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Hybrid Micro-Macro Modeling Approach for Segmental Self-Centering Rocking Structures

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Abstract

Segmental self-centering (SC) structures are proper alternatives for conventional structures as they can be constructed using precast techniques. Several numerical modeling approaches are proposed to simulate the nonlinear behavior of SC structures but their advantages over each other are not clarified yet. In this paper, two numerical modeling approaches are adopted and compared to each other; Distributed Springs and Fiber-based model. The Distributed Springs is a macro modeling approach, which uses a number of springs along the gap opening to simulate the rocking motions. On the contrary, the Fiber-based model uses a fiber-discretized section at the contact interface. Combining these methods, a new hybrid micro-macro method is proposed for segmental SC structures, which uses the Fiber-based technique at lower gap openings with higher damage probability and the Distributed Springs at higher contact interfaces. It is concluded that both approaches are capable of simulating the rocking motion of SC structures. The Fiber-based model has a higher computational cost than the Distributed Springs model, however, it is a better option when the SC structure is expected to undergo high extents of nonlinearity in the vicinity of rocking joints.

Keywords: Self-centering Structures, Numerical Modeling Technique, Non-linear Behavior, Rocking

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1. Introduction

Current design codes ensure the seismic stability of structures at the cost of large plastic deformations in lateral force-resisting systems. In other words, the deformability and energy dissipation (ED) capacity of the structures are provided by the nonlinear behavior of the members (Lee & Billington, 2010; Poorahad Anzabi et al., 2024; Sadeghi et al., 2026). The residual deformation left in the structures as a result of the nonlinear behavior of the members interrupts their functionality after the seismic event and the damage is mostly so severe that rebuilding is more cost-beneficial than repairing the structure (Poorahad & Shiravand, 2026; Poorahad et al., 2026; Poorahad Anzabi & Shiravand, 2025). Self-centering (SC) structures emerged as a great alternative to current conventional structures due to their minimized residual deformation and ability to withstand large deformations without any significant drop in strength (Ashouri & Shiravand, 2024; Hosseini et al., 2025; Sabagh & Shiravand, 2026).

SC systems have been used in different engineering structures; bridge superstructures and substructures (Sideris et al., 2014), shear walls, frames, beam-column connections (Moradifard et al., 2022), etc. Bridges are one of the most important components of a country's transportation network and their post-earthquake performance is of significance. Thus, many studies focused on the use of SC systems in bridge piers or bents (Jia et al., 2020; Rassoulpour et al., 2023; Thapa & Pantelides, 2021; Xu et al., 2022). To reduce residual deformations of buildings, SC-reinforced concrete shear walls are developed (Kian & Cruz-Noguez, 2023; Liu et al., 2023; Xiao et al., 2020; Xu et al., 2021). Building frames and braces are also self-centered in various studies (Eatherton et al., 2014; Huang et al., 2020; Lin et al., 2013). Numerical modeling methods are proposed to predict the seismic performance of SC structures (Rassoulpour et al., 2025). In these sources, SC systems are used to reduce residual deformation of structures. However, it is shown in the probabilistic research done by Poorahad Anzabi and Shiravand (2024) that the prestressing of post-tensioned tendons decays with time and the structure may not fulfill its initial performance objectives.

In the case of concrete segmental SC structures, precast concrete parts can be manufactured off-site and then transported to the construction site, which significantly reduces the construction time. The segments of the precast concrete shear walls can be placed above (Kurama et al., 1999; Smith & Kurama, 2009) or alongside each other (Henry, 2011). The yielding energy dissipators can be utilized between these horizontally or vertically split segments (Sritharan et al., 2015). Kurama (2000) utilized viscous dampers to increase the energy dissipation capacity of post-tensioned segmental concrete walls. The use of viscous dampers was examined to mitigate the drift of these walls without forfeiting their advantageous qualities.

Precast post-tensioned segmental (PPS) piers have also drawn researchers' attention in the past few years (Poorahad Anzabi & Shiravand, 2024). In some cases, the internal energy dissipating

bars pass through horizontal joints (Ou et al., 2007). These bars have an unbonded length at each joint which yields due to relative displacement of the segments under seismic loading, providing energy dissipation capacity. External energy dissipators can also be connected to the pier (Chou & Chen, 2006). In some studies, the energy dissipation was provided by a shear-slip mechanism between the segments (Sideris et al., 2014; Yang et al., 2019).

Considerable efforts have been directed toward experimental investigation of SC structures. On the other hand, many researchers tried to propose methods to numerically simulate the seismic behavior of SC structures. The main challenge in the numerical modeling of SC structures is how to model the rocking joints and the nonlinear behavior of the material there. In this paper, a macro in addition to a micro modeling approach is adopted, and SC shear wall models are built using them. Models built with the two approaches are compared with each other to examine their ability to simulate the gap behavior of the rocking joints and to capture the nonlinear behavior of SC structures with or without ED bars. Consequently, a new modeling method is proposed for segmental SC structures that combine these two methods. In this modeling technique, the micro-modeling approach is employed in contact interfaces with higher damages which depending on boundary conditions is in lower segments most of the time, and the macro-modeling approach is used between other segments. For this purpose, first, the behavior of SC structures is explained so the results that are expected from simulations become clear. Then, the two mentioned modeling approaches are introduced, and the proposed modeling technique is described. Using these approaches SC shear walls and piers are modeled and the accuracy of the models was examined by comparing them with experimental results.

2. Force-Displacement Relationship of SC Structures

Many factors like conditions of post-tensioning (PT), stiffness of the pier, using dissipators, and type of dissipators can affect the force-displacement relationship of an SC rocking structure. For example, consider an SC rocking pier. Figure 1 shows the force-displacement behavior of a pier under different conditions considering small deformations, using a force-control protocol. To study the influence of the stiffness of the pier, the behavior of a special state in which the stiffness of the pier tends to infinity (i.e., a rigid pier) is shown in all scenarios.

As an exception, the hysteretic behavior of a non-rocking post-tensioned pier is shown in Figure 1a. The SC capacity of this system is generated by its increased stiffness, resulting in less residual displacement than the corresponding simple reinforced concrete (RC) pier. If the pier is assumed to be elastic, the stiffness of the system will be equal to the stiffness of the cantilever pier plus the stiffness provided by the PT. The plastic hinge formation moves the curve smoothly away from the elastic line, leading to energy dissipation and residual displacement.

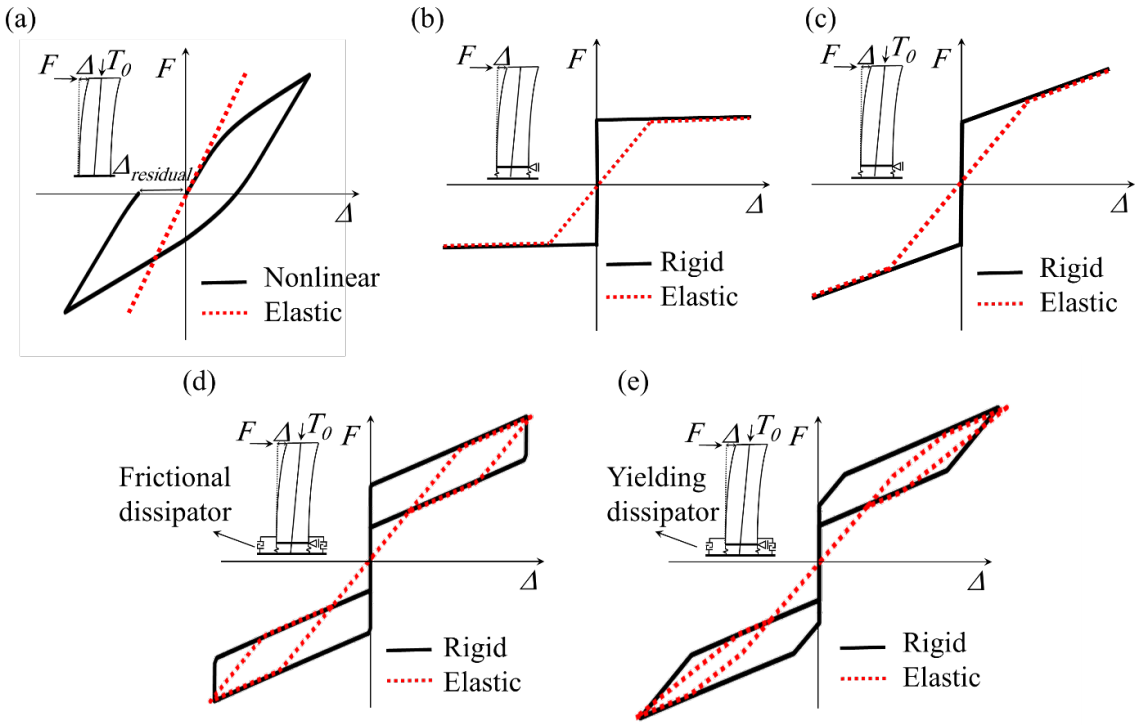


Figure 1. Force–displacement behavior of: (a) post-tensioned RC pier, and (b-e) self-centering rocking piers under different conditions.

The behavior of a rocking pier self-centered by a tendon with zero PT force is shown in Figure 1b. As seen, as the force increases, no displacement will occur before the rotation of the rigid pier. When the pier is assumed to be elastic until the rotation, the slope of the curve will be equal to the stiffness of the pier. In the instance of rotation, the moment caused by the lateral force (F) overcomes the moment caused by the weight of the pier. After that, the stiffness of the system drops to zero, and the force-displacement curve of the system will be a horizontal line.

If the tendon is post-tensioned, the system of Figure 2c is obtained, which is shown along with its associated rigid system. In addition to the moment caused by weight, the lateral force required to start the rotation must also overcome the moment caused by the PT force. After the rotation, the stiffness of the pier is eliminated, and only the post-tensioning stiffness remains, so the secondary stiffness of the rigid and elastic piers is equal.

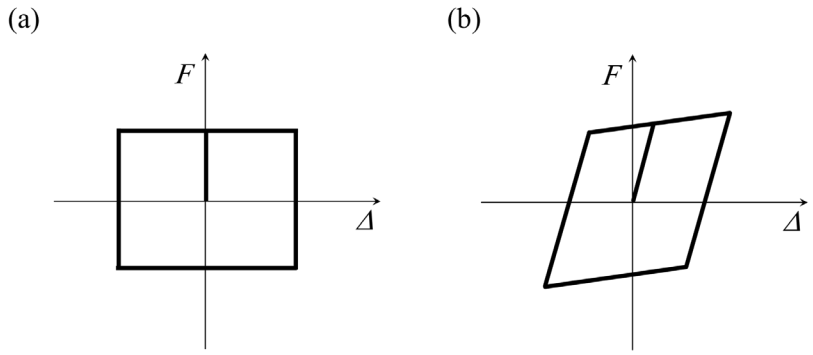


Figure 2. Force–displacement behavior of: (a) frictional, and (b) yielding dissipators.

In Figure 2a, the hysteretic behavior of frictional dissipators is shown, and Figure 2b shows that for yielding dissipators. Adding external frictional or yielding dissipators to the bottom of the SC rocking pier of Figure 1c gives the hysteretic response shown in Figures 1d and 1e, respectively. Prior to rotation, the dissipators do not have any displacements; therefore, they do not affect the behavior of the system, but once the rotation begins, the dissipators behave in series with the pier, and their set behaves in parallel with the tendon. In other words, the dissipators add stiffness to the pier-base connection, which makes the pier play a role in lateral resistance after rotation.

Thus, when frictional dissipators are utilized, the uplift force increases because its initial stiffness is infinite, and the uplift will not happen before the sliding force of the dissipator is attained. As a result, instead of three lines, the loading and unloading branches consist of two lines. When yielding dissipators are used, the uplift force will not change, and after rotation, the behavior of the system depends first on the elastic stiffness of the dissipator and, after yielding occurs, on its post-yield stiffness. In addition, using dissipators increases the stiffness of the pier and, consequently, increases the dissipated energy, which slightly reduces the final displacement in a force-control cycle.

3. Modeling Approaches

3.1. Distributed Spring Method

In the distributed spring method which can be categorized as a macro modeling approach, rocking joints are modeled with multiple spings as depicted in Figure 3a. Sensitivity analysis is required in order to determine the minimum number of distributed springs. In this model, the joint opening mechanism is modeled explicitly by rigid link elements connecting the upper node of springs. Springs are modeled with zero-length elements. An elastic no-tension material is assigned to the springs to allow for the joint opening between the rigidLinks. The slippage between the foundation and the SC structure is constrained by shear keys in practice. Hence, the horizontal degree of freedom (DOF) of the rightmost node of the bottom link is restrained. From another perspective, this constraint may be applied to the model by setting an equal DOF

in the horizontal direction between the upper and lower spring nodes. The weighting and position of each spring can be determined by the Lobatto quadra integration scheme (Spieth et al., 2004).

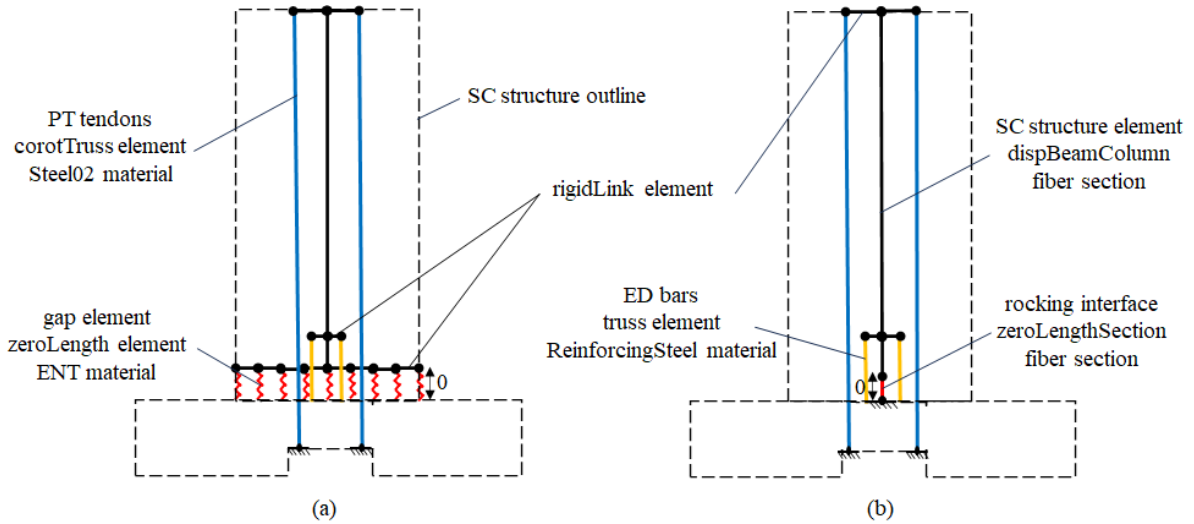


Figure 3. Modeling techniques: (a) Distributed Spring Model and (b) Fiber Model

PT tendons consist of a bundle of strands that is modeled by an axial element. i.e. corotTruss element. The prefix "corot" is the shortened form of corotational, which implies that this element accounts for geometrical nonlinearities. PT tendons are tensile members so the constitutive relationship of the assigned material should not include compression. Steel02 material is used in series with a tension-only material built with an ElasticMultiLinear material so-called hook material. An initial strain or stress is incorporated into the material to account for the initial post-tensioning.

When nonlinear behavior is not expected in the rocking member, it may be modeled by elasticBeamColumn element, for instance, Concrete Filled Tube piers, piers that are globally strengthed with fiber-reinforced polymer, etc. However, distributed plasticity through the dispBeamColumn element is required to capture the nonlinear behavior of the section provided that plastic behavior is expected from the member.

3.2. Fiber-Based Model

In the Fiber model, a zeroLengthSection element is used to model the rocking joint, as shown in Figure 3b. The fiber section must be built according to the cross-section of the SC structure and then paralleled to no-tension material to make a fiber section that has no bearing capacity in tension. This fiber-discretized section can capture the nonlinear stress distributed along the section from each fiber and its act on the structure. The SC member and PT tendons are modeled with the same technique as described in the previous section.

3.3. Proposed Hybrid Model

This study introduces a new method, combining two previous approaches for segmental SC structures. In the proposed model a zero-length section is assigned to the gap openings that the structure is expected to undergo higher plastic deformations around them and distributed

springs are assigned to the other joints. Figure 4a shows a schematic of this method. At the bottom-most contact interface, a zero-length section that corresponds to the cross-section of the SC structure itself paralleled to no-tension material is used to model the contact interface. To model other gap openings zero-length elements with ENT material are distributed along the rocking joints.

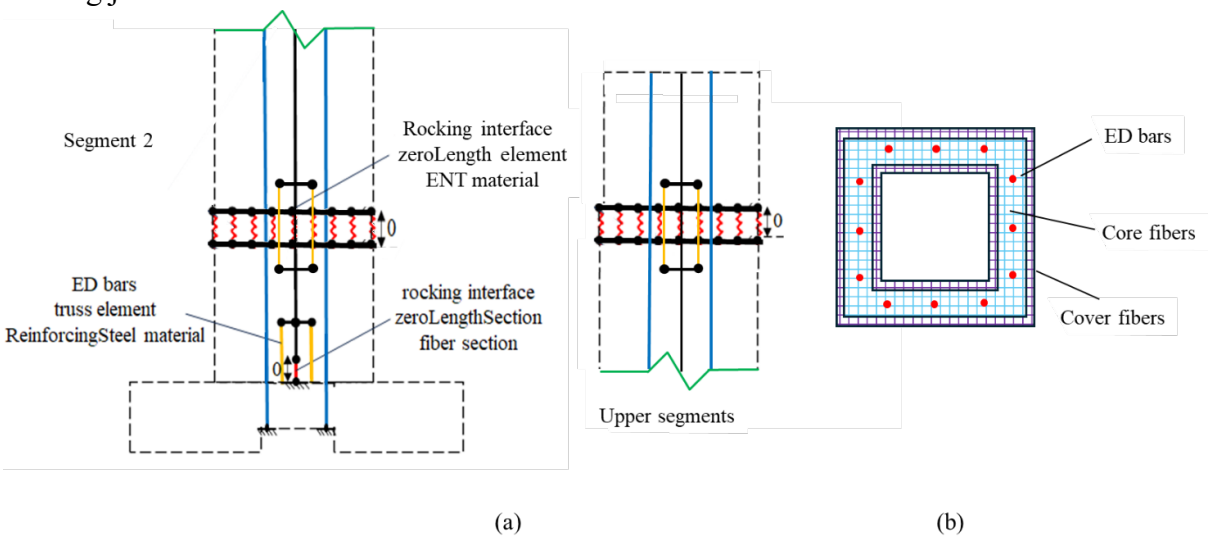
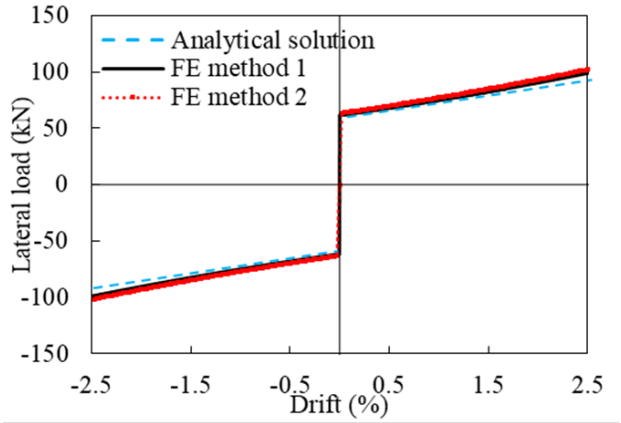


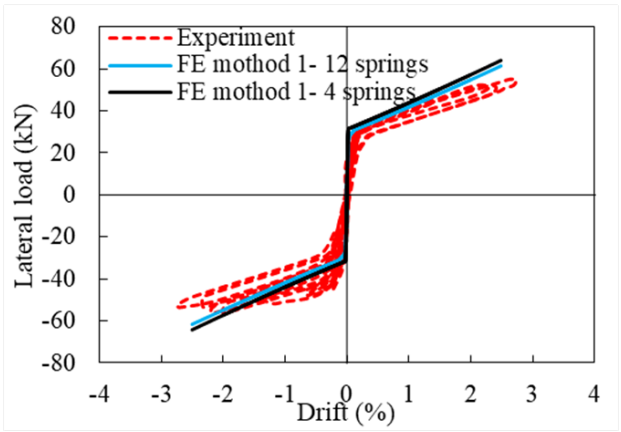
Figure 4. (a) Hybrid modeling techniques using fiber model for the bottom-most contact interface and distributed springs for other interfaces, and (b) fiber section corresponding to Ou et al's (Ou et al., 2010) study.

4. Results

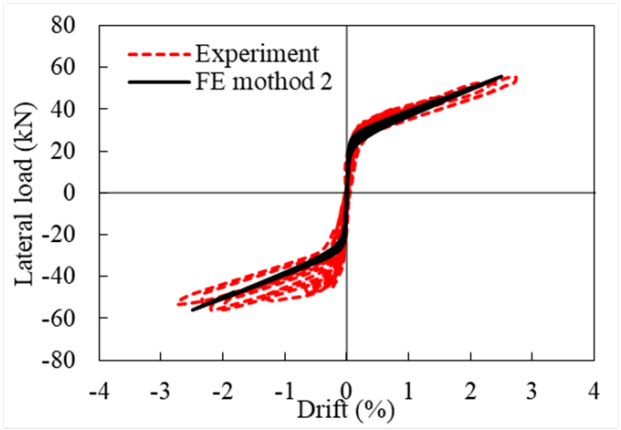
Models with the two introduced methods are built in the OpenSees (McKenna, 2011) platform and are analytically and experimentally (Rahman & Restrepo-Posada, 2000) verified as illustrated in Figure 5. For analytical verification, it is assumed that the wall is rigid and the corresponding force-displacement relationship was adopted from Rassoulpour et al. (2023). As seen in Figure 5(a), the results of both methods and the analytical solution are very similar. Figures 5(b) and (c), compare the experimental results of Unit 1 with methods 1 and 2, respectively. A sensitivity analysis is also conducted to determine the appropriate number of springs to be placed at the gap opening. As seen in Figure 5(b) the difference between 4 and 12 springs is not significant, and Method 2 has a better agreement with experimental results.



(a)



(b)



(c)

Figure 5. Verification of modeling approaches: (a) analytical, (b) method 1 (Unit 1), (c) method 2 (Unit 1).

Figures 5 (a) and (b) compare the experiment results of Unit 3 with methods 1 and 2, respectively. The geometrical properties of Units 1 and 3 are identical. However, unbonded ED bars are added in Unit 3, and an additional 200 kN gravitational load is applied. It can be

observed that method 2 has a better estimation of the nonlinear behavior of the rocking shear wall.

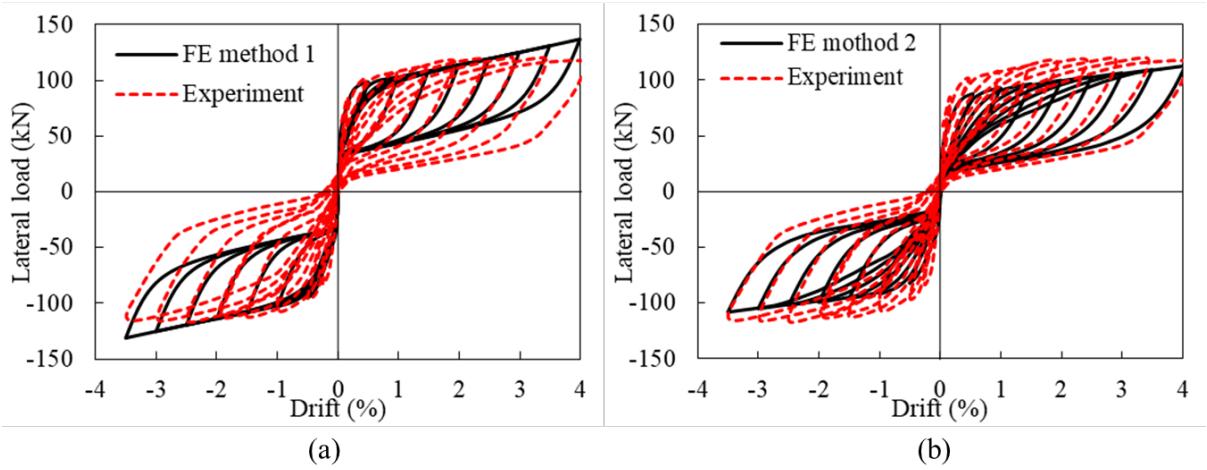


Figure 6. Verification of modeling approaches: (a) method 1 (Unit 3), and method 2 (Unit 3).

SC shear walls experience more nonlinearity than SC piers due to their rectangular cross-section, i.e. the ratio of length over width is large. The difference visible in the hysteresis behavior resulting from the two methods is rooted in the high nonlinearity of the shear wall, which method 2 is more capable of capturing. Two more models are built in which the width of the cross-section of the models is increased to a quarter and half of the cross-section's length as illustrated in Figures 7(a) and (b), respectively. It is obvious in Figure 7(a) that the two hysteresis curves are becoming more consistent with each other. The more the cross-section becomes closer to the square, the response of the models becomes closer (Figure 7(b)).

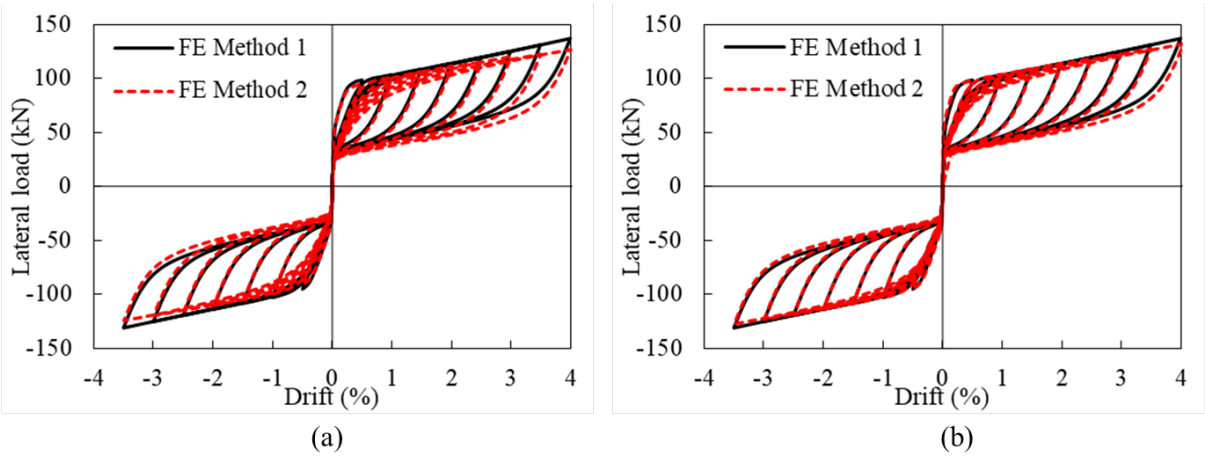


Figure 7. Comparison of modeling approaches: (a) rectangular pier with 0.25 width/length ratio, and (b) 0.5 width/length ratio.

Ou et al. (2010) conducted a series of large-scale tests on precast segmental SC bridge piers. The C5C specimen of this study had a PT force of , whereandare compressive concrete strength and the column's gross cross-sectional area, respectively. The gravitational load was equal to 1456 kN. This pier was post-tensioned by four tendons and had a hallow cross-section as shown in Figure 4b. As presented in Figure 8, using methods 1 and 2 this pier was modeled. Using method 1 the model didn't have any convergence issues during the analysis, and analysis was finished with relatively low computational cost. Nevertheless, the model overestimates the lateral load and it couldn't capture the strength softening that happened during the experiment as can be seen in Figure 8a. On the other hand, method 2 had more computational cost and took more time to finish the analysis. The accuracy of this method is higher than that of method 1. This is because of the hollow cross-section of this specimen which results in high plastic deformations.

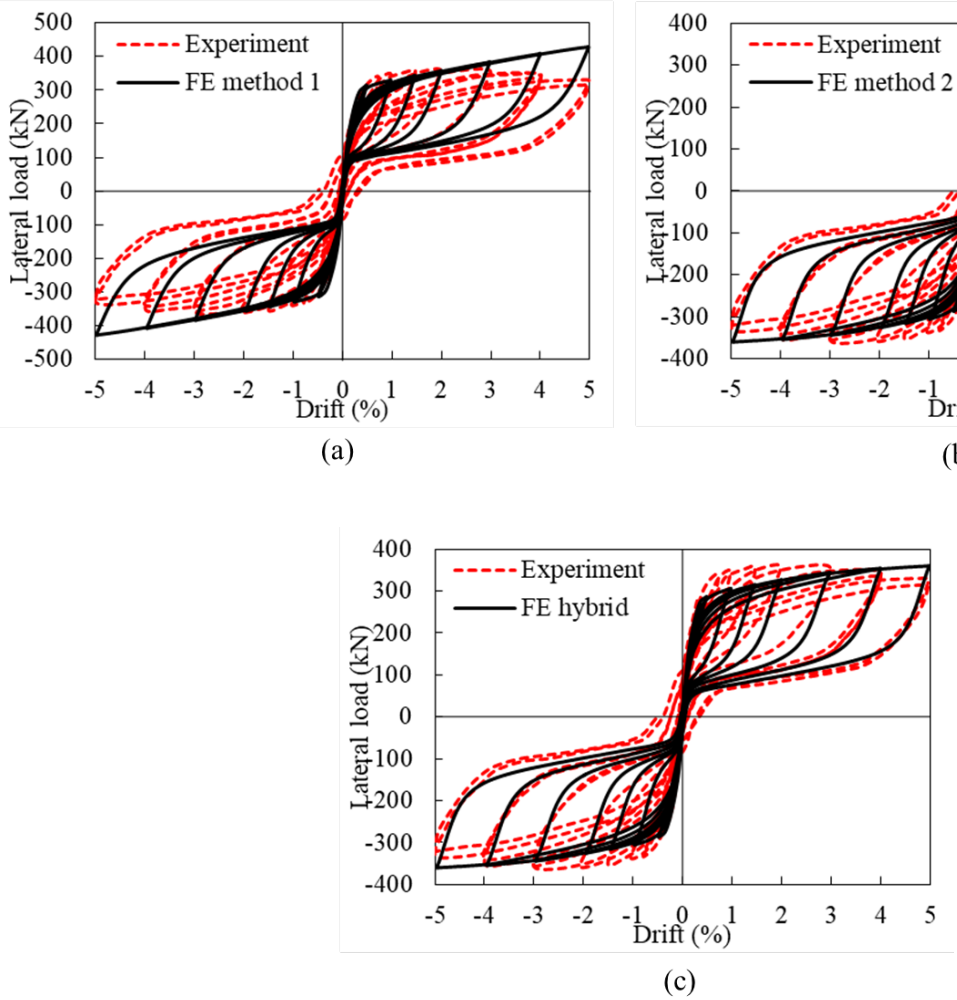


Figure 8. Verification of modeling approaches for C5C segmental rocking pier of Ou et al's (2010) study: (a) method 1, (b) method 2, and (c) proposed hybrid model.

The hybrid model is constructed as shown in Figure 4a. This model faced no convergence issues during the analysis and it took a much shorter time to finish the analysis. As shown in

Figure 8c, the proposed method is in good agreement with the experimental result, which means it has the advantages of both method 1 and 2 modeling methods.

5. Conclusion

This study proposes a new modeling approach for segmental SC structures. First, two modeling approaches are investigated for the numerical simulation of SC structures that have been adopted in previous studies. These methods are initially verified with numerical and experimental results. Then, models with different length-over-height ratios are built and compared. Combining these two approaches a new method is introduced that uses zero-length sections at lower segment interfaces that usually have concrete damage around them, and distributed springs in upper segments. The following conclusions are yielded from this study:

- The proposed hybrid model has a lower computational cost than the micro-modeling method (zero-length section), and it has higher accuracy than the distributed springs method, which means it has the advantages of both micro and macro modeling approaches.
- When it is assumed that the SC structure is rigid, the results of the numerical models, from either method, coincide with the analytical results. It implies that both modeling methods are capable of simulating the rocking joints in the absence of the nonlinear behavior of the SC structure.
- The fiber-based model has a better estimation of SC structures than the Distributed Spring model when the behavior of the SC structure is highly nonlinear. The difference between the two approaches is also obvious if ED bars are included in the SC structure.
- Some measures may be done to reduce the nonlinearity that the SC structure undergoes or some structures, namely piers, basically experience lesser nonlinearity rather than shear walls. In such cases, both methods are equally suitable. Distributed Spring model may be adopted when it is intended to simulate SC piers due to its better computational efficiency compared to the Fiber model. Nevertheless, if a segmental SC structure is expected to have a highly nonlinear behavior, it is suggested to be modeled by the proposed hybrid model as an alternative to the other two modeling approaches.

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