Comparison of shear displacement models for reinforced concrete columns

Betonarme kolonlar için kesme yer değiştirmesi modellerinin karşılaştırılması

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Abstract

This study investigates the influence of different shear displacement modeling approaches on the predicted seismic behavior of reinforced concrete (RC) columns. Two previously proposed shear models are applied in the open-source simulation platform OpenSees within a displacement component modeling framework. A shear-critical RC column previously tested is modeled using both approaches, and the analytical results are compared with test results. The comparison focuses on the lateral load–displacement relationship, including parameters such as peak lateral strength, initial stiffness, and post-peak strength degradation. Results indicate that both models accurately reproduce the global cyclic behavior of the tested column, with the LeBorgne and Ghannoum model better capturing the initial stiffness and unloading stiffness degradation, while the Bicici and Sezen model provides a more realistic representation of post-peak strength loss and residual displacements. The findings confirm that both shear models can reliably represent the nonlinear lateral response of non-ductile RC columns, providing useful tools to calculate the seismic performance of existing RC structures.

Keywords: Reinforced concrete columns, Shear failure, Cyclic behavior, Shear displacement, OpenSees.

Öz

Bu çalışma, farklı kesme yer değiştirmesi modelleme yaklaşımlarının betonarme (BA) kolonların öngörülen sismik davranışı üzerindeki etkisini incelemektedir. Daha önce önerilmiş iki kesme modeli, yer değiştirme bileşeni modelleme çerçevesi kapsamında açık kaynaklı simülasyon platformu OpenSees'e uygulanmıştır. Daha önce test edilmiş kesme-kritik bir BA kolon, her iki yaklaşım kullanılarak modellenmiş ve analitik sonuçlar deneysel verilerle karşılaştırılmıştır. Karşılaştırma, tepe yatay taşıma gücü, başlangıç rijitliği ve tepe sonrası dayanım azalışı gibi parametreleri içeren yatay yük–yer değiştirme ilişkisine odaklanmaktadır. Sonuçlar, her iki modelin de test edilen kolonun genel çevrimsel davranışını doğru bir şekilde yeniden ürettiğini göstermektedir. LeBorgne ve Ghannoum modeli başlangıç rijitliği ile boşalma rijitliği azalışını daha iyi yakalarken, Bicici ve Sezen modeli tepe sonrası dayanım kaybı ve artık yer değiştirmeleri daha gerçekçi biçimde temsil etmektedir. Bulgular, her iki kesme modelinin de sünek olmayan BA kolonların doğrusal olmayan yatay tepkisini güvenilir biçimde temsil edebildiğini doğrulamakta ve mevcut BA yapıların sismik performansının değerlendirilmesinde yararlı araçlar sunduğunu göstermektedir.

Anahtar kelimeler: Betonarme kolonlar, Kesme çökmesi, Döngüsel hareket, Kesme yer değiştirmesi, OpenSees.

1 Introduction

Earthquakes may be one of the most important natural disasters threats structures and human life. To minimize the casualties and damage, it is essential to understand both the nature of earthquake and its effect on structures. Reinforced concrete (RC) is being widely used around the world due to its applicability and affordability. However, RC structures designed without seismic code are vulnerable against earthquake (Figure 1). Unlike seismically designed RC structures, these structures exhibit non-ductile behavior under earthquake loading due to lack of sufficient and well-designed transverse reinforcement. It is important to evaluate the performance of such structures to prevent devastating life and economic loss. Thus, there is accepted need for improved analytical simulation tools to assess the seismic collapse vulnerability of existing structures, especially those constructed before the 1970s with non-seismically detailed RC columns prone to axial load-carrying capacity loss and poor seismic performance [1].

There may be two major approaches to model RC columns; a) micro model and b) macro model. Micro model includes bi- or tri- dimensional detailed material models with concrete crack calculations [2]. That may improve the accuracy of the behavior prediction, however it may need extremely intense calculation when it comes to complex structures. On the contrary, in macro model, the lateral behavior of an RC column can be modeled with fiber-sections, springs and elements. Macro model may use overall assumptions and lower the accuracy, however, the approach can be suitable for the complex structure due to easy applicability. Displacement component model is one the macro modeling approach. Each lateral displacement component of an RC column can be calculated and combined into together to predict total lateral displacement of the column. However, the accuracy of the modeling approach mainly relies on the validity of the models for each

Figure 1. Shear cracks in an existing building after Van Earthquake [11]

displacement component calculation. In this study, two previously developed shear displacement models [3,4] are studied. A shear critical RC column tested by Sezen [5] is modeled with two different shear displacement models and results are compared to investigate the applicability, advantages and disadvantages of both model.

In this study, an open-source structural engineering earthquake simulation software, OpenSees [6] is used for both modeling and analyzing. Displacement component model can easily be applied to an RC column model in OpenSees software. Once each displacement model applied and combined, the recorded displacements during experiment are applied to top of the column and base reactions are calculated for each displacement.

2 Displacement component model

Displacement component model can be considered as an efficient method to predict accurate lateral response of a column under cyclic loading. The summation of three separately calculated displacement components; flexural displacement, slip displacement, shear displacement yields the total lateral response of an RC column

A widely accepted method to calculate the flexural displacement component of the lateral displacement is moment-curvature analysis of the column section. Material constitutive models can lead the calculation of moment-curvature relation of an RC section [7]. Once it is obtained, the integration of the curvature distribution along the column's length leads the flexural deformation. Due to lack of tensile stress resistance, cracks are appeared at the beam-column or foundation-column connections at the very early loading stages. The cracks became more apparent and the stress along the cracks are carried by the longitudinal reinforcing bar. The stress accumulation leads elongation of the bars which creates additional lateral displacement. The displacement named as slip displacement. The sum of strain on embedded reinforcing bar gives the slippage of the bar. There have been several studies to model slip displacement component of RC columns [8-10]. Lastly, shear

displacement is the additional displacement component of RC column should be considered.

3 Shear displacement

In columns designed by following to seismic provisions, the effect of shear deformation on total lateral displacement is generally negligible, typically contributing less than 10% [12]. In contrast, for columns not detailed for seismic resistance, shear deformations can be much more significant, contributing up to about 40% of the total lateral displacement, which is often observed in existing concrete structures worldwide [5]. Therefore, when modeling RC members that lack adequate seismic detailing, shear contributions must be explicitly considered. The lower shear strength leads diagonal cracks at the early loading stages (Figure 1). The opening and widening of these cracks decreases the stress transfer along the length of the crack. This causes shear strength degradation before reaching column's flexural capacity. Thus, the lack of seismic design and lower shear capacity leads non-ductile behavior and failure at early loading stage and ignoring the shear displacement model may lead overestimation for both lateral load and displacement capacity of an RC column.

There have been several studies to model shear behavior of an RC column [1,4,13,14,]. However, it is hard to capture shear displacement component out of other displacement components during experiments. Thus, there is not many experimental results to validate the models. It is important to understand capability and applicability of each models. In this study, two shear displacement models are implemented and applied to a previously tested RC column in order to evaluate their accuracy and suitability.

3.1 Bicici and Sezen model

A model to calculate shear displacement under cyclic loading was developed by Bicici and Sezen [4] which relies on a user-defined envelope, that serves as the boundary for shear behavior, and some rules to reproduce shear response without requiring parameter updates during each cycle.
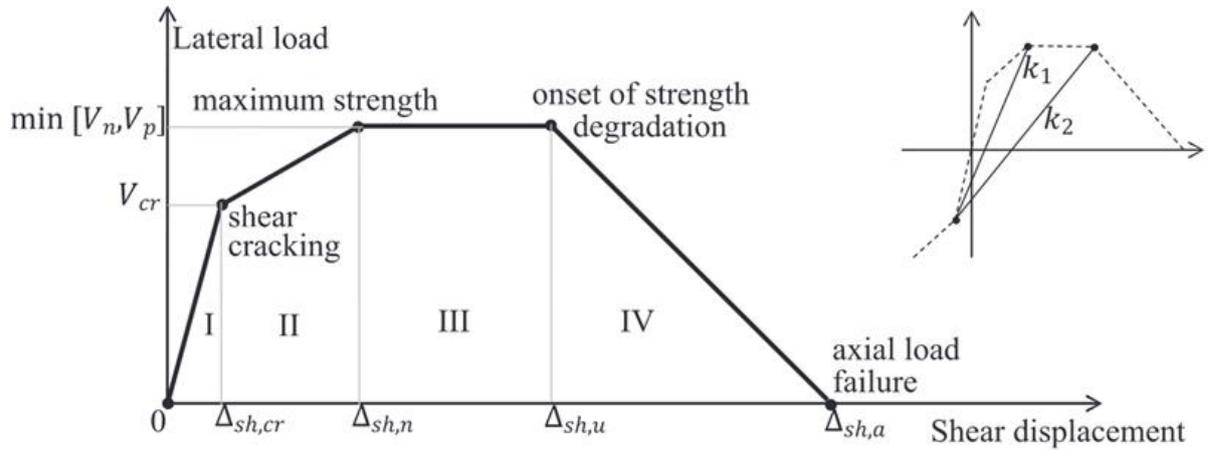
Figure 2. Shear displacement model by Bicici and Sezen [4]

The model addresses critical hysteretic features such as stiffness deterioration, strength degradation, and pinching effect, as well as the interaction between axial load, shear, and flexure.

The user-defined envelope for shear deformation is a multilinear curve defined by four critical mechanical points (Figure 2). Shear cracking point represents the initiation of diagonal cracks. The shear response is assumed elastic until this point. The point of maximum shear strength achieved labeled as Peak lateral strength point. Onset of strength degradation is the point where shear strength begins to decrease due to widening shear cracks. Finally, axial failure point represents the total loss of lateral and axial load-carrying capacity. These four points divide the shear behavior into four unique regions: elastic (I), stiffness degradation (II), peak (III), and strength degradation (IV) (Figure 2). The cyclic rules govern the behavior of the element depends on the region the lateral displacement is reached for both directions.

3.2 LeBorgne and Ghannoum model

An analytical element proposed by LeBorgne and Ghannoum [1,3] was designed to simulate the strength degradation of concrete members under lateral loading, particularly shear-critical RC columns, subjected to seismic loading. The proposed element consists of a zero-length shear spring that connects in series with a beam-column flexural element. The proposed method provides an opportunity for the decoupling of shear and flexural deformations, a crucial aspect for simulating the complex behavior of RC columns. The element is implemented in the modular open-source earthquake simulation package, OpenSees.
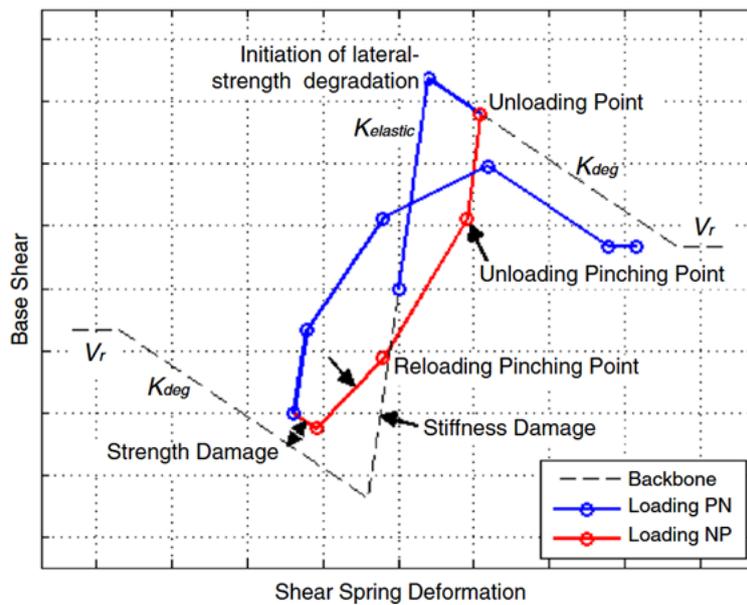

Figure 3. Shear displacement model by LeBorgne and Ghannoum [1,3]

The model operates in two primary formats:

1. Manual calibration format [3]: Users define parameters such as a limiting column deformation and a limiting shear force. Once the first of these limits is reached, a degrading lateral strength behavior is triggered.

2. Automatic calibration format [1]: This version simplifies the process, requiring only user input of column material and geometric properties. It then automatically determines the limiting shear displacement and corresponding load that initiate strength degradation, and estimates all necessary damage parameters governing the cyclic behavior until total loss of lateral strength.

The deformation response of the zero-length shear spring is governed by a nonlinear material model that incorporates stiffness degradation effects. The corresponding shear force–deformation relationship developed from this model is presented in Figure 3. At the initial loading stage, the shear spring exhibits linear elastic behavior, defined by a user-specified initial stiffness ($K_{elastic}$). Once the onset of lateral strength degradation occurs, the material model establishes a backbone curve that governs the maximum shear force corresponding to a given deformation, defined by a degrading stiffness slope (K_{deg}) and a residual shear strength (V_r). Under load reversals, the model employs a trilinear pinching relationship characterized by user-defined pinching parameters. The cyclic response during reloading is further controlled through stiffness and strength degradation algorithms. The implemented damage accumulation schemes can be formulated based on cycle count, dissipated energy, or displacement demand.

The element features an adaptive degradation trigger that continually monitors forces and deformations in the flexural elements. It initiates lateral-strength degradation when a critical user-defined limiting shear force or a limiting plastic-hinge rotation (or lateral drift) is reached, whichever occurs first. A novel flexural-deformation compensation algorithm is implemented to automatically adjust the shear-spring stiffness and backbone curve to achieve a symmetric global member response, addressing issues of unsymmetrical behavior caused by flexural element unloading during degradation.

4 Analysis and discussion

Displacement component model can easily be applied structural analysis software with flexural element applied zero length spring at the ends (Figure 4). OpenSees is an efficient software for applying the idea. In this study, a previously tested specimen was recreated two times by using OpenSees. Flexural and slip deformations were calculated with same approach for both model [7]. However, for the shear spring, two different shear displacement model are used to compare the results and applicability of both models.

The measured top displacements during experiment are applied top of the created analytical model. Then, the calculated joint reactions for each applied displacement are recorded. The relationship of lateral load – displacement is obtained with both shear displacement models.
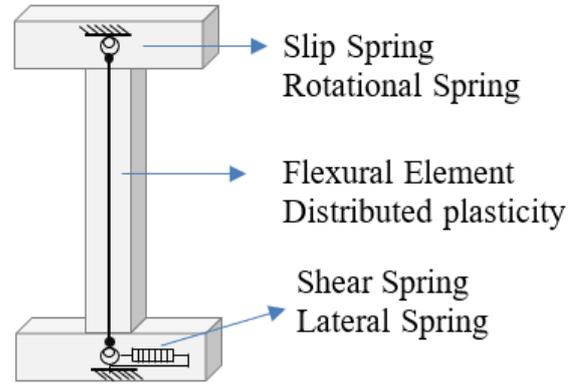

Figure 4. Representation of analytical model for an RC column

4.1 Details of tested column

Experimental results from tests by Sezen [5] were used to compare capabilities of two shear displacement models. These specimens were chosen because detailed lateral force–displacement measurements were available for each deformation mode. The columns had a 457.2 mm × 457.2 mm square section and a height of 2.946.4 mm. Both ends were fixed during testing. The specimens were designed to experience shear or axial failure following flexural yielding under seismic loading conditions, ensuring comparable shear and flexural strength capacities. Longitudinal reinforcement consisted of eight Ø28.7 mm (No. 9) bars. Transverse reinforcement was provided by Ø9.5 mm (No. 3) bars with 90° hooks, spaced at 304.8 mm. Figure 5 shows the reinforcement details.
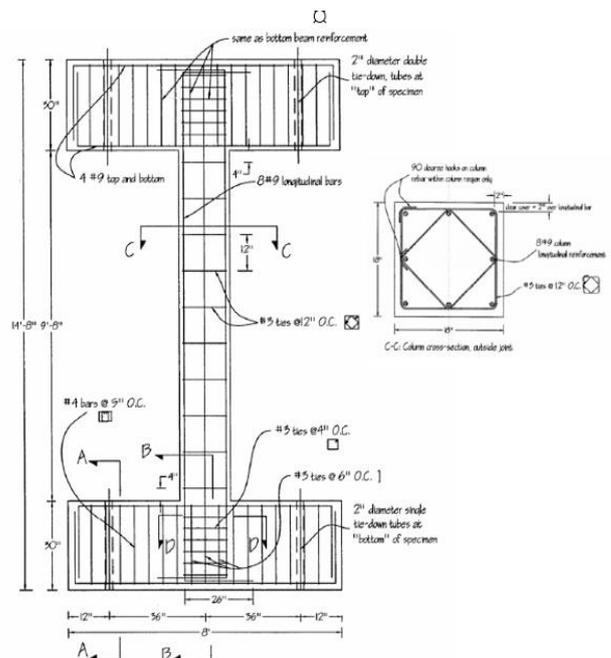

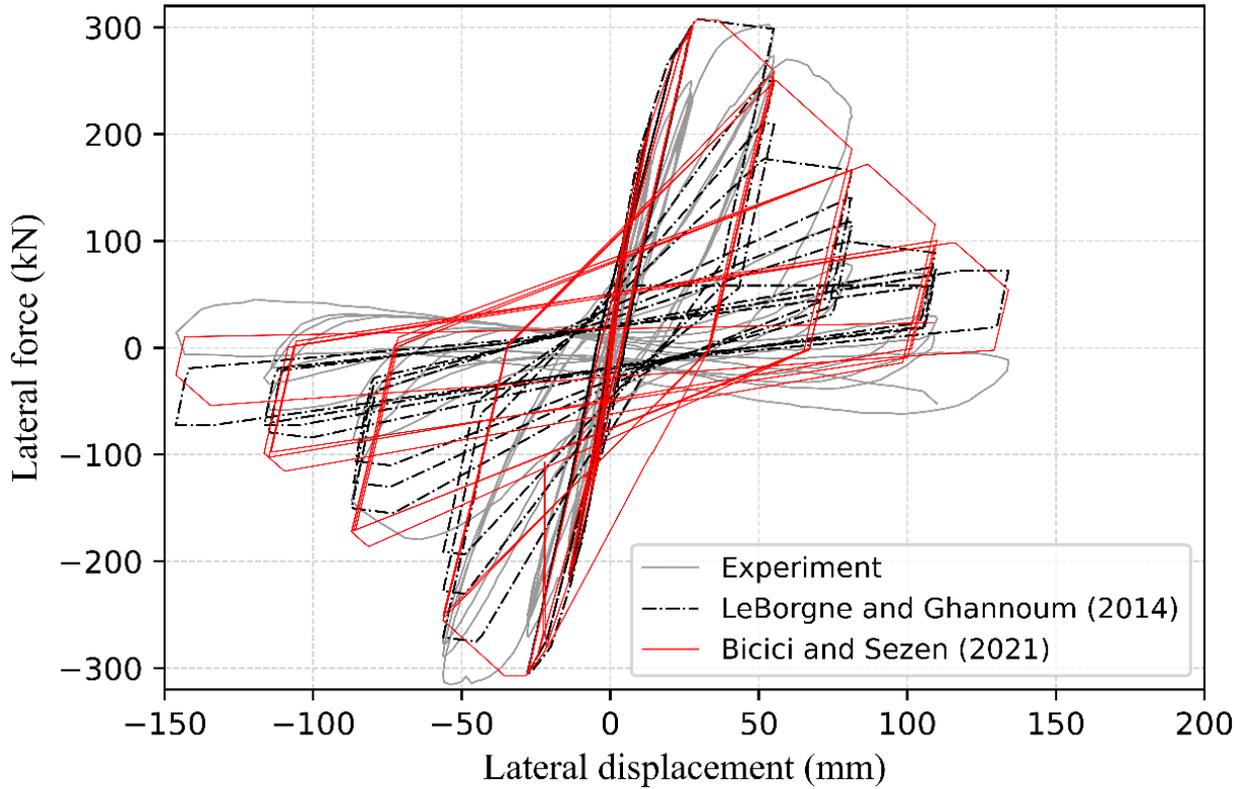**Figure 5.** Details and steel configuration of Specimen-1 [5]

Figure 6. The test results and calculated lateral load-displacement relationship of Specimen-1.

Specimen 1 was subjected to a constant axial compressive load of 667.2 kN, while Specimen 2 carried a sustained compressive load of 2,668.9 kN. Specimen 3 experienced varying axial forces ranging from 266.9 kN in tension to 2,668.9 kN in compression. All column specimens were tested under unidirectional cyclic lateral loading. Specimen 4 was initially subjected to cyclic loading up to the point of yielding, after which it was loaded monotonically to failure.

4.2 Results of analysis

A previously tested RC column was created and the lateral deformation and corresponding force was calculated by using OpenSees with two distinct modeling approaches. The primary distinction between these adequate for simulating the nonlinear lateral response of RC columns, provided that the shear behavior is appropriately approaches lies in the representation of the shear response under lateral loading.

Figure 6 presents a comparison between the experimentally measured lateral load–displacement relationship and the corresponding numerical predictions obtained from the two models. Additionally, Figure 7 highlights the comparison by splitting for both loading sides of positive and negative.

The results demonstrate that both shear modeling approaches are capable of accurately reproducing the overall lateral load–displacement behavior of the tested column. In particular, the predicted responses closely match the experimental data in terms of peak lateral strength, initial

stiffness, and post-peak strength degradation. These findings indicate that either modeling approach can be considered adequate for simulating the nonlinear lateral response of RC columns, provided that the shear behavior is appropriately represented within the analytical framework.

4.3 Discussion

Figure 6 and 7 compares results between the experimentally measured lateral force–displacement response of the reinforced concrete (RC) column and the numerical predictions obtained using two different shear modeling approaches: LeBorgne and Ghannoum [1] and Bicici and Sezen [4]. Both analytical models reproduce the general shape and hysteretic behavior of the experimental response, demonstrating good agreement in terms of peak lateral strength, stiffness, and cyclic degradation. The LeBorgne and Ghannoum [1] model exhibits a relatively closer match to the experimental loops in the early loading cycles, particularly in capturing the initial stiffness and unloading stiffness degradation.

On the other hand, the Bicici and Sezen [4] model provides a more accurate representation of the post-peak strength deterioration and residual displacements at larger deformation levels. Minor discrepancies between the simulated and measured responses can be attributed to simplifications in the modeling of shear–flexure interaction and the assumed material constitutive relationships. Overall, both models effectively capture the nonlinear cyclic behavior of the tested column, validating their applicability for simulating RC column response under lateral loading.
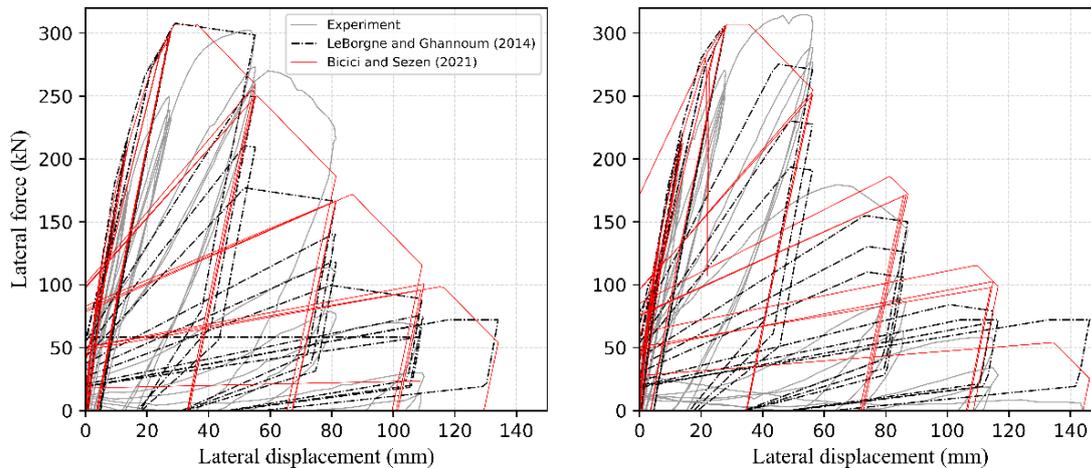
Figure 7. The test results and predicted lateral load-displacement relationship of Specimen-1 for positive (left) and negative (right) loading sides.

5 Conclusion

Earthquakes remain among the most significant natural hazards posing serious risks to human life and the built environment. Reducing casualties and structural damage requires a comprehensive understanding of both the characteristics of earthquakes and their effects on structures. Reinforced concrete (RC), owing to its versatility and cost-effectiveness, continues to be one of the most widely used construction materials worldwide.

This study presented a comparative evaluation of two shear displacement models—LeBorgne and Ghannoum [1] and Bicici and Sezen [4] —implemented within a displacement component modeling framework for reproducing the nonlinear lateral behavior of RC columns. The analytical results were compared with the experimental response of a shear-critical RC column tested by Sezen [5]. Both models successfully captured the overall lateral load–displacement response, including peak strength, initial stiffness, and strength degradation under cyclic loading.

Although both approaches provided comparable results, the LeBorgne and Ghannoum model offered a slightly better representation of early-cycle stiffness and unloading behavior, whereas the Bicici and Sezen model more accurately captured post-peak degradation and residual displacements. These differences highlight the importance of selecting a shear model based on the expected performance range and the specific objectives of analysis.

In summary, both shear displacement models demonstrated sufficient accuracy and practicality for use in analytical studies of RC columns, particularly in the assessment of existing non-ductile structures. Future studies may extend this work by applying the models to multi-degree-of-freedom systems and investigating the interaction between shear, flexure, and axial load under more complex loading histories.

Conflict of interest

The authors declare that there is no conflict of interest.

Similarity rate (iThenticate): 12%

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