges were located at both ends, as illustrated in Fig. 8.

Pushover analyses are performed to obtain the monotonic force–displacement response. The resulting force–displacement curves are subsequently assigned as the backbone behavior of the user-defined link elements available in SAP2000. The backbone curves assigned to the link elements are then combined with the appropriate hysteretic model (Pivot or Takeda), selected according to the behavioral category and governing failure mechanism of each specimen, to define the nonlinear cyclic response of the columns (Fig. 9).

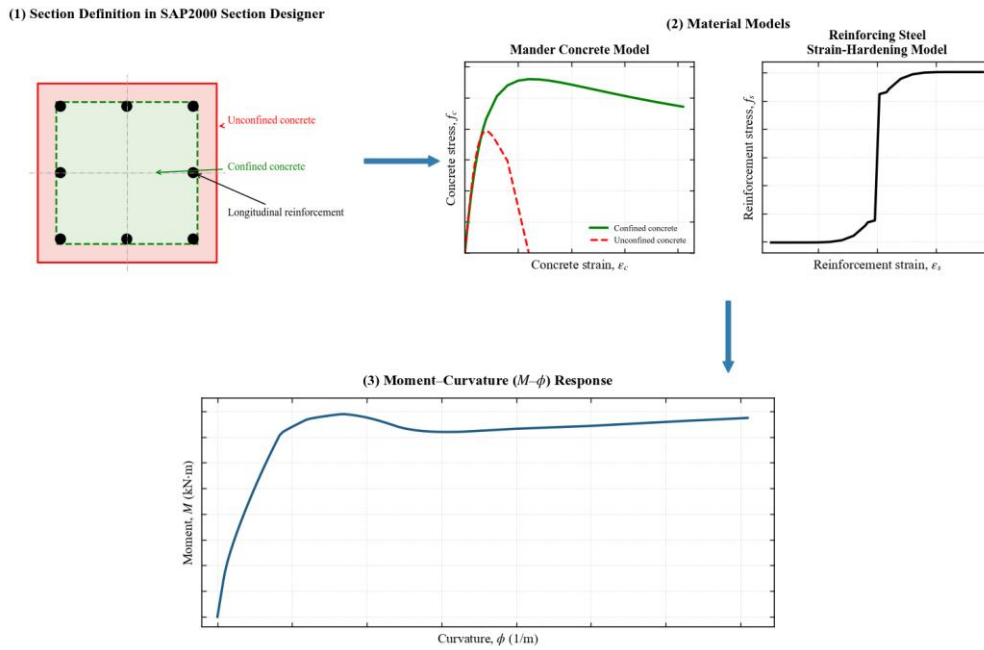


Fig. 6. SAP2000 Section Designer implementation: section definition, nonlinear material models, and moment–curvature response

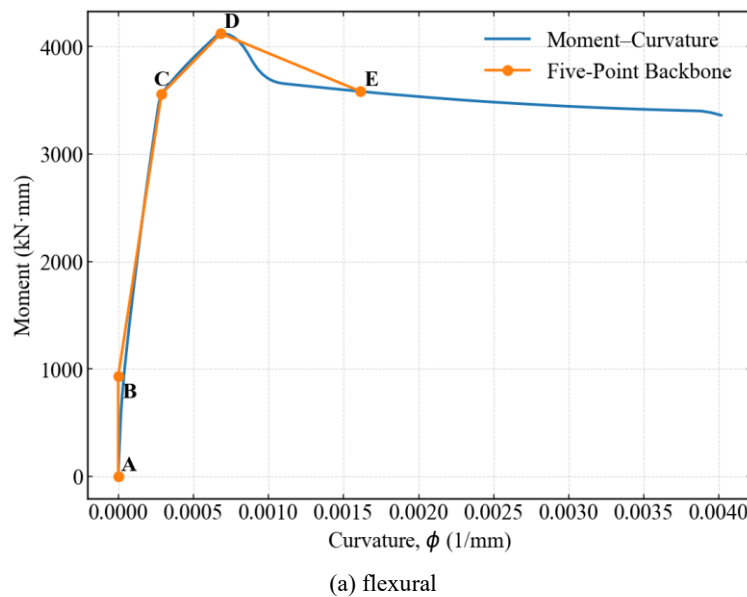


Fig. 7. Development of five-point backbone curves from the nonlinear component responses: (a) flexural, (b) bar-slip, and (c) shear deformation

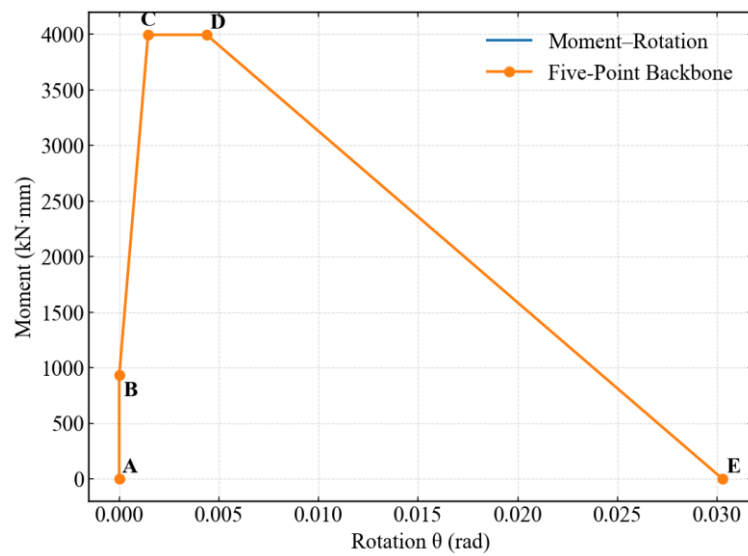
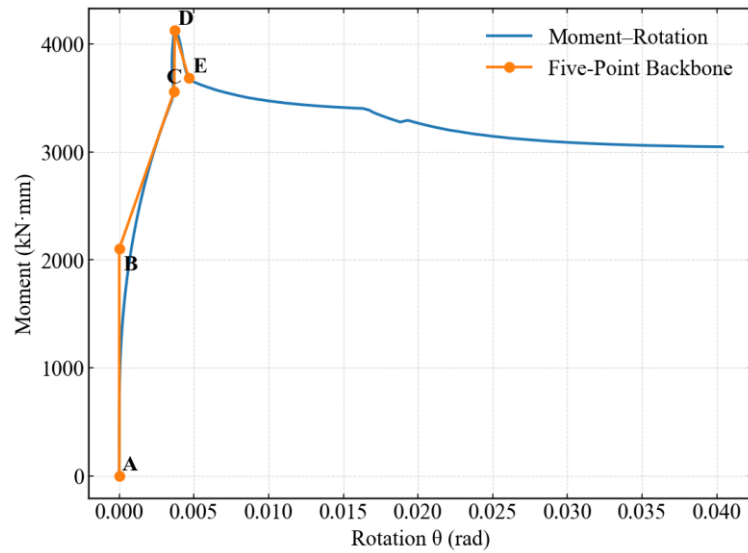


Fig. 7. Continued

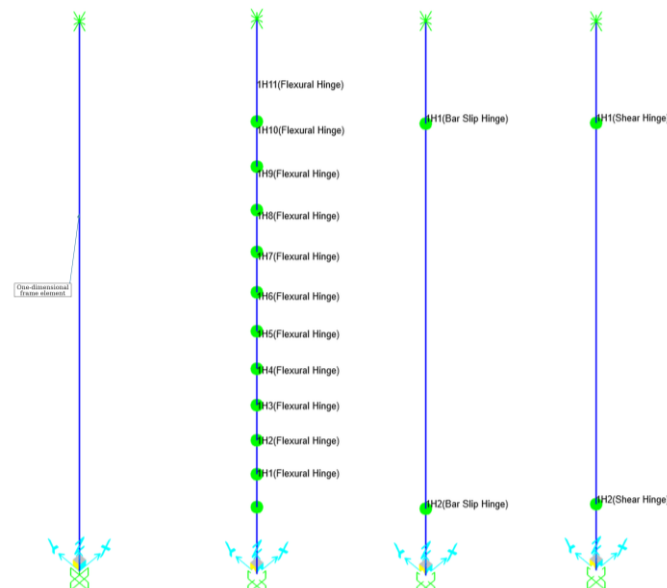


Fig. 8. Plastic hinge placement for flexural, bar slip, and shear deformations

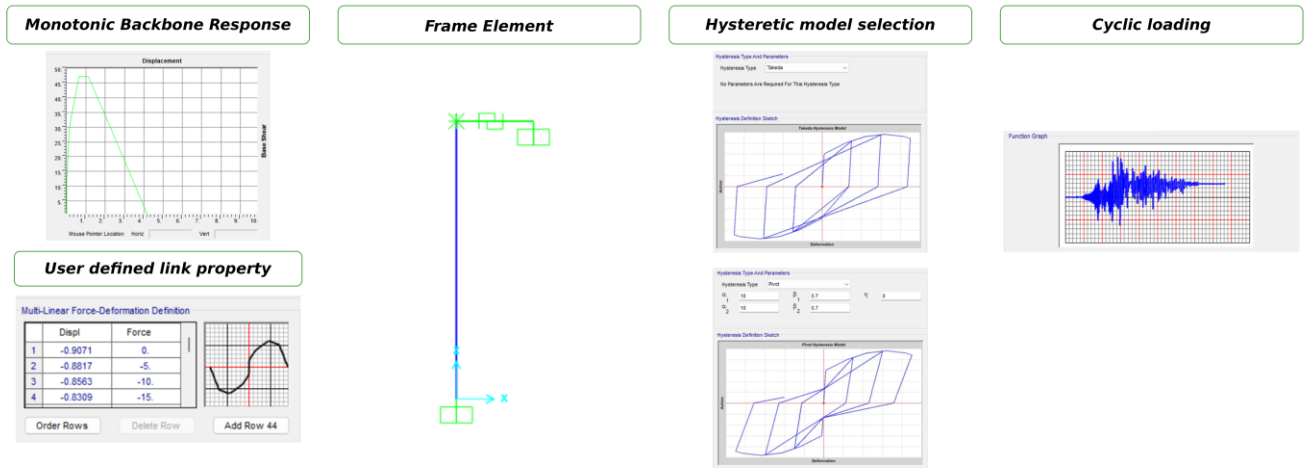


Fig. 9. SAP2000 implementation procedure for cyclic analysis: (a) monotonic backbone response, (b) user-defined link implementation, (c) hysteretic model selection, and (d) cyclic loading protocol

Finally, the cyclic loading protocols reported in the corresponding experimental studies are directly applied to the numerical models. Consequently, the number of loading cycles, loading direction, and displacement amplitudes were identical to those used in the experimental programs. Through this implementation procedure, the monotonic column response obtained from the proposed component-based plastic hinge model was transferred directly to an equivalent user-defined link element, enabling the combined effects of flexural, bar-slip, and shear deformation mechanisms to be represented under cyclic loading within the SAP2000 environment.

4. OpenSees numerical modeling

OpenSees (Open System for Earthquake Engineering Simulation) [29] is an open-source software framework used for modeling and simulating the nonlinear behavior of structural and geotechnical systems, particularly under seismic loading. Developed at the Pacific Earthquake Engineering Research (PEER) Center [34], it provides a flexible object-oriented platform for defining materials, sections, elements, and analysis procedures, enabling advanced research and performance-based engineering studies. Its modular architecture allows the combination of distinct material and element formulations to capture individual deformation mechanisms—flexural, shear, and bond-slip—within a single analytical model, which makes it particularly well suited for simulating the complex hysteretic response of RC members under cyclic loading. Previously tested RC columns were modeled and analyzed using OpenSees (version 3.6.0), with the analytical results validated against the corresponding experimental data.

4.1. Element formulation

To model the columns, a distributed plasticity element combined with zero-length springs at both ends was employed, allowing the total lateral displacement to be

decomposed into flexural, shear, and slip components that could be independently calculated. Fiber sections were defined at the column cross-section, discretizing the concrete core into confined and unconfined regions and explicitly modeling the longitudinal reinforcing bars as individual fibers. Specifically, cross-sections were discretized into ten rectangular fiber layers for confined concrete. For unconfined concrete, two layers at both the top and bottom of the section and ten layers for the sides of the section were used. The Concrete01 material model, based on the modified Kent–Park concrete stress–strain relationship, was utilized for both confined and unconfined concrete, with the confined concrete parameters (peak strength, corresponding strain, and ultimate strain) increased relative to the unconfined values to reflect the confinement effect provided by the transverse reinforcement. For unconfined concrete, the peak compressive strength was taken from experimental test data; the strain at peak strength was set to $\epsilon_0=0.002$, and the ultimate crushing strain was assumed as $\epsilon_{cu}=0.005$ with zero residual strength. For confined concrete, the peak strength (f'_{cc}) and peak strain (ϵ_{cc}) were computed based on Mander's confinement model, with ultimate confined strain (ϵ_{cu}) ranging from 0.012 to 0.018 depending on the transverse tie ratio. The Steel01 model, a bilinear stress–strain relationship with kinematic hardening, was used to represent the reinforcing steel, with material parameters (yield strength, elastic modulus, and strain-hardening ratio) obtained from coupon test results where available. The elastic modulus of reinforcing steel was set to $E_s = 200$ GPa, and a uniform strain-hardening ratio of $b = 0.01$ was assumed for all longitudinal bars. For each column, a force-based beam-column element with five integration points was utilized to simulate the flexural component of the total lateral displacement, as force-based formulations allow for accurate representation of the spread of plasticity along the member length without requiring prior discretization into multiple elements.

4.2. Zero-length springs

In addition, a rotational zero-length spring assigned a Hysteretic material was introduced at the column base to account for slip displacement resulting from strain penetration and bond-slip of the longitudinal reinforcement within the foundation or joint region. The moment–rotation backbone of this spring was calibrated based on the bond-slip mechanics of the anchored reinforcing bars, capturing the pinching and stiffness degradation typically observed in the experimental hysteretic response. The yield moment and rotation limits were evaluated using an elastic bond stress of $u_b = \sqrt{f'_c}$ (MPa) and development length $l_d = d_b f_y / 4u_b$, with pinching parameters set to $P_x = 0.6$ and $P_y = 0.2$, and cyclic degradation parameters set to $\beta_1 = 0.00$ and $\beta_2 = 0.01$. Shear displacement was modeled using a previously developed approach with the Shear01 material, implemented through an additional zero-length spring oriented in the shear degree of freedom, which enabled the shear force–deformation response to be represented independently of the flexural behavior captured by the beam-column element. The shear limit points, including cracking (V_{cr} , Δ_{cr}) and peak strength (V_n , $\Delta_{v,n}$) were determined directly from the Modified Compression Field Theory (MCFT) relations using the column geometry and applied axial load. This uncoupled treatment of flexural, shear, and slip deformations allowed the overall model to reproduce the combined stiffness and strength degradation mechanisms observed in columns exhibiting mixed flexure–shear failure modes. Further details regarding the OpenSees model, including the derivation and calibration of the spring parameters, can be found in Bicici [35].

4.3. Analysis procedure

Geometric nonlinearity was not considered in the OpenSees analyses; thus, P-Delta effects were neglected, consistent with the relatively low axial load levels and stocky geometry of the tested specimens. During the analysis, axial loads were applied to the columns in accordance with the experimental conditions and held constant throughout the loading history to replicate the test setup. The Krylov-Newton algorithm was selected for the solution process due to its improved convergence characteristics in highly nonlinear regimes involving strength and stiffness degradation. Displacement increments were set between 0.05 mm and 0.1 mm per step, and convergence was checked using an energy increment tolerance of 10^{-6} , with temporary automated fallback to Newton-LineSearch. Experimentally recorded displacement histories were imposed at the top of the modeled columns in a quasi-static, displacement-controlled manner, and the corresponding base reactions were computed at each analysis step. Finally, the resulting lateral load–displacement relationships were compared with the experimental data to assess the accuracy of the numerical model in capturing the

initial stiffness, peak strength, and post-peak degradation behavior of the tested columns.

5. Experimental database and validation strategy

5.1. Specimen selection

An experimental database consisting of 24 RC column specimens collected from the literature was compiled to evaluate the accuracy and applicability of the proposed component-based modeling approach. The selected specimens cover a wide range of geometries, concrete strengths, reinforcement details, axial load levels, and failure mechanisms, providing a representative dataset for assessing the proposed methodology under different structural conditions.

The geometry, material properties, reinforcement details, axial load levels, loading histories, and experimental responses of all specimens were obtained from the corresponding reference studies. A single, consistent list of 24 specimens was used throughout the manuscript and across all numerical and statistical evaluations. The assessment of cyclic behavior, maximum lateral strength, displacement capacity, and cumulative energy dissipation was performed using the same set of 24 specimens, with no specimens excluded from any of these evaluations.

The database includes flexure-controlled, flexure–shear, and shear-controlled columns, allowing the proposed modeling approach to be evaluated under different governing failure mechanisms. The fundamental geometric, material, and reinforcement properties of the specimens are summarized in Table 2. The table includes eleven key parameters: column length (L), section width (b), section depth (h), shear span ratio (a/d), axial load (P), concrete compressive strength (f'_c), longitudinal reinforcement yield strength (f_{yl}), transverse reinforcement yield strength (f_{yt}), longitudinal reinforcement ratio (ρ_l), transverse reinforcement ratio (ρ_t), and transverse reinforcement spacing (s).

Among the 24 specimens, only Specimen 3, reported by Sezen [10], was tested under variable axial load, whereas the remaining 23 were subjected to constant axial load. In the present study, this specimen was treated as a single physical specimen, and both the minimum and maximum axial load levels were reported in a single record.

5.2. Failure classification

The behavioral category of each specimen was determined using the classification procedure described in Section 2. The classification was based on the relationships among the calculated shear strength (V_n), yield strength (V_y), and flexural capacity (V_p), assigning each specimen to one of five behavioral categories (Categories I–V). The corresponding experimental failure mechanisms were independently obtained from the PEER Structural Performance Database [34] and used to verify the analytical classification. The

calculated strength parameters together with the assigned behavioral categories are summarized in Table 3. The same behavioral classification was adopted in both the SAP2000 and OpenSees models to ensure a consistent basis for the numerical comparisons.

5.3. Model input parameters

The input parameters used in the proposed modeling methodology were classified into four groups according to their source: (i) experimentally measured parameters, (ii) parameters calculated using literature-based analytical models, (iii) general modeling assumptions, and (iv) specimen-specific calibrated parameters.

The first group comprises parameters obtained directly from the experimental studies, including the column geometry, concrete compressive strength, reinforcement properties and layout, axial load level, and loading history. These parameters were directly transferred to the numerical models without modification.

The second group consists of parameters calculated using established analytical models reported in the literature. Flexural deformation was determined from the moment–curvature analysis, bar-slip deformation was calculated using the model proposed by Setzler and Sezen [31], and shear

deformation was determined using the analytical model developed by Patwardhan.

The third group includes the general modeling assumptions adopted throughout the study. These assumptions comprise the backbone curve idealization, behavior-dependent backbone modifications, plastic hinge implementation procedure, and the selection of the hysteretic model according to the behavioral category. The same assumptions and modeling procedure were applied consistently to all specimens.

The fourth group corresponds to specimen-specific calibrated parameters. No specimen-specific parameter calibration was performed in this study. The hysteretic model was selected solely according to the behavioral category of each specimen, and no model parameters were adjusted to improve agreement with the experimental load–displacement responses.

Accordingly, all model inputs were established from experimentally measured data, literature-based analytical formulations, and predefined modeling assumptions. The experimental results were used exclusively to evaluate the predictive capability of the proposed modeling methodology and were not used for parameter tuning or model calibration.

Table 2. Properties of RC columns

Specimen	Parameters of cross-section and axial load					Parameters of material and rebars					
	L - mm	b -mm	h - mm	a/d	P - kN	f_c - MPa	f_{yl} - MPa	f_{yt} - MPa	p_l - %	p_t - %	s - mm
1. U1 [36]	1000	350	350	3.28	0	43.57	438	470	3.31	0.29	150
2. U4 [36]	1000	350	350	3.28	596	31.99	438	470	3.31	0.89	50
3. U6 [36]	1000	350	350	3.28	596	37.30	438	425	3.31	0.84	50
4. C1-1 [37]	1400	400	400	3.99	449	24.89	496	455	2.14	0.63	50
5. C1-2 [37]	1400	400	400	3.99	676	26.68	496	455	2.14	0.63	50
6. FS1[38]	900	300	300	3.53	632	27.03	387	355	3.8	0.63	75
7. 2CLH18 [39]	2946	457	457	3.71	503	33.09	497	400	1.94	0.07	457
8. 2CMH18 [39]	2946	457	457	3.71	1512	25.51	497	400	1.94	0.07	457
9. 3CLH18 [39]	2946	457	457	3.74	503	26.89	497	400	3.03	0.07	457
10. 3CMH18[39]	2946	457	457	3.74	1512	27.58	497	400	3.03	0.07	457
11. Spec.-1 [10]	2946	457	457	3.73	667	21.10	407	476	2.5	0.20	305
12. Spec.-2 [10]	2946	457	457	3.73	2669	21.10	407	476	2.5	0.20	305
13. Spec.-3 [10]	2946	457	457	3.73	-267 – 2667	20.89	407	476	2.5	0.20	305
14. Spec.-4 [10]	2946	457	457	3.73	667	21.58	407	476	2.5	0.20	305
15. C1 [40]	900	300	300	1.73	365	13.51	401	587	1.69	0.08	160
16. C8 [40]	900	300	300	1.73	485	18.00	401	384	1.69	0.28	75
17. C12 [40]	900	300	300	1.73	324	18.00	401	384	1.69	0.28	75
18. Kansas1 [41]	2946	457	457	3.74	2224	33.09	441	372	2.45	0.07	457
19. Kansas2 [41]	2946	457	457	3.74	1512	33.65	441	372	2.45	0.07	457
20. Kansas3 [41]	2946	457	457	3.74	2224	17.31	448	372	3.03	0.07	457
21. Kansas4 [41]	2946	457	457	3.74	1512	18.62	441	372	2.45	0.17	457
22. Purdue-1 [42]	1473	457	457	1.87	1512	19.99	455	490	1.48	0.07	457
23. Purdue-2 [42]	1473	457	457	1.87	1512	19.31	455	455	1.48	0.07	203
24. Purdue-4 [42]	1473	457	457	1.87	2224	24.13	441	490	2.45	0.07	457

Table 3. Shear and flexural strength of RC column and category selection

Specimen	SAP2000				OPENSEES				SPD
	V _n (kN)	V _y (kN)	V _p (kN)	Cat	V _n (kN)	V _y (kN)	V _p (kN)	Cat	
1. U1 [36]	276.19	225.97	295.63	2	248.61	184.87	282.15	2	F
2. U4 [36]	590.28	253.95	343.53	5	588.90	242.74	316.76	5	F
3. U6 [36]	526.84	256.75	340.38	5	525.69	258.26	356.17	5	F
4. C1-1 [37]	537.25	218.67	264.18	5	555.82	199.50	237.62	5	F
5. C1-2 [37]	519.46	202.48	249.63	5	574.21	220.54	252.08	5	F
6. FS1[38]	273.61	178.42	204.08	4	276.59	185.93	206.40	4	F-S
7. 2CLH18 [39]	224.55	188.74	234.38	3	245.18	197.54	245.99	3	F-S
8. 2CMH18 [39]	272.59	268.63	286.33	3	307.73	275.30	287.44	4	F-S
9. 3CLH18 [39]	209.47	232.55	316.67	1	246.21	259.33	318.76	1	S
10. 3CMH18[39]	275.97	336.77	361.91	1	313.33	344.38	361.06	1	S
11. Spec.-1 [10]	306.48	270.01	318.94	3	308.71	258.22	311.46	3	F-S
12. Spec.-2 [10]	410.17	302.74	320.49	4	413.37	257.68	315.42	4	F-S
13. Spec.-3 [10]	222.37, 410.17	185.89, 302.74	272.19, 320.49	2, 4	220.32, 413.37	179.57, 257.68	251.77, 315.42	2, 4	F-S
14. Spec.-4 [10]	308.30	270.27	321.87	3	310.53	260.53	314.18	3	F-S
15. C1 [40]	174.01	183.67	196.25	1	182.20	180.33	193.94	2	S
16. C8 [40]	sa	210.44	224.86	4	263.42	207.06	222.94	4	F-S
17. C12 [40]	228.86	183.44	209.38	4	241.23	180.33	205.06	4	F-S
18. Kansas1 [41]	323.74	406.43	414.17	1	324.14	395.53	420.49	1	S
19. Kansas2 [41]	287.40	360.57	388.15	1	287.80	351.19	397.89	1	S
20. Kansas3 [41]	275.08	336.19	345.27	1	275.52	320.58	345.63	1	S
21. Kansas4 [41]	319.02	326.90	330.59	1	268.18	256.35	314.13	2	S
22. Purdue-1 [42]	470.44	515.68	528.67	1	471.15	496.95	530.05	1	S
23. Purdue-2 [42]	461.81	514.83	523.51	1	463.72	496.86	524.49	1	S
24. Purdue-4 [42]	565.90	708.51	722.92	1	566.79	730.79	742.00	1	S

6. Results and discussion

6.1. Cyclic load–displacement response results

The cyclic load–displacement responses obtained from the proposed component-based SAP2000 model and the OpenSees model were compared with the experimental hysteresis curves. The comparisons for RC columns are presented in Figures 10–14. In all cyclic analyses, the displacement-controlled loading protocols reported in the corresponding experimental studies were adopted, and the same loading histories were applied to the numerical models [10], [35–41].

- Category I: The proposed SAP2000 model reproduced the main characteristics of the experimental hysteretic response, including stiffness and strength degradation. The OpenSees model also showed good agreement with the experimental response, although differences between the numerical and experimental responses were observed in some loading cycles (Fig. 10).
- Category II: Both numerical models captured the main characteristics of the experimental cyclic response. The SAP2000 model accurately represented the progressive stiffness degradation and reduction in lateral load capacity, although slight discrepancies were observed in the unloading

stiffness and pinching behavior during some loading cycles. Overall, both numerical approaches provided satisfactory agreement with the experimental hysteretic response (Fig. 11).

- Category III: Good agreement was observed between the numerical and experimental responses. The proposed SAP2000 model successfully captured the load–displacement relationship and stiffness degradation, whereas the OpenSees model reproduced the cyclic behavior with slightly greater detail. Nevertheless, the overall responses obtained from the two numerical approaches were very similar (Fig. 12).
- Category IV: The SAP2000 model successfully represented the dominant features of the cyclic response, including the degradation of stiffness and strength throughout the loading history. The differences observed in the unloading branches and the degree of pinching in some specimens are mainly attributed to the inability of simplified hysteretic rules to explicitly represent local damage mechanisms such as crack propagation and cumulative damage (Fig. 13).
- Category V: The proposed SAP2000 model adequately reproduced the stable hysteretic response and progressive stiffness degradation observed experimentally. The remaining differences between the numerical and experimental responses may be associated with localized

damage mechanisms and cyclic deterioration effects that are not fully captured by the adopted idealized hysteretic formulation (Fig. 14).

Overall, both numerical models reproduced the experimental cyclic responses with satisfactory accuracy across the five behavioral categories. While the distributed-

plasticity formulation adopted in OpenSees provided a more detailed representation of local cyclic phenomena, the proposed component-based SAP2000 methodology achieved a comparable level of accuracy using a substantially simpler modeling procedure.

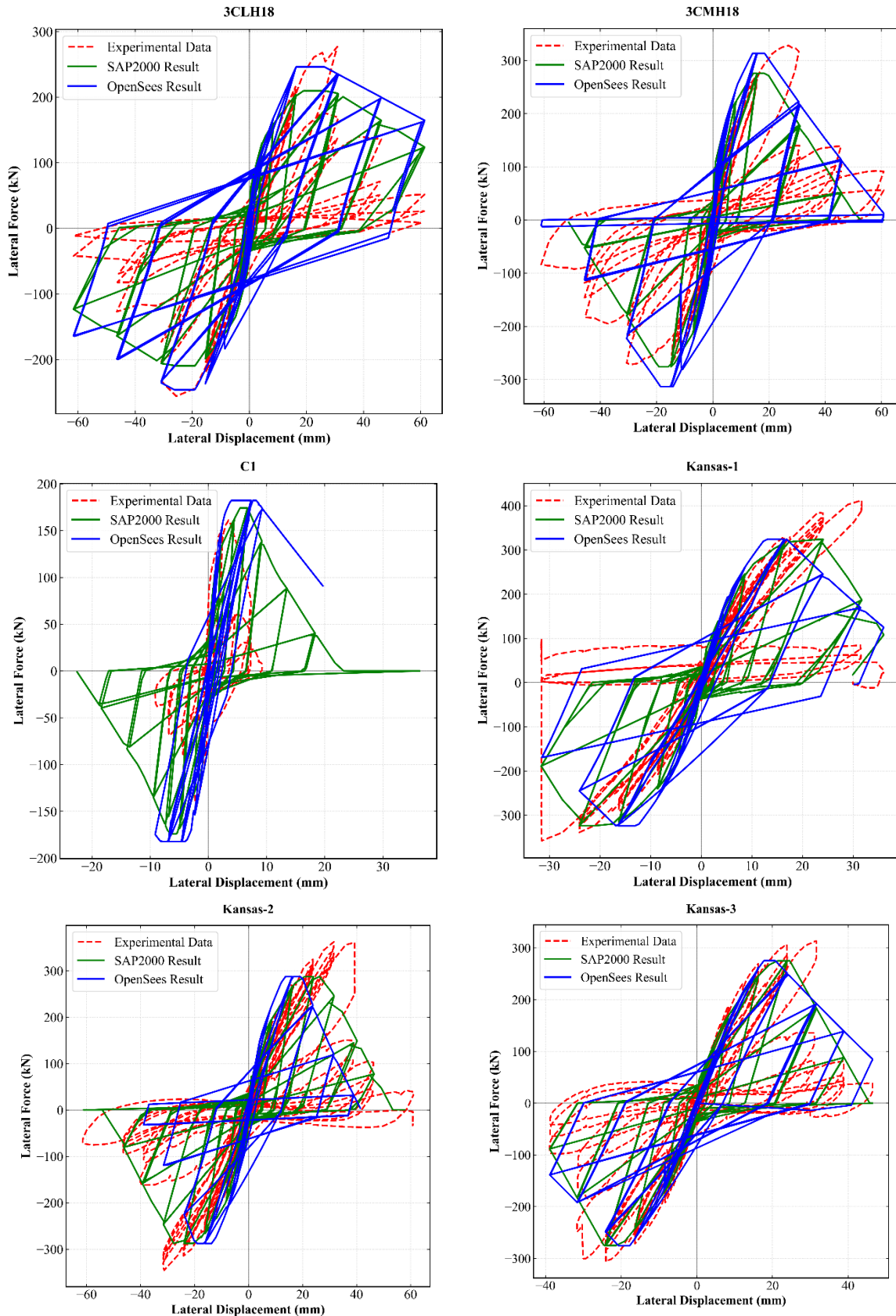


Fig. 10. Comparison of analytical and experimental load-displacement graphs for Category I columns

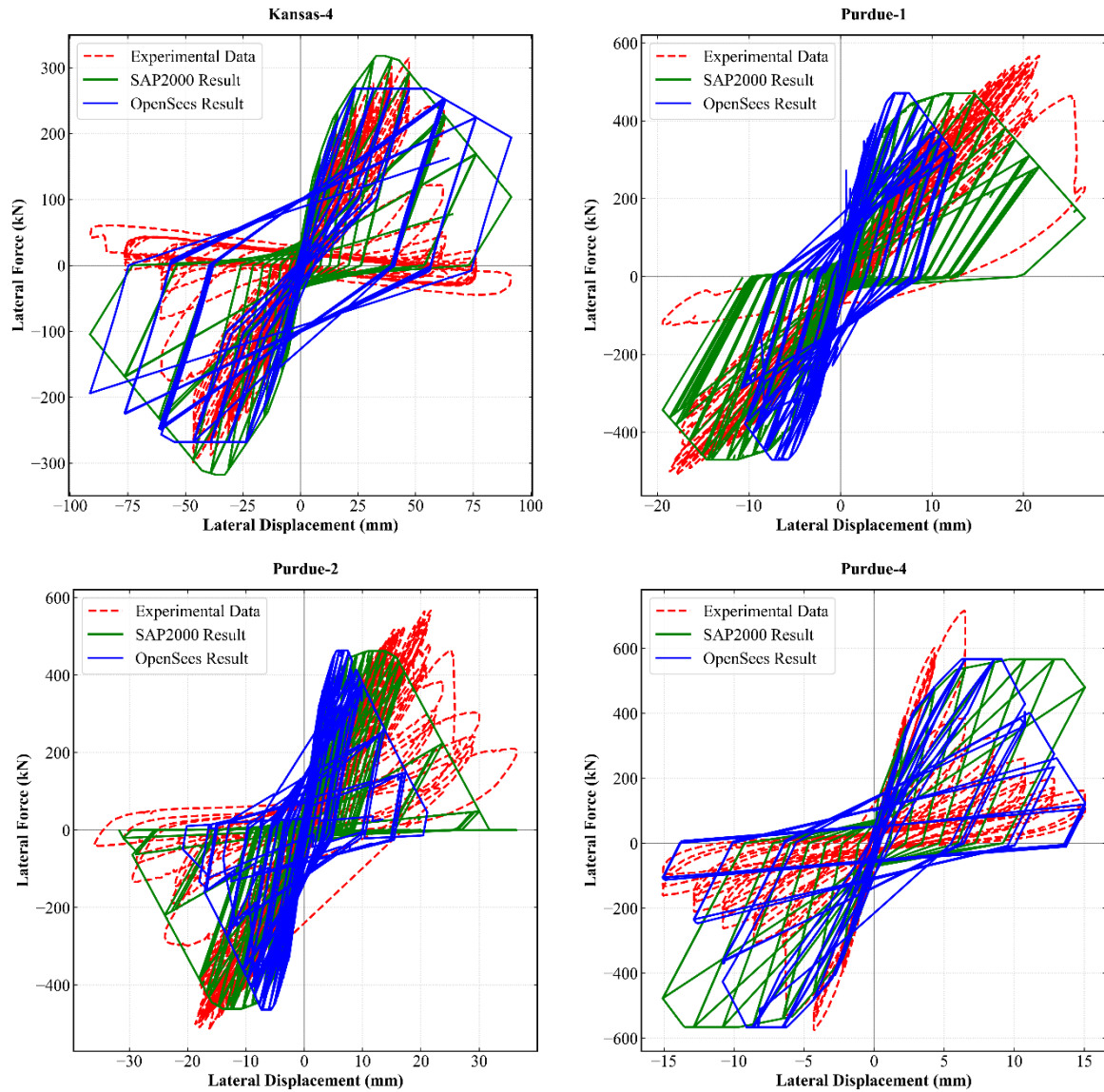


Fig. 10. Continued

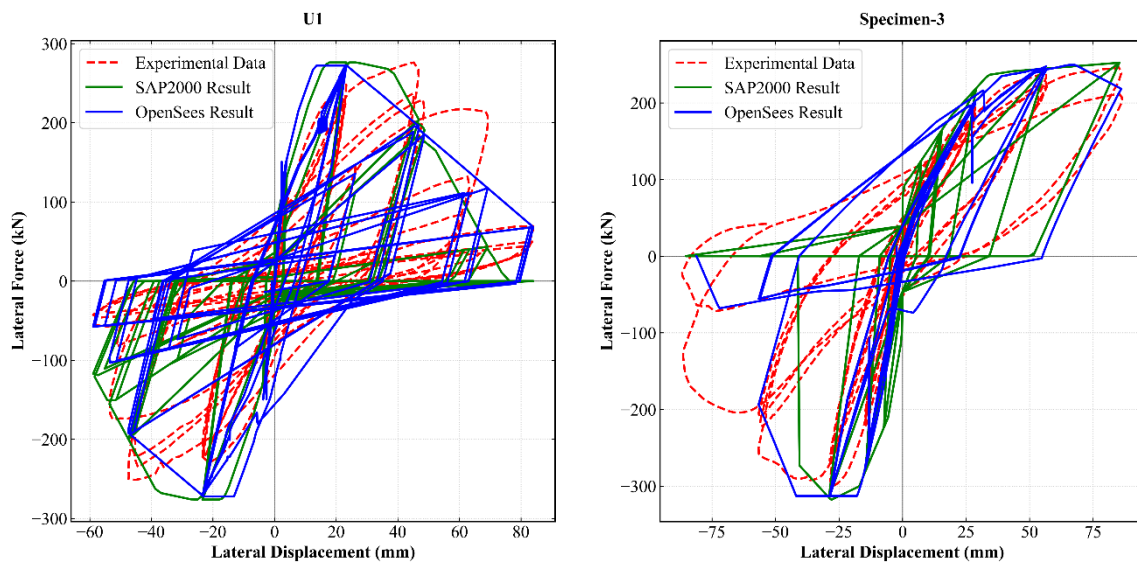


Fig. 11. Comparison of analytical and experimental load-displacement graphs for Category II columns

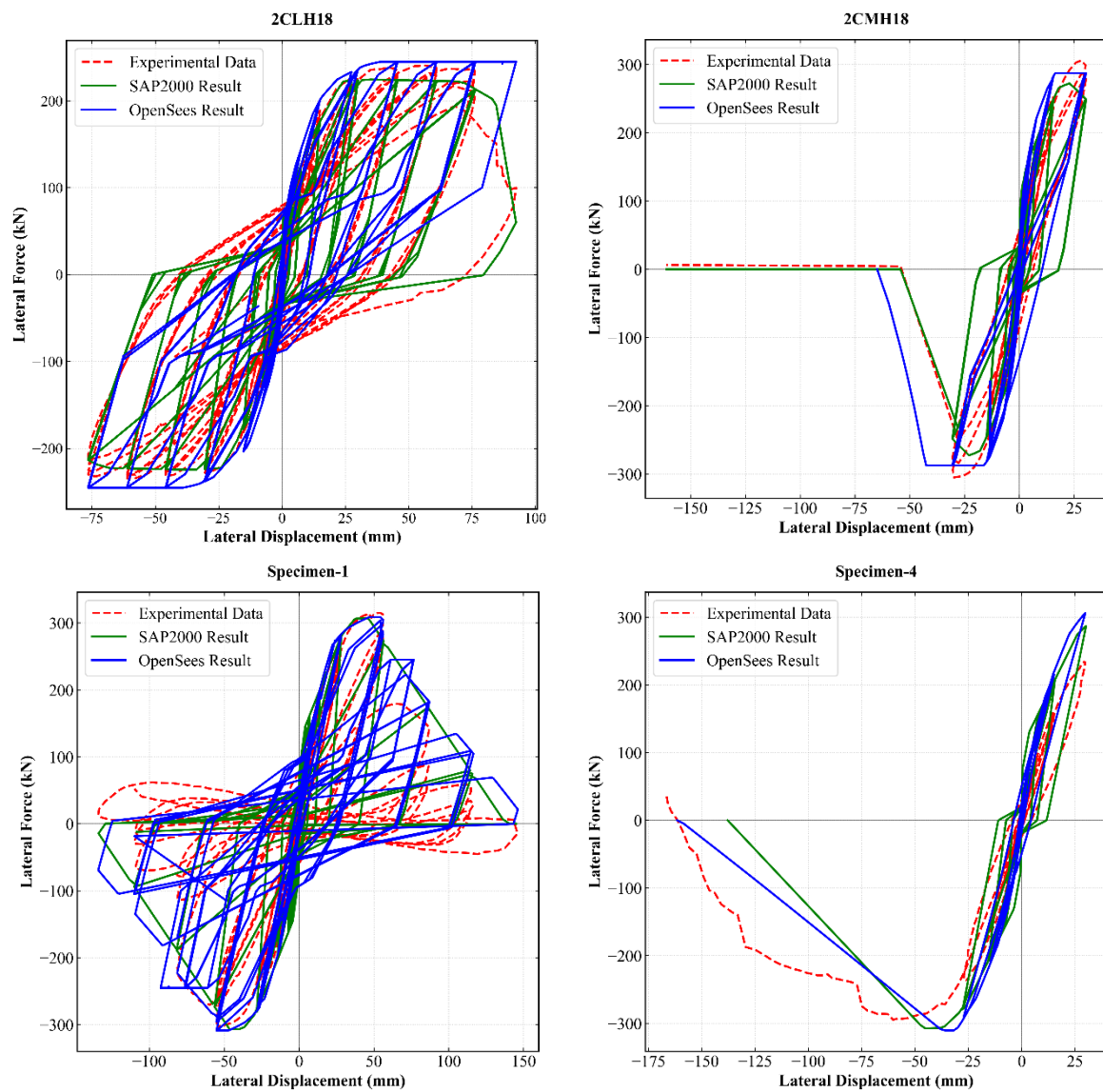


Fig. 12. Comparison of analytical and experimental load-displacement graphs for Category III columns

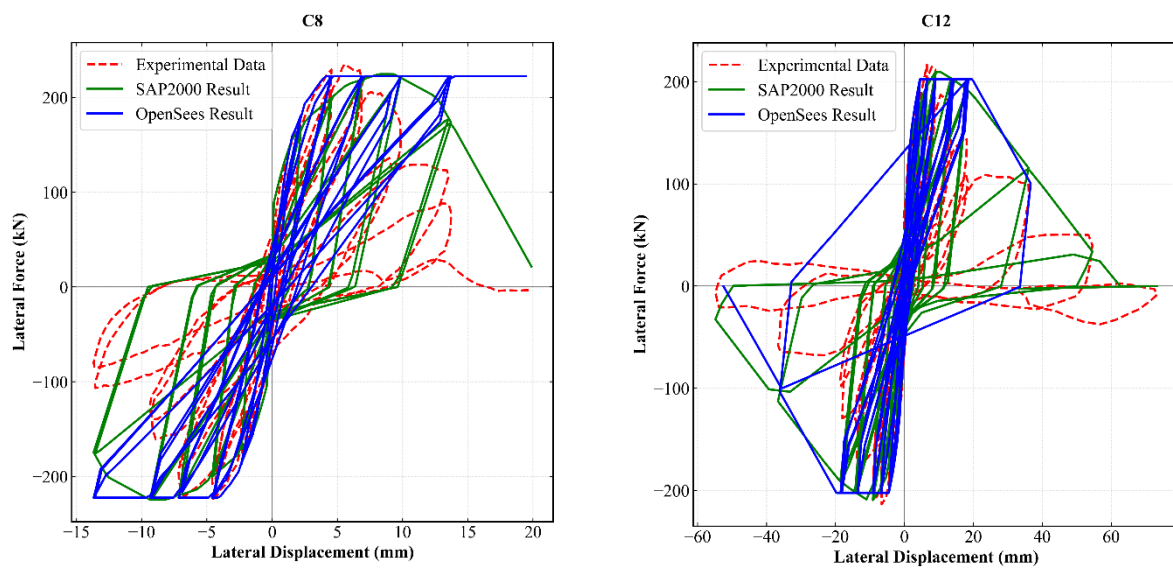


Fig. 13. Comparison of analytical and experimental load-displacement graphs for Category IV columns

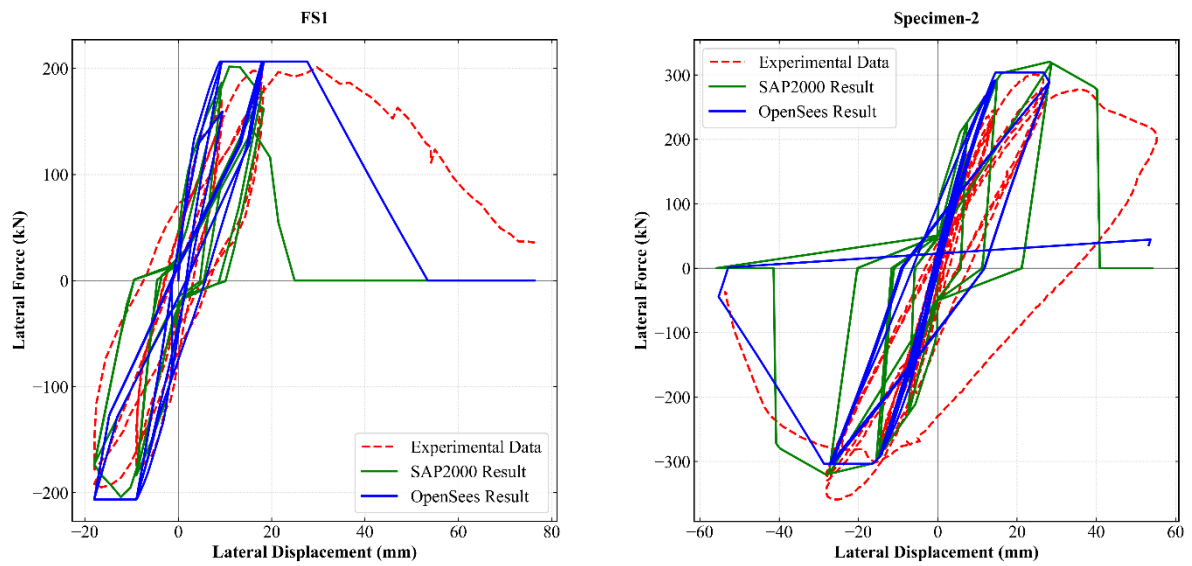


Fig. 13. Continued

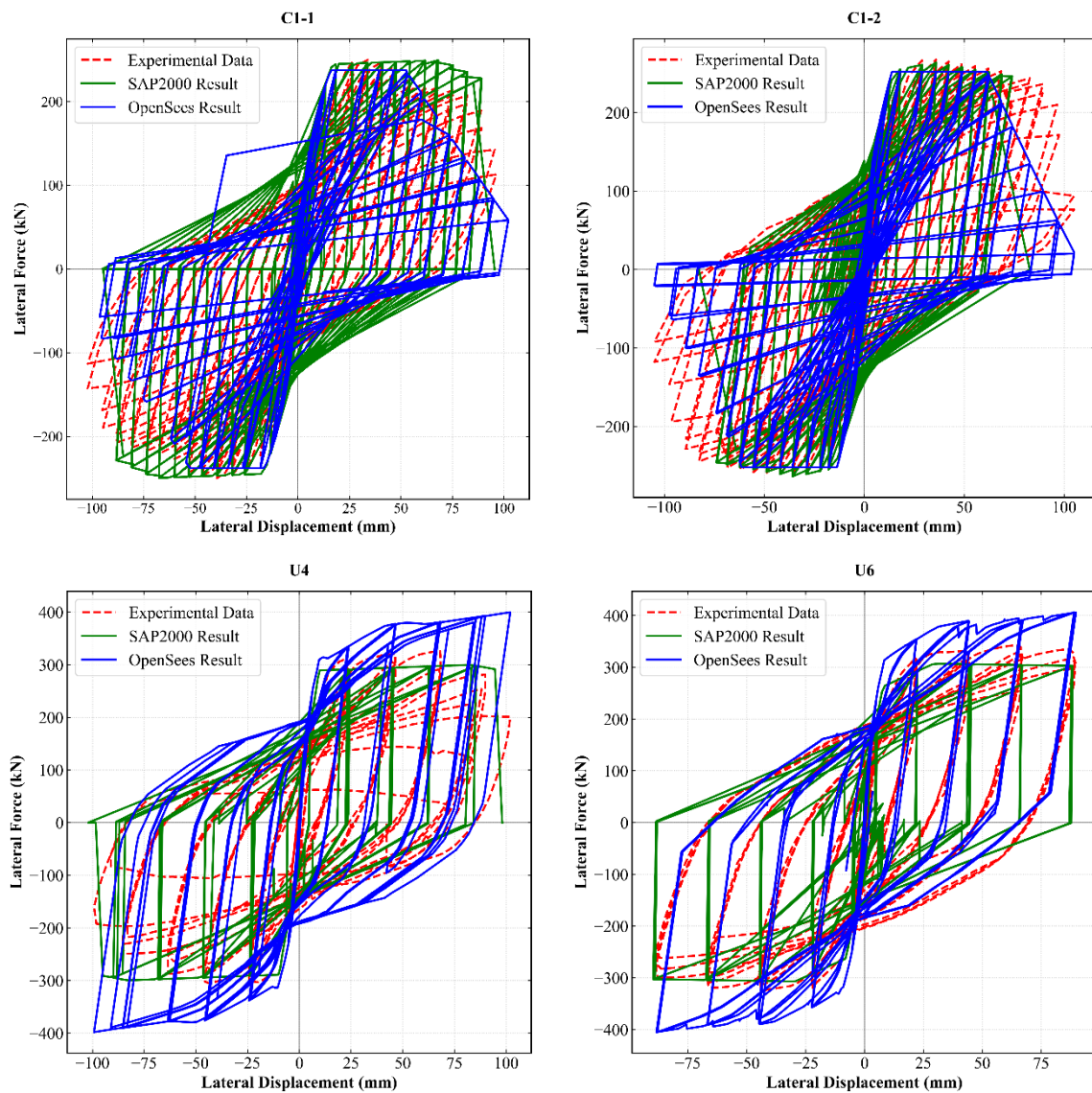


Fig. 14. Comparison of analytical and experimental load-displacement graphs for Category V columns

6.2. Quantitative accuracy assessment

The results obtained from the SAP2000 and OpenSees models were evaluated against the experimental results in terms of ultimate displacement capacity, maximum lateral strength, and cumulative hysteretic energy dissipation. The predictive performance of both numerical models was assessed separately for each response quantity using the coefficient of determination (R^2) and the root mean square error ($RMSE$). All statistical evaluations and regression analyses were performed using the complete experimental database consisting of 24 RC column specimens ($N=24$). No specimen exclusion, data normalization, filtering, or averaging was applied during the statistical evaluation. The calculated quantities were converted to SI units before the statistical analyses and graphical comparisons.

6.2.1. Statistical assessment

To evaluate the predictive accuracy of the numerical models, the coefficient of determination (R^2) and the root mean square error ($RMSE$) were employed. The coefficient of determination (R^2) quantifies the proportion of the variance in the experimental data explained by the numerical

predictions, whereas $RMSE$ measures the average deviation between the numerical predictions and the experimental results. The two statistical indices were calculated using Eqs. (12) and (13), respectively

$$R^2 = 1 - \frac{\sum_{i=1}^N (y_i - \hat{y}_i)^2}{\sum_{i=1}^N (y_i - \bar{y})^2} \quad (12)$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (y_i - \hat{y}_i)^2} \quad (13)$$

Where y_i is the experimental value, $\hat{y}_i$ is the corresponding value predicted by the numerical model, $\bar{y}$ is the mean of the experimental values, and N is the total number of specimens.

6.2.2. Maximum lateral strength accuracy

The comparison of the maximum lateral strengths obtained from the experimental results and the numerical models is presented in Table 4, while the corresponding correlation plots are shown in Fig. 15. Overall, both numerical models reproduced the experimental maximum strengths with satisfactory accuracy.

Table 4. Comparison of experimental and analytical results in terms of lateral strength

Specimen	Experimental		SAP2000		OpenSees V- (kN)	
	V ⁺ (kN)	V ⁻ (kN)	V ⁺ (kN)	V ⁻ (kN)	V ⁺ (kN)	V ⁻ (kN)
1. U1 [36]	276.19	-251.29	276.23	-276.23	272.23	-272.23
2. U4 [36]	325.89	-305.49	299.36	-299.70	399.70	-398.09
3. U6 [36]	342.79	-324.19	306.84	-306.81	406.41	-405.04
4. C1-1 [37]	249.99	-249.99	249.55	-249.49	237.62	-237.62
5. C1-2 [37]	267.57	-261.46	263.85	-263.85	252.08	-252.08
6. FS1[38]	201.09	-194.99	201.60	-204.09	206.41	-206.41
7. 2CLH18 [39]	240.76	-234.58	224.63	-224.44	245.16	-245.16
8. 2CMH18 [39]	305.99	-304.99	272.42	-272.66	287.43	-287.43
9. 3CLH18 [39]	276.99	-255.99	209.59	-209.59	246.22	-246.22
10. 3CMH18[39]	327.99	-271.99	275.99	-275.99	313.32	-313.32
11. Spec.-1 [10]	314.80	-302.57	307.03	-306.86	308.72	-308.72
12. Spec.-2 [10]	301.04	-359.16	320.40	-320.26	303.72	-303.72
13. Spec.-3 [10]	246.60	-300.78	252.47	-317.80	249.55	-313.15
14. Spec.-4 [10]	234.10	-294.63	286.89	-307.28	306.16	-310.49
15. C1 [40]	160.99	-144.69	174.09	-174.09	182.22	-182.22
16. C8 [40]	235.09	-223.79	224.70	-224.70	222.47	-222.47
17. C12 [40]	216.49	-213.49	209.40	-209.40	202.40	-202.40
18. Kansas1 [41]	412.14	-357.83	323.78	-323.78	324.16	-324.16
19. Kansas2 [41]	362.37	-345.23	287.49	-287.49	287.80	-287.80
20. Kansas3 [41]	313.48	-306.85	275.10	-275.10	275.38	-275.38
21. Kansas4 [41]	314.31	-299.09	317.75	-317.75	268.16	-268.16
22. Purdue-1 [42]	566.30	-509.15	470.64	-470.64	471.16	-471.16
23. Purdue-2 [42]	566.30	-516.57	461.97	-461.97	463.72	-463.72
24. Purdue-4 [42]	716.06	-575.51	566.12	-566.12	566.80	-566.80

In the negative loading direction, the proposed SAP2000 model achieved a coefficient of determination of $R^2 = 0.925$ with an $RMSE = 27.10$ kN, whereas the OpenSees model produced $R^2 = 0.857$ and an $RMSE = 37.58$ kN. Most of the SAP2000 predictions were closely distributed around the reference line, indicating good agreement with the experimental results. In contrast, the OpenSees model exhibited larger deviations for several specimens, particularly within the intermediate strength range. For the positive loading direction, the predictive accuracy decreased slightly for both numerical models. The SAP2000 model yielded $R^2 = 0.810$ and an $RMSE = 54.64$ kN, while the corresponding values for the OpenSees model were $R^2 = 0.798$ and $RMSE = 56.36$ kN. The reduction in the correlation coefficients is primarily associated with high-strength specimens from the

Purdue and Kansas test series, for which both numerical models tended to underestimate the experimental maximum strengths.

Overall, both numerical approaches provided satisfactory estimates of the maximum lateral strength. The proposed SAP2000 model yielded higher R^2 and lower $RMSE$ values than the OpenSees model in both loading directions, indicating comparatively closer agreement with the experimental maximum strengths.

6.2.3. Ultimate displacement accuracy

The comparison of the maximum displacement capacities obtained from the experimental results and the numerical models is presented in Table 5, while the corresponding correlation plots are shown in Figure 16.

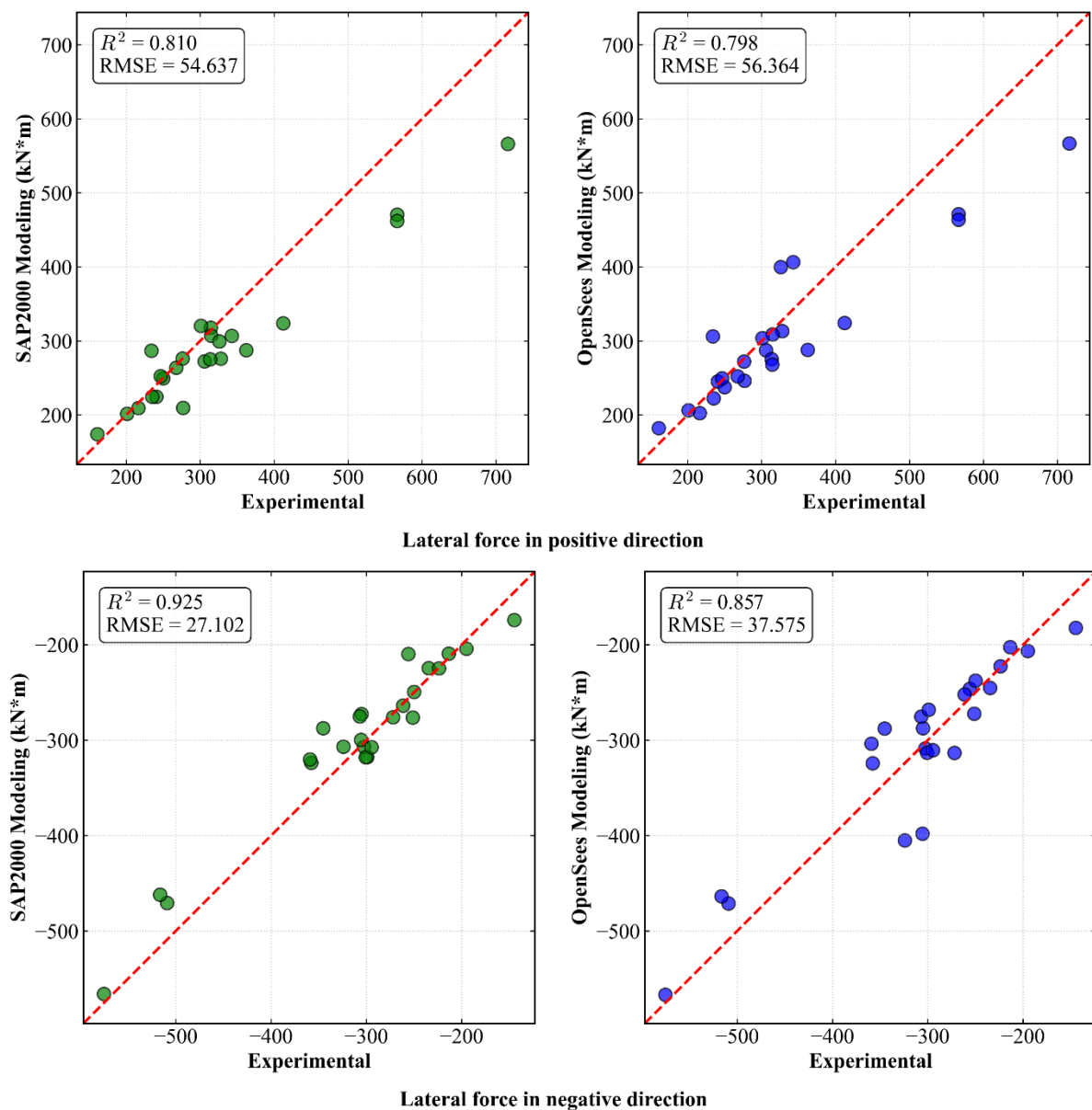


Fig. 15. Comparison of experimental results with SAP2000 and OpenSees in terms of lateral strength

In the negative loading direction, the proposed SAP2000 model achieved a coefficient of determination of $R^2 = 0.963$ with an $RMSE = 8.36$ mm, whereas the corresponding values in the positive loading direction were $R^2 = 0.954$ and $RMSE = 7.26$ mm. Most of the numerical predictions were closely distributed around the reference line, indicating excellent agreement with the experimental displacement capacities.

The OpenSees model exhibited lower predictive accuracy, particularly in the negative loading direction, where $R^2 = 0.777$ and $RMSE = 20.57$ mm were obtained. Although the predictive performance improved in the positive loading direction ($R^2 = 0.915$ and $RMSE = 9.82$ mm), noticeable deviations remained for several specimens with displacement capacities between approximately 30 and 70 mm.

Table 5. Comparison of experimental and analytical results in terms of displacement

Specimen	Experimental		SAP2000		OpenSees V- (kN)	
	Δ^+ (mm)	Δ^- (mm)	Δ^+ (mm)	Δ^- (mm)	Δ^+ (mm)	Δ^- (mm)
1. U1 [36]	84.00	-58.90	84.00	-58.90	84.00	-58.90
2. U4 [36]	102.00	-99.20	98.10	-102.00	102.00	-99.20
3. U6 [36]	89.80	-88.40	88.40	-89.80	89.80	-88.40
4. C1-1 [37]	96.41	-102.26	95.55	-95.11	102.26	-96.41
5. C1-2 [37]	105.05	-105.05	82.82	-82.82	105.05	-105.05
6. FS1[38]	76.45	-18.01	74.75	-18.01	76.40	-18.01
7. 2CLH18 [39]	92.40	-76.60	92.40	-76.60	92.40	-76.60
8. 2CMH18 [39]	30.40	-161.00	30.40	-161.00	30.40	-64.88
9. 3CLH18 [39]	61.40	-61.60	61.40	-61.60	61.40	-61.60
10. 3CMH18[39]	60.80	-61.00	60.80	-51.20	60.80	-61.00
11. Spec.-1 [10]	146.20	-134.06	145.29	-133.86	146.20	-134.06
12. Spec.-2 [10]	55.27	-53.67	54.10	-55.88	53.67	-55.27
13. Spec.-3 [10]	86.49	-86.74	85.34	-85.34	86.08	-81.13
14. Spec.-4 [10]	29.90	-166.65	30.23	-137.96	29.90	-161.62
15. C1 [40]	9.24	-9.14	36.33	-22.55	19.66	-9.14
16. C8 [40]	19.88	-13.68	19.88	-13.68	19.44	-13.68
17. C12 [40]	73.37	-54.82	73.37	-54.82	36.68	-52.48
18. Kansas1 [41]	36.08	-31.63	36.08	-31.63	36.07	-31.50
19. Kansas2 [41]	61.11	-61.48	57.81	-61.11	41.38	-38.86
20. Kansas3 [41]	46.49	-38.91	46.49	-38.91	46.49	-38.91
21. Kansas4 [41]	91.57	-91.40	91.57	-91.40	91.57	-91.40
22. Purdue-1 [42]	26.71	-19.43	26.71	-19.43	12.60	-10.84
23. Purdue-2 [42]	36.37	-35.91	36.37	-31.71	21.10	-20.83
24. Purdue-4 [42]	15.05	-15.09	15.05	-15.09	15.05	-15.09

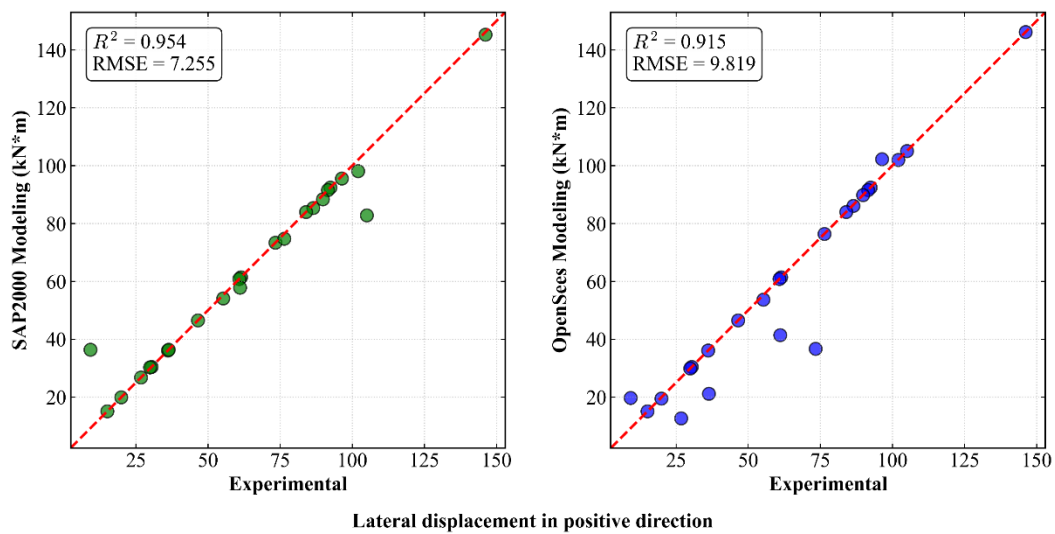


Fig. 16. Comparison of experimental results with SAP2000 and OpenSees in terms of ultimate displacement

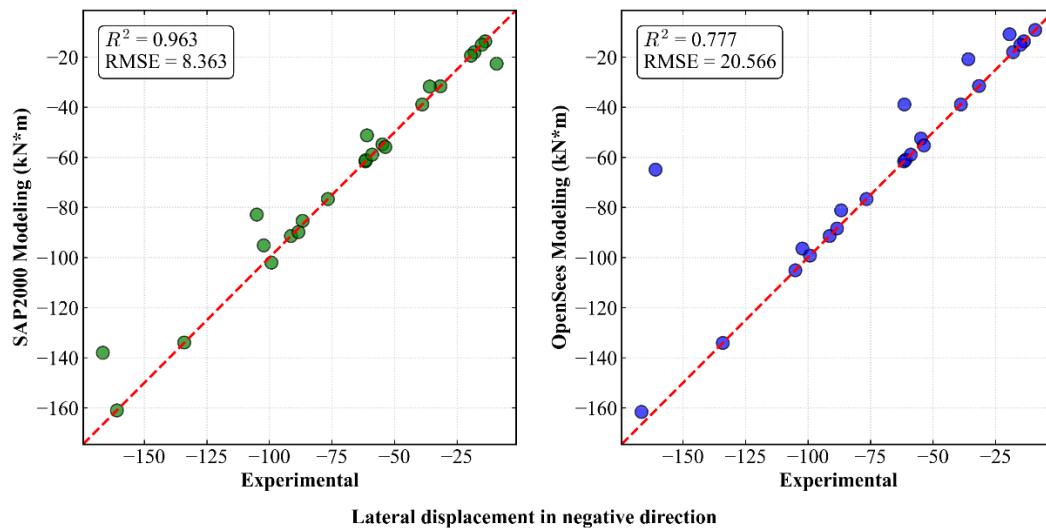


Fig. 16. Continued

Based on the R^2 values, displacement capacity exhibited stronger experimental–numerical agreement than maximum lateral strength for both numerical approaches. The proposed SAP2000 model yielded higher R^2 and lower $RMSE$ values than the OpenSees model in both loading directions, indicating closer agreement with the experimental displacement capacities. These results demonstrate that the proposed component-based framework provides reliable predictions of the displacement capacity of RC columns.

6.2.4. Cumulative hysteretic energy dissipation

Cumulative hysteretic energy dissipation was calculated as the sum of the areas enclosed by the load–displacement hysteresis loops throughout the cyclic loading history and is expressed by Eq. (14):

$$E = \oint F d\Delta \quad (14)$$

where E is the cumulative hysteretic energy dissipation (kN·mm), F is the lateral load (kN), and Δ is the lateral displacement (mm).

Because the experimental and numerical load–displacement responses consisted of discrete data points, cumulative energy dissipation was computed using the trapezoidal numerical integration method according to Eq. (15):

$$E_{cum} = \sum_{i=1}^{N-1} \left| \frac{F_i + F_{i+1}}{2} (\Delta_{i+1} - \Delta_i) \right| \quad (15)$$

where F_i and F_{i+1} are two consecutive lateral load values (kN), Δ_i and Δ_{i+1} are the corresponding lateral displacement values (mm), and N is the total number of data points.

The trapezoidal integration procedure was implemented using a Python-based post-processing script. The same calculation algorithm was consistently applied to the experimental, SAP2000, and OpenSees responses, ensuring a uniform basis for the comparison of cumulative energy dissipation.

All loading cycles up to the termination of the analyses were included in the energy calculations for the experimental results, SAP2000 model, and OpenSees model. Incomplete or asymmetric loading cycles were evaluated without modification, and the enclosed area of each hysteresis loop was calculated directly from the load–displacement data. To prevent positive and negative energy contributions from canceling each other, the absolute value of each energy increment was accumulated to obtain the total cumulative hysteretic energy dissipation.

The comparison of cumulative hysteretic energy dissipation obtained from the experimental results and the numerical models is presented in Table 6, while the corresponding correlation plots are shown in Fig. 17. The proposed SAP2000 model achieved $R^2 = 0.799$ with an $RMSE = 103.35$, whereas the OpenSees model yielded $R^2 = 0.488$ and $RMSE = 164.92$. For both numerical models, good agreement with the experimental results was observed for specimens exhibiting low to moderate energy dissipation. However, the scatter increased considerably for specimens with high energy dissipation. In the SAP2000 model, these deviations were limited to a small number of specimens, whereas the OpenSees model exhibited substantially larger deviations from the reference line at higher energy levels, resulting in lower correlation and higher prediction error.

To further quantify the discrepancies in cumulative hysteretic energy dissipation, specimen-level percentage errors were examined relative to the experimental values. For the SAP2000 model, the largest overestimations were observed for C1 (361.79%), Purdue-4 (109.87%), and Kansas4 (44.18%). For the OpenSees model, the largest overestimations occurred for C1 (255.24%), Spec.-1 (118.45%), and 3CLH18 (112.18%). The exceptionally high percentage error for C1 should be interpreted with caution because its experimental cumulative energy dissipation was only 4.58 kN·m; consequently, a relatively small absolute difference produced a very large percentage error. More

generally, the specimen-level results indicate that the magnitude of the energy prediction error is not directly associated with the absolute level of experimental energy dissipation. Since cumulative hysteretic energy depends on the complete cyclic load–displacement history, differences in the representation of stiffness degradation, strength deterioration, and pinching behavior can accumulate over successive loading cycles and affect the predicted cumulative energy.

Estimating cumulative hysteretic energy dissipation is inherently more challenging than predicting maximum lateral strength or ultimate displacement capacity because it depends

not only on the peak response but also on the complete cyclic response, including stiffness degradation, strength deterioration, pinching behavior, and the accumulated effects of repeated loading cycles. Consequently, lower statistical agreement is expected for this response quantity. Nevertheless, the higher coefficient of determination and lower *RMSE* obtained by the proposed SAP2000 model demonstrate that the component-based modeling framework provides a reliable and practical approach for estimating cumulative hysteretic energy dissipation in reinforced concrete columns.

Table 6. Comparison of experimental and analytical results in terms of energy

Specimen	Experimental energy (kN.m)	SAP2000 energy (kN.m)	OpenSees energy (kN.m)
1. U1 [36]	163.01	144.96	191.16
2. U4 [36]	507.96	489.72	818.70
3. U6 [36]	549.94	468.12	657.25
4. C1-1 [37]	612.66	621.44	459.32
5. C1-2 [37]	790.75	522.14	550.42
6. FS1[38]	29.37	19.14	29.49
7. 2CLH18 [39]	331.25	274.20	341.51
8. 2CMH18 [39]	91.98	69.99	101.17
9. 3CLH18 [39]	92.60	131.91	196.48
10. 3CMH18 [39]	115.80	83.51	137.26
11. Spec.-1 [10]	248.48	297.06	542.81
12. Spec.-2 [10]	118.44	92.34	100.34
13. Spec.-3 [10]	199.52	148.97	169.11
14. Spec.-4 [10]	61.49	62.60	73.02
15. C1 [40]	4.58	21.15	16.27
16. C8 [40]	21.61	27.03	36.17
17. C12 [40]	37.85	53.89	55.43
18. Kansas1 [41]	145.68	130.81	137.02
19. Kansas2 [41]	213.98	167.05	121.17
20. Kansas3 [41]	123.25	114.21	153.84
21. Kansas4 [41]	521.72	752.22	892.35
22. Purdue-1 [42]	473.30	359.68	229.18
23. Purdue-2 [42]	662.16	364.51	271.25
24. Purdue-4 [42]	76.42	160.38	132.29

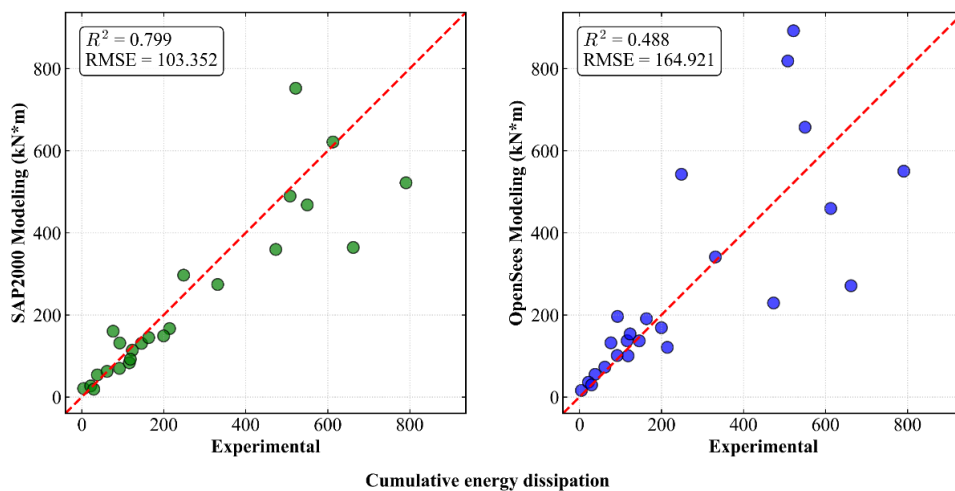


Fig. 17. Comparison of experimental results with SAP2000 and OpenSees in terms of cumulative energy dissipation

7. Conclusion

This study presented a component-based modeling framework for representing the nonlinear behavior of RC columns subjected to lateral loading within SAP2000. The proposed methodology independently evaluates the flexural, bar-slip, and shear deformation mechanisms contributing to the total lateral displacement and represents them within a single finite element model using user-defined plastic hinges. Consequently, existing analytical deformation models were transformed into a systematic, practical, and reproducible modeling procedure that can be directly implemented in a commercial finite element software without developing new finite element formulations or user-defined elements.

Within the proposed framework, nonlinear response curves obtained from analytical deformation models were converted into behavior-dependent backbone curves and subsequently defined as user-defined plastic hinge properties in SAP2000. Nonlinear static analyses were first performed using these plastic hinges to generate the monotonic load-displacement response of each deformation mechanism. The resulting backbone curves were then assigned to user-defined link elements to represent cyclic behavior. Through this procedure, the combined effects of flexural, bar-slip, and shear deformations were consistently represented within a unified modeling framework for both monotonic and cyclic analyses. This procedure enabled flexural, bar-slip, and shear deformation mechanisms to be incorporated systematically within a unified SAP2000 modeling workflow.

The proposed methodology was validated using an experimental database consisting of 24 RC column specimens with different geometries, axial load levels, reinforcement details, and failure modes. The numerical results were compared with the experimental hysteretic responses and with fiber-based distributed plasticity models developed in OpenSees. The proposed SAP2000 model showed good agreement with the experimental cyclic responses and provided satisfactory predictions of maximum lateral strength and displacement capacity. For the present database, the SAP2000 model yielded higher R^2 values and lower RMSE values than the OpenSees model for maximum lateral strength and displacement capacity in both loading directions. The prediction of cumulative hysteretic energy dissipation exhibited greater scatter than the strength and displacement predictions; however, the SAP2000 model also provided higher R^2 and lower RMSE values than the OpenSees model for this response quantity.

The study also demonstrated that the selection of the hysteretic model plays an important role in accurately representing cyclic behavior. The Pivot hysteretic model successfully reproduced the pinching behavior and stiffness degradation observed in shear-controlled specimens, whereas the Takeda model provided a more appropriate representation of the cyclic stiffness degradation and stable hysteretic response of flexure-controlled columns. These findings

confirm that selecting the hysteretic model according to the behavioral category improves the predictive capability of the proposed modeling approach.

Some discrepancies between the numerical and experimental responses were particularly evident for specimens exhibiting complex cyclic deterioration. These differences may be associated with the inherent limitations of concentrated-plasticity and idealized hysteretic representations, which cannot explicitly capture all local nonlinear phenomena, including crack propagation, localized bond deterioration, concrete crushing, and cumulative damage evolution. Despite these limitations, the proposed methodology achieved satisfactory agreement with the experimental responses while maintaining a comparatively simple modeling procedure.

In summary, the proposed component-based SAP2000 framework provides a systematic, practical, and reproducible nonlinear modeling methodology for explicitly incorporating flexural, bar-slip, and shear deformation components within a commercial structural analysis platform. Rather than introducing new analytical deformation formulations, its principal contribution lies in providing an integrated implementation procedure that converts established analytical models into component-specific nonlinear properties suitable for SAP2000. The framework therefore provides an intermediate modeling approach between conventional simplified plastic hinge representations and more elaborate distributed-plasticity simulations for the seismic assessment of existing RC columns.

Declarations

Conflict of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author contributions

Conceptualization: Mehmet Metin Köse, Sıla Avgın; Methodology, Software, and Validation: Sıla Avgın, Erkan Biçici; Formal analysis: Sıla Avgın; Investigation, Writing—original draft preparation, and Writing—review and editing: Sıla Avgın, Erkan Biçici, Mehmet Metin Köse; Supervision: Mehmet Metin Köse. All authors have read and agreed to the published version of the manuscript.

Data availability statement

The experimental data used in this study were compiled from previously published peer-reviewed studies, all of which are properly cited in the manuscript. The processed datasets

generated during this study, SAP2000 numerical models, OpenSees analysis scripts, and statistical calculation files supporting the reported results are available from the corresponding author upon reasonable request. The original experimental data remains subject to the availability conditions and copyright policies of their respective sources.

Use of generative AI and AI-assisted technologies

During the preparation of this manuscript, the authors used generative artificial intelligence tools to assist with language editing, grammar improvement, and text refinement. All scientific content, methodology, analyses, interpretations, and conclusions were developed, verified, and approved by the authors, who take full responsibility for the content of this publication.

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