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Seismic performance evaluation of self-centering concrete shear walls

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Abstract

Self-centering concrete shear walls have been increasingly recognized as an effective lateral force-resisting system for enhancing the seismic resilience of structures. Unlike conventional reinforced concrete shear walls, self-centering concrete walls with controlled rocking, are designed to undergo controlled rotation at their base with minor residual drifts and damage following an earthquake. This behavior, combined with the restoring capability provided by unbonded post-tensioning tendons, allows the structure to re-center after seismic events and significantly limits permanent deformations and damage to structural and nonstructural components. In this regard, this paper presents a detailed numerical investigation of the behavior of self-centering concrete shear walls. A numerical macro model was developed using OpenSees to simulate the nonlinear response of the system under lateral loading. The model incorporates material and geometric nonlinearities to capture the wall's flexural and rocking behavior accurately. Next, a validation of the proposed model was carried out by comparing the model results with the published experimental results found in literature. The results showed that the model simulation, demonstrated strong agreement in terms of walls strength, stiffness, and displacement capacity. Following validation, an extensive parametric study is performed to examine the influence of key design parameters including wall geometry, and concrete strength on the overall response. The findings of the current study provided a valuable insight into the fundamental mechanics governing self-centering wall systems and offer practical recommendations for their design and implementation in earthquake-resistant structures.

Keywords: Seismic performance, self-centering, unbonded tendons, precast concrete, shear walls, post-tensioning

1. Introduction

Structures designed according to the most recent building codes are expected to experience considerable structural and nonstructural damage during severe earthquakes. Conventional design targets a life-safety performance level, ensuring occupant protection during rare seismic events. However, this design performance level allows yielding, buckling, and residual drifts, which hinders the facility operation and service after an earthquake. Such damage can lead to costly and time-consuming repairs, and in extreme cases, complete demolition. In addition, widespread damage can cause serious economic and societal disruptions, particularly in regions with a highly dense population.

To address the limitations of conventional seismic design and to promote more resilient and sustainable cities, recent research has focused on developing high-performance structural systems capable of withstanding strong ground motions with minimal permanent damage. These self-centering or damage-resistant systems reduce damage in primary structural components by allowing controlled gap opening mechanism rather than relying on inelastic yielding of bonded reinforcement at the plastic hinge zone. Energy dissipation is achieved through replaceable yielding elements or friction-based devices, while unbonded post-tensioned tendons provide restoring forces that return the structure to its original position after the earthquake.

Among these systems is self-centering precast concrete walls, which effectively combine the advantages of precast construction and prestressing technology to deliver superior seismic performance. They employ unbonded post-tensioned tendons anchored between the wall top and the foundation, allowing the wall to rock and uplift during lateral loading as shown in Figure 1. The elastic elongation of the tendons generates a restoring force that re-centers the wall once the load is removed, enabling the structure to resist earthquake-induced forces with

minimal damage compared with conventional monolithic reinforced concrete walls.

To improve the seismic performance of buildings, many researchers have focused on developing self-centering structural systems that can resist strong earthquake shaking with little damage and very small or no residual deformations. Unbonded post-tensioned (UPT) precast concrete walls are one important type of these systems. Similar self-centering concepts have also been applied to precast concrete frames [1, 2] and steel-braced frames [3, 4], and have been successfully used for seismic strengthening of existing buildings [5]. Priestley and Tao proposed the same concept on moment-resisting frames prestressed with partially unbonded tendons as an alternative lateral force-resisting system. Results from a series of nonlinear time-history analyses confirmed the effectiveness of this concept. Priestley and Tao highlighted that the primary advantage of this system is its ability to eliminate residual drifts after an earthquake.

The research focus on precast seismic systems began in the early 1990s with the Precast Seismic Structural Systems (PRESSSS) program, which culminated in the pseudo-dynamic experiment of a 0.6-scale, five-story precast concrete building [6]. The PRESSSS prototype featured coupled unbonded post-tensioned (UPT) walls in one direction, where the coupling mechanism consisted of U-shaped flexural steel plates between adjacent wall panels, and precast concrete frames with different types of beam-column connections in the perpendicular direction. It was reported that the residual drift in direction of the UPT walls was 0.06% only after experiencing a peak drift of 1.8% representing just 3% of its maximum drift and with minimal

damage. Later experimental studies on UPT walls primarily investigated the behavior of individual uncoupled walls, including those without energy dissipators [7, 8], those with bonded mild steel reinforcement as an energy dissipator [9-11], and those employing alternative energy dissipation mechanisms [12].

Hassanli *et al.* [13] carried out experimental tests on four unbonded post-tensioned (PT) masonry walls with different initial prestressing levels. The results indicated that PT losses were mainly influenced by tendon yielding, toe crushing, and anchorage slip. Nazari *et al.* [14] performed a series of shaking table experiments on four 5/18-scale concrete rocking walls and analyzed their dynamic response under multiple ground motion intensities. The findings revealed that rocking and impact mechanisms dissipated limited energy, while additional energy dissipation occurred at the wall toe through the plastic stage due to localized crushing. Furthermore, several researchers [15-17] have developed numerical models capable of accurately representing the seismic behavior of rocking walls under cyclic and earthquake loading.

The current study investigates the behavior of unbonded post-tensioned (UPT) concrete walls using nonlinear numerical macro modeling. The research involves developing the numerical model using Open Sees and then validating the numerical model against experimental results conducted by other researchers, followed by a parametric study to examine the effects of key parameters, including wall geometry and concrete strength. The findings provide insight into the influence of these factors on the wall's strength, stiffness, and deformation capacity.

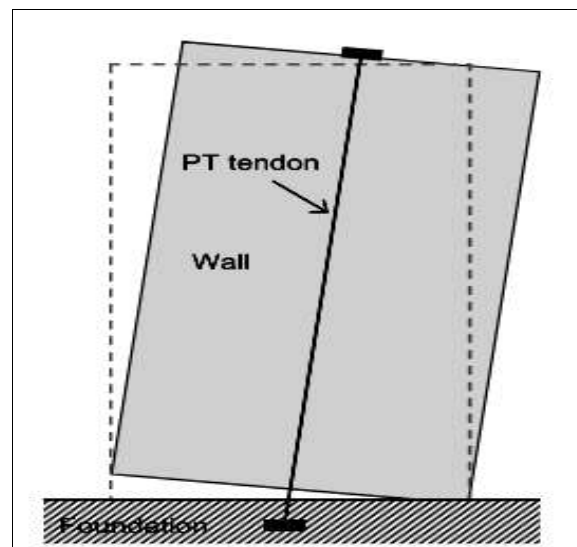


Fig 1: Unbonded post-tensioned concrete wall behavior under lateral load.

2. Model Verification: The experimental wall specimen E-iii, tested by Henry *et al.* [16], was selected as a benchmark to validate the accuracy of the developed numerical model. This specimen was chosen as the test program provided detailed measurements for both global and local responses, including the change of compressive strain values during loading at the wall toe, which are essential for assessing the nonlinear behavior of controlled rocking walls with self-centering capability.

In the experimental setup, the precast wall panels were directly mounted on the strong floor with a thin layer of

bedding material to ensure uniform stress distribution and prevent premature localized crushing. Unbonded post-tensioning tendons were extended continuously through the height of the wall and were anchored at the top loading beam and the base foundation, allowing free elongation during rocking while maintaining the self-centering capability. The main geometric and material properties of the tested specimen adopted in the numerical model are presented in Table 1, and the overall experimental configuration and details of the specimen are illustrated in Figure 2a and b.

The wall was reinforced with four evenly distributed layers of 4 mm diameter reinforcing bars spaced at 150 mm in both directions, providing an overall reinforcement ratio of 0.28% horizontally and vertically. Notably, no confinement reinforcement was provided at the wall toe. A monotonic lateral displacement was imposed at the top of the wall

through the loading beam using a fixed-step displacement control protocol, while no external axial load was applied during the test. This configuration facilitated a clear observation of the wall's rocking behavior and the development of localized compression damage at the toe region.

Table 1: Details of validated Model

Wall ID	L_w (m)	H_e (m)	h_e/l_w	B_w (m)	No. of tendons	A_{ps} (mm ²)	f_{se} (% f_y)	f'_c (Mpa)	f_c/f'_c
E-iii	1.0	3.0	3	0.12	3	439.65	50%	42.4	0.070

Where: f_{se} is the initial prestressing, A_{ps} is the total prestressing steel area, and f_c/f'_c is the axial stress ratio

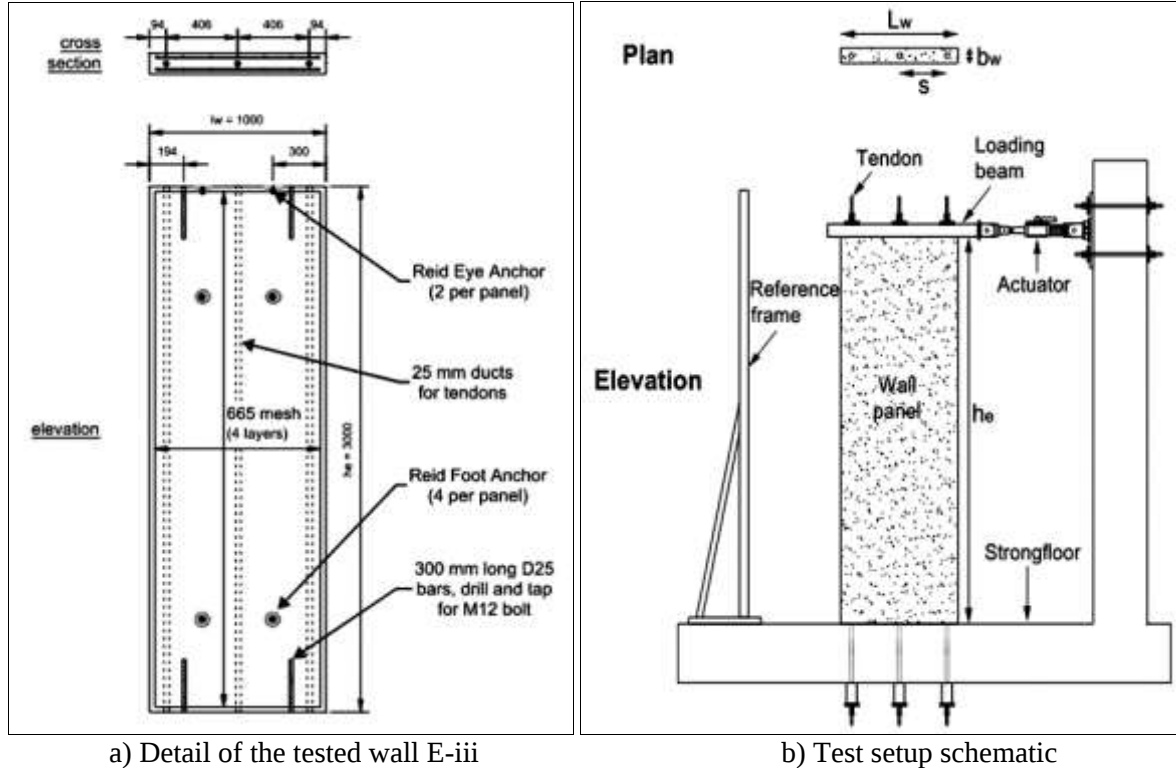


Fig 2: Tested Wall Details by Henry ^[16]. (All dimensions are in mm)

2.1 Model Description

A nonlinear numerical macro model was developed using OpenSees to simulate and validate the experimental response of wall specimen E-iii tested by Henry *et al.* ^[16]. The wall was modeled using a multi-layer shell element, and formulated based on the theory proposed by Dvorkin *et al.* ^[18], which employs the Mixed Interpolation of Tensorial Components (MITC) approach. This element type was later implemented into OpenSees ^[19] by Lu *et al.* ^[20] and has been effectively used to model the nonlinear seismic behavior of reinforced concrete (RC) shear walls in high-rise buildings. In this study, the wall cross-section was represented by ten layers, comprising outer concrete cover layers, longitudinal and transverse reinforcement layers, and core concrete layers. This multi-layered formulation allows for capturing stress and strain variation through the wall thickness, providing an accurate representation of the nonlinear behavior of reinforced concrete. The unbonded post-tensioning tendons were modeled using truss elements. The wall-foundation interface was idealized using compression-only springs, which were linked through rigid beam-column elements to connect each other and shell nodes. A rigid beam-column element was also defined at the wall top to represent the loading beam used in the experimental setup.

The monotonic lateral loading applied at this location simulated the experimental test procedure.

In the experiment, base sliding was prevented by frictional resistance between the wall and the strong floor. In the numerical model, this behavior was represented by a roller support at the wall base, allowing rotation while restraining horizontal translation, consistent with the experimental boundary conditions.

2.2 Material models

The constitutive materials adopted for the multilayer shell elements were defined using the built-in nDMaterial Plane Stress User Material model available in OpenSees. This model was selected for its ability to accurately simulate the nonlinear stress-strain behavior of concrete. For the concrete layers, the compressive stress-strain response was characterized by considering a compressive strain of 0.0022 corresponding to the maximum compressive strength f'_c , and a crushing strain of 0.01 [16] with a corresponding crushing stress level of 10% of f'_c . The tensile strength of the concrete was taken as $0.62\sqrt{f'_c}$ MPa [22].

Compression-only springs were implemented using the Concrete02 material model in OpenSees, with all tensile-related parameters set to zero to prevent tension transfer once wall uplift occurs. The post-tensioned (PT) tendons were modeled using the Steel02 material model, defined by a yield strength of 1580 MPa and an elastic modulus of 200 GPa. This steel model considers cyclic degradation, and hysteretic behavior of steel when it undergoes repeated cycles of loading and unloading.

2.3 Numerical Model Results and Discussion

The validation of the numerical model is shown in Figure 3, which reflects an excellent agreement between the numerical model predictions and the experimental results for wall specimen E-iii. The comparison demonstrates that the developed model successfully captures both the initial

stiffness and the post-yield stiffness, as well as the overall lateral load-displacement response. The predicted peak lateral strength differs from the experimental value by 4% while the predicted displacement at peak strength differs from the experimental value by 4%, confirming the model's high accuracy in predicting the global behavior of the tested wall.

Overall, the close correlation between experimental and numerical outcomes demonstrates that the proposed numerical model can accurately capture the response characteristics of self-centering unbonded post-tensioned concrete walls. Moreover, the validated model provides a reliable analytical framework for conducting an extensive parametric study aimed at investigating the influence of key design parameters on the seismic behavior of this wall system.

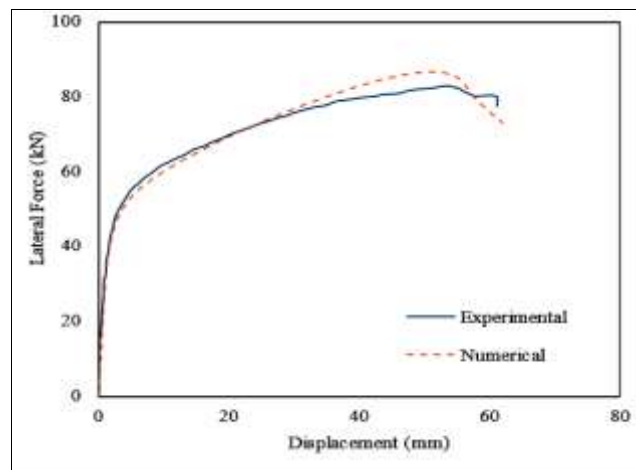


Fig 3: Lateral Force Displacement Relationship of wall E-iii

3. Parametric Study

After validating the numerical model, a comprehensive parametric study was conducted to gain a deeper understanding of the behavior of unbonded post-tensioned concrete (UPT) walls under lateral loading. The objective of this study is to examine the influence of key design and material parameters on both the global and local seismic responses of these walls, including their strength, stiffness, ductility, and self-centering performance.

The details of the analyzed models are summarized in Table 2, which presents the parametric matrix comprising 8 wall specimens. The parameters considered in this study include wall geometry, thickness, and concrete compressive strength. Specifically, the wall lengths were set to 1.0 m, while the wall heights varied from 2.0 m to 5.0 m,

maintaining height-to-length ratios between 2 and 5. The wall thickness was chosen as 120 mm, 160 mm, and 180 mm to evaluate the effect of this parameter. The three concrete compressive strengths of 30, 40, and 50 MPa were considered to capture material strength variations. In addition, unbonded prestressed tendons with a yielding stress of 1580 MPa and a Young's modulus of 200 GPa were used, consistent with the validation model, and each tendon had a cross-sectional area of 146.55 mm².

This systematic parametric investigation was employed to provide a broad understanding of the factors governing the nonlinear response of unbonded post-tensioned concrete (UPT) walls and to assist in evaluating their seismic performance and developing design recommendations.

Table 2: Parametric matrix

Wall ID	L _w (m)	H _e (m)	h _e /l _w	B _w (m)	No. of tendons	A _{ps} (mm ²)	F _{se} (%f _y)	f' _c (Mpa)	f _c /f' _c
W1	1.0	2.0	2.0	0.12	3	439.65	50%	40	0.074
W2	1.0	3.0	3.0	0.12	3	439.65	50%	40	0.074
W3	1.0	4.0	4.0	0.12	3	439.65	50%	40	0.075
W4	1.0	5.0	5.0	0.12	3	439.65	50%	40	0.075
W5	1.0	3.0	3.0	0.16	3	439.65	50%	40	0.056
W6	1.0	3.0	3.0	0.18	3	439.65	50%	40	0.050
W7	1.0	3.0	3.0	0.12	3	439.65	50%	30	0.099
W8	1.0	3.0	3.0	0.12	3	439.65	50%	50	0.059

where l_w is the wall length, h_e is the wall height, b_w is the wall thickness, A_{ps} is the total area of prestressing tendons, f_{se} is the initial prestress expressed as a percentage (or fraction) of the tendon yield stress, f'_c is the concrete compressive strength, and f_c/f'_c is the axial stress ratio.

3.1 Results and Discussion

This section discusses the influence of various parameters on the behavior of unbonded post-tensioned concrete walls. The first parameter examined is the concrete compressive strength. The effect of concrete strength on wall performance was investigated using 30, 40, and 50 MPa for specimens W7, W2, and W8, respectively. These strength levels were selected as they represent the typical range of concrete grades commonly used in structural wall applications, covering normal- to high-strength concrete

commonly adopted in practice. As shown in Figure 4, increasing the concrete grade enhances both the lateral strength, initial stiffness, and post-yield stiffness of the wall. When the compressive strength increased from 30 MPa to 40 MPa, the wall strength increased by about 12%, while a further increase to 50 MPa yielded an 8% gain. Overall, a 30% increase in concrete strength resulted in roughly a 10% improvement in wall capacity.

The second parameter investigated is the wall thickness (b_w), which directly affects the flexural stiffness and lateral load resistance of the wall. Three thicknesses 120, 160, and 180 mm were analyzed for wall specimens W2, W5, and W6, respectively. As illustrated in Figure 5, increasing the wall thickness leads to a noticeable improvement in the initial stiffness due to the larger moment of inertia. This enhancement in stiffness is accompanied by a corresponding increase in lateral strength

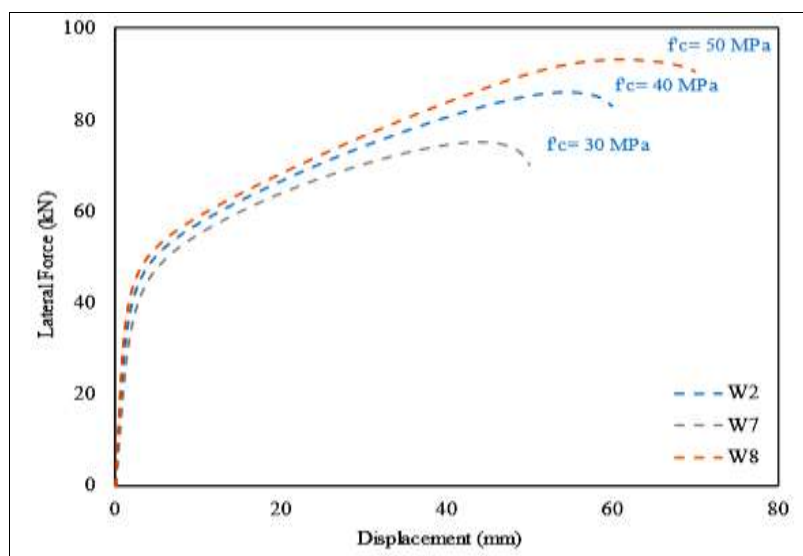


Fig 4: The influence of the concrete compressive strength

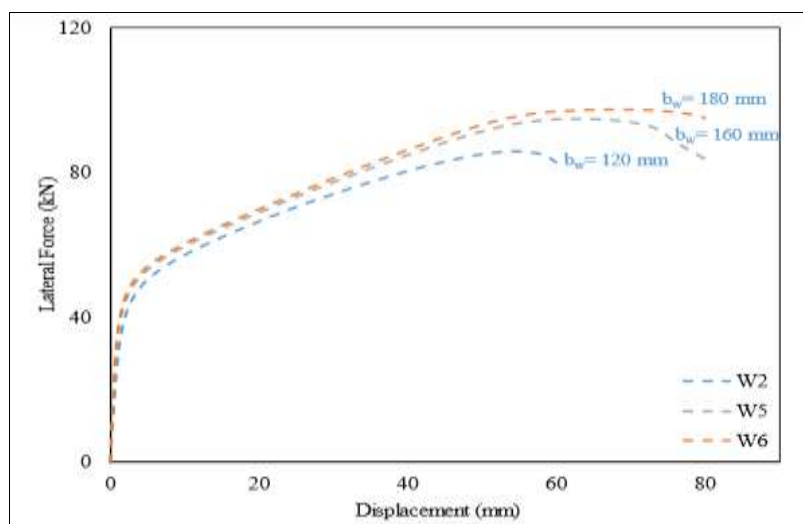


Fig 5: The influence of the wall thickness

The next parameter investigated is the wall height, which significantly influences the global response of unbonded post-tensioned concrete walls. Figure 6 illustrates the effect of wall height on wall behavior for specimens (W1-W4).

The results indicate that increasing the wall height leads to a reduction in both initial stiffness and lateral strength, while having larger lateral displacements. This behavior can be attributed to the increased flexibility associated with taller

walls and the fact that the unbonded length of the post-tensioning tendons increases with height. Consequently, for a given lateral displacement, taller walls develop smaller tendon strains compared to shorter ones, allowing a greater

range of deformation before yielding. Quantitatively, a 10% reduction in wall height results in approximately a 15-20% increase in peak lateral strength.

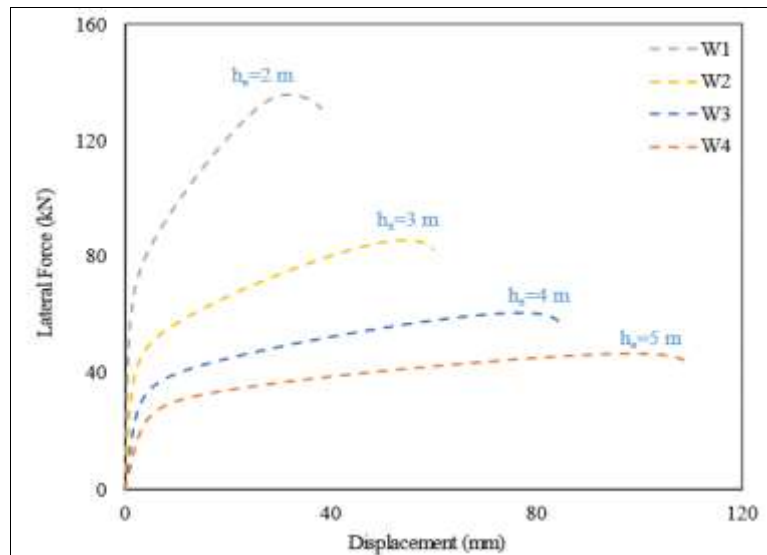


Fig 6: The influence of the wall height

Conclusions

This paper investigates the behavior of unbonded post-tensioned concrete walls through developing a numerical model, validating it, and evaluating the influence of various parameters on their structural response. The parameters investigated include wall geometry (height and thickness) and concrete compressive strength. Based on the numerical and analytical findings, the following conclusions can be drawn:

- Modelling unbonded post-tensioned concrete walls using OpenSees provides an effective means of simulating their behavior, showing excellent agreement with experimental results.
- Concrete compressive strength: Increasing concrete strength enhances both the lateral load capacity and the initial stiffness of the wall. A 30% increase in concrete compressive strength results in approximately a 10% gain in wall strength.
- Wall thickness: Increasing the wall thickness enhances both the initial stiffness and overall strength.
- Wall height: Wall height is inversely related to stiffness and strength but directly related to ductility. A 10% reduction in wall height can increase the peak lateral strength by approximately 15-20%.

Overall, the results highlight the importance of achieving a balanced design between strength and ductility. Optimizing these parameters allows for improved structural efficiency and enhanced seismic performance of unbonded post-tensioned concrete wall systems.

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