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Behavior of Externally Reinforced Post-Tensioned Shear Walls under Lateral Loads

Ghida Edlebi[1], Adnan Masri[1], Nour Wehbi [1],Oussama Baalbaki[1]
[1]Beirut Arab University
Beirut , Lebanon

Abstract – In high seismic regions, numerous older reinforced concrete (RC) buildings, constructed before modern seismic codes require strengthen to withstand major earthquakes. This research presents an experimental and numerical investigation of strengthen technique for shear walls that are susceptible to brittle failure modes due to deficient detailing or a lack of properly confined boundary elements. The strengthen process involves the addition of steel members. This study primarily focuses on comprehending the flexural characteristics and lateral resilience of a scaled specimen: post-tensioned (PT) walls. Following testing until failure, a strengthening strategy was implemented by attaching steel components to the lower section in the PT wall. These modified configurations are now recognized as the other specimen. Importantly, the ABAQUS model effectively simulates the lateral response of the tested specimens, with minor variations compared to the experimental results falling within an acceptable range. The strengthened walls exhibited ductile failure, as opposed to the original walls that experienced brittle failure. Furthermore, the incorporation of steel components had minimized cracking, increased load-bearing capacity, and improved stiffness and ductility. This enhancement is anticipated to minimize earthquake-induced damage, leading to shorter repair times.

***Keywords*:** shear wall, strengthening, retrofitting, lateral loads, bearing capacity.

1- Introduction

Reinforced concrete (RC) shear walls are standard structural elements in regions prone to earthquakes. They provide an effective solution for improving buildings' resistance to lateral forces, offering high in-plane stiffness and rigidity, and limiting harm to both structural and non-structural components. Thanks to their considerable strength, they can weather significant horizontal forces generated by support gravitational loads and seismic activity such as earthquakes and wind loads that can lead to various failure modes, such as diagonal compression, diagonal tension, or sliding shear, due to the lateral and axial loads they impose. [1]. At the same time, many shear walls suffer from poor design and construction flaws, ranging from inadequate reinforcement to unfavorable dimensions. To avoid such failures, it is important to investigate various strengthening techniques for retrofitting existing RC walls and providing sufficient stiffness and ductility.

A sizable literature has addressed the performance of strengthened RC shear walls. In an important experiment, Elnashi et al. [2] considered experimental investigation on various arrangements of steel elements to improve stiffness, ductility, and ultimate load-bearing capacity of RC walls and proposed intervention techniques for retrofitting structures damaged by earthquakes. Taghadi et al. [3] tested a retrofitting approach that attached two vertical steel strips on each side of non-ductile and low-rise RC shear walls. This approach increased bearing capacity by 50% and altered the failure mode to shear sliding. Christidis et al. [4] explored the performance of non-compliant RC shear walls using various arrangements of steel angles and steel straps to improve response parameters. The test was performed on five shear walls, four that had been strengthened and one that served as control. These walls had a slenderness ratio of approximately 2.0 and were subjected to displacement-controlled cyclic loading. They obtained that all the strengthened RC walls lessened crack propagation along the wall's surface and precluded longitudinal reinforcement buckling in the compression zone. On the other hand, Kheyroddin et al [5] replaced traditional boundary elements with steel jackets in squat RC shear walls. They assessed the efficacy of this strengthening method in terms of its impact on ultimate load capacity and ductility.

Other researchers have investigated self-centering (rocking) and selective weakening as a retrofit strategy. Self-centering structures can revert to their original position after earthquakes, without any residual displacement. When rocking is the mechanism of self-centering, either the structure's own weight or unbonded post-tensioning strands can be used to generate the restoring forces. In this field, several studies have examined the implementation of self-centering in new precast concrete beam-column joints and precast walls through unbonded post-tensioning and sacrificial energy dissipators [6; 7; 8; 9]. Self-centering has also been investigated in the context of bridge piers [10; 11; 12]. However, weakening, and selective weakening are retrofit strategies that intentionally weaken or unstiffen elements of a structure to reduce the force requirements on the system. As Viti et al. [13] explain, this weakening comes with the tradeoff of increasing displacement demands. External reinforcements from plates, jacketing, or damping devices, can be used to improve the weakened structures and meet the heightened displacement demands and required capacity design principles [14, 15].

In the context of this literature, further research is required to compare the seismic response of various strengthening methods that can enhance the performance of RC shear walls. At the same time, it is critical to identify the failure mechanisms that can result from the proposed strengthening methods. Such analysis should examine not just the bearing capacity but also the impact of changes on various parameters (stiffness, energy dissipation, ductility).

This paper focuses on strengthening RC walls with internal post tensioned (PT) cable and external steel elements. It relies on both experimental testing and non-linear numerical investigation using “ABAQUS”, a finite element analysis software, to verify the obtained results. The performance of the RC walls under static loading is evaluated by examining stiffness, ductility, and energy absorption. The paper then compares the efficacy of the post tensioned strengthening approach to the steel elements approach and quantifies the performance improvement from each.

2- Experimental Testing

The experimental procedure considered two types of walls: Post-tensioned wall (PTW) and strengthened post-tensioned wall (SPTW). These scaled specimens were tested to evaluate the failure modes. Both specimens have identical geometric dimensions and reinforcement configurations. The wall specimens were divided into two segments: the upper part of measurements 80 cm in width, 160 cm in height, and 16 cm in thickness, while the lower part had dimensions of 130 cm in width, 30 cm in height, and 30 cm in thickness with height-width ratio of these specimens being around 2, as shown in figure 1. The lower part was used for anchoring the specimen onto the solid floor as a fixation using four anchor bolt of 20 mm diameter each side of the wall. The out-of-plane movements of the wall were restrained by lateral supports. The flexure reinforcements consisted of 6Ø14-mm-diameter rebar and transversal reinforcement of Ø10-mm-diameter located on each side of the wall. The reinforcement percentage and diameter were maintained consistent in both parts of the wall.

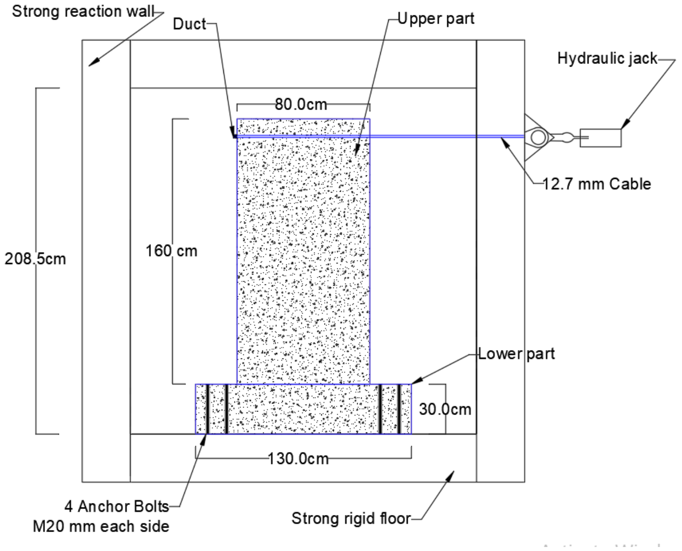


Figure 1: Schematic Representation of the test setup

2.1 Material properties

The average compressive strength of concrete used in this study was measured as 40 MPa.

2.2 Lateral loading

The experimental program procedure included the application of lateral forces that were typically exerted parallel to the wall plane and are situated around the shear wall's strong axis using hydraulic jack, every click in the actuator produced additional stress in the post tension cable. The hydraulic jack was used to apply a static pulse load.

PTW was tested until it reached the point of failure, after which it underwent strengthening with steel members to become SPTW and was subsequently retested.

2.3 Strengthening method

In the upcoming section, details about the addition of steel components to the wall specimen on each side is found, shown in figure 2.

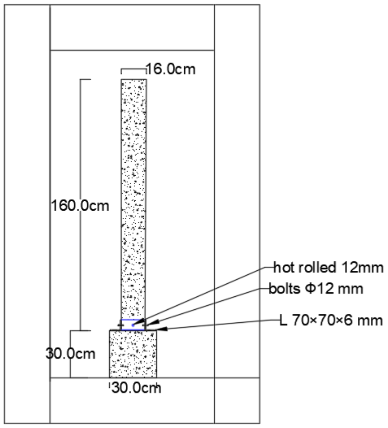


Figure 2: Side view of the strengthened wall with steel members

In the lower portion of the wall, two steel L-section elements, with dimensions of 7 cm x 7 cm x 0.6 cm each, were securely attached. Additionally, a steel plate measuring 130 cm x 30 cm x 0.6 cm was affixed, as shown in figure 2. These steel components were fastened to the lower part of the wall using M16 mm bolts, and they were interconnected by welding with a 4 mm thick electrode (480xx).

2.4 Post-tension.

The primary prestressing reinforcement is a single-strand 7-wire tendon with a diameter of 15.2 mm and a total cross-sectional area of 138.7 mm².

Two post tensioned cables were introduced to PTW in braced shape (X) inclined. These two cables are of 153 cm length, pass through the two parts of the wall as shown in Figure 3.

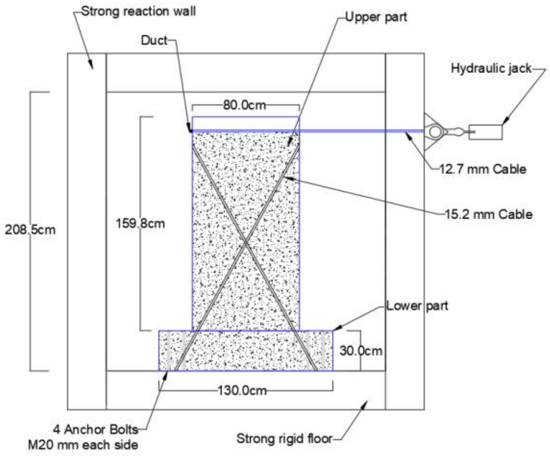
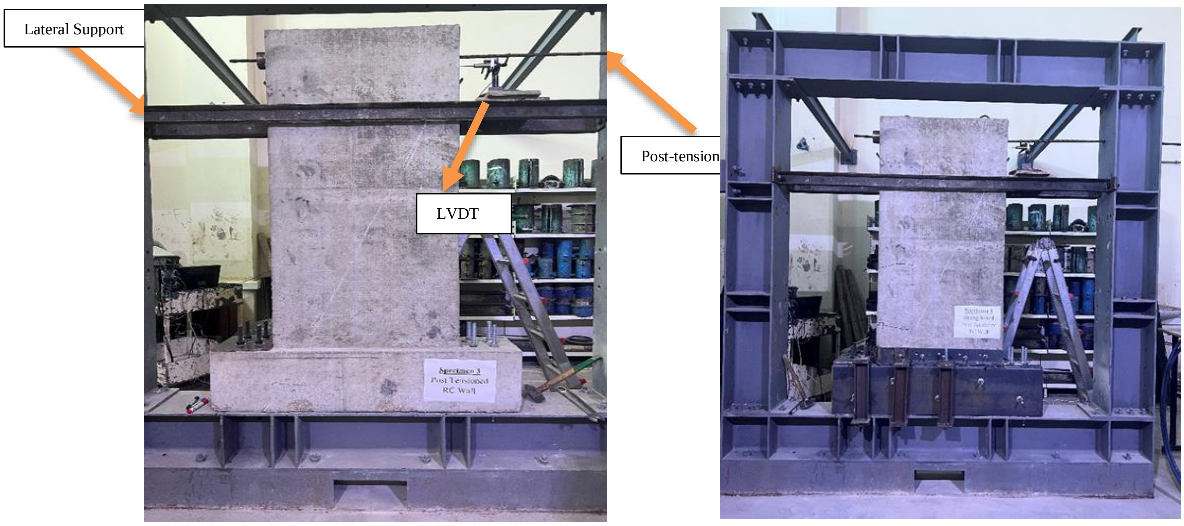


Figure 3: schematic representation of PTW

3.1 Experimental Setup And Results



(a) PTW

(b) SPTW

Figure 4: Initial condition of specimens

3.2 Behavior of PTW

The failure mode of the first specimen was primarily localized in a specific area of the specimen, which forms the lower section of the wall. This segment did not exhibit rigid behavior, causing the initiation of crack patterns within this wall section as shown in figure 5. The provided figure illustrates the progression of crack development in the tested PTW prior to strengthening. In the intact wall under normal conditions, the initial crack observed was a horizontal tension crack positioned at the lower left corner of the upper part of the wall. This crack emerged due to the application of a lateral load at 5.73 tons with 14.2 mm displacement.

Over time, these cracks continued to propagate, culminating in a larger diagonal crack, and extending further into the lower part. The progression of these diagonal cracks eventually led to diagonal shear failure at 9 tons with 33.7 mm displacement, the lower part of specimen one had been damaged with only two cracks in the upper part.

Figure 5: Failure mechanism of PTW

3.3 Behavior of SPTW

After the occurrence of damage, the wall was strengthened by adding steel members in the lower part of the wall as shown in figure 4(b) and subsequently subjected to reloading. After applying the load, the initial crack developed in the upper section with a force of 8.5 tons with 9.55 mm displacement. The length of the cracks continued to grow as the top displacement was introduced, and through gradual increments in load, the force eventually reached 20 tons. The failure mechanism of the specimen retrofitted with steel members can be described as a ductile combination of bending and shear modes. In contrast, the unstrengthened reference specimen (PTW) failed primarily due to shear with a lower level of ductility. This strengthening method is utilized to resist and reduce shear failure and shear slippage between the two parts of the wall. In the strengthened post tensioned wall, the initial crack observed was a horizontal tension crack positioned at the upper part of the wall. With the gradual increase in lateral load, subsequent cracks appeared. The progression of these cracks subsequently increased with load until reaching 20 tons with 21.75 mm displacement, subsequently the load was stopped as displayed in Figure 7.

Figure 6: Failure mechanism of SPTW

As shown in figure 6, cracks are distributed over the height of the wall and not concentrated over a specific area, this ensure that the strengthening techniques used had effectively improved the lower portion of the wall and contributed to a more even distribution of cracks by enhancing the strength of the damaged part.

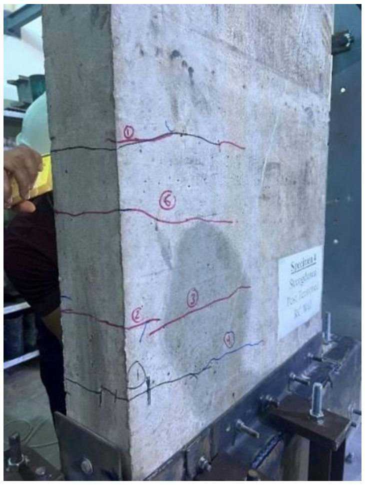


Figure 6: Failure mechanism of SPTW

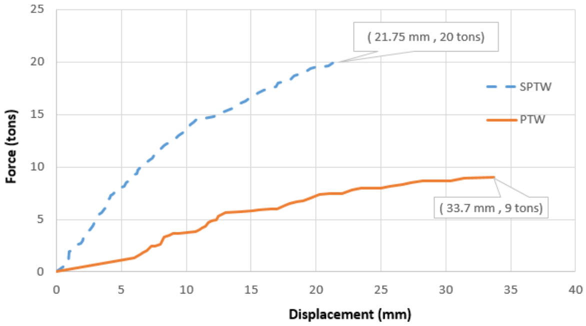


Figure 7: Pushover curve (load- displacement) of specimens.

5. Finite element modelling

(a) PTW

(b) SPTW

Figure 8: 3D view of each specimen modelled in Abaqus.

Two models are done using ABAQUS software, the 3D views of each model are shown in figure 8 (a and b).

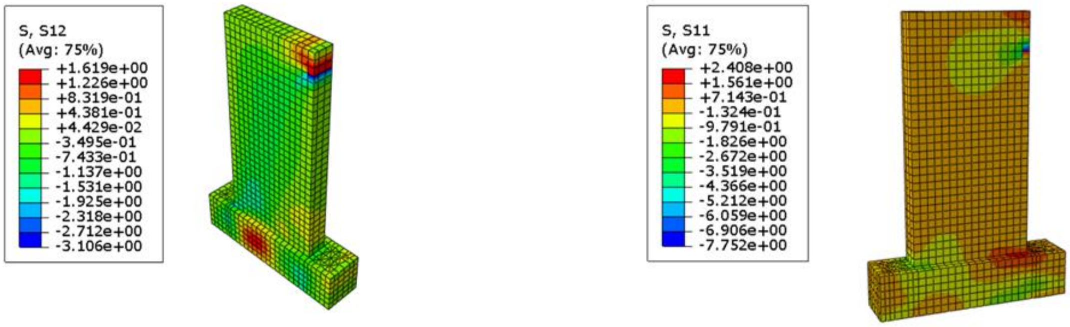
6. Validation of the FEM

5.1 Failure Mode

(a) PTW

(b) SPTW

Figure 9: Tension damage at failure



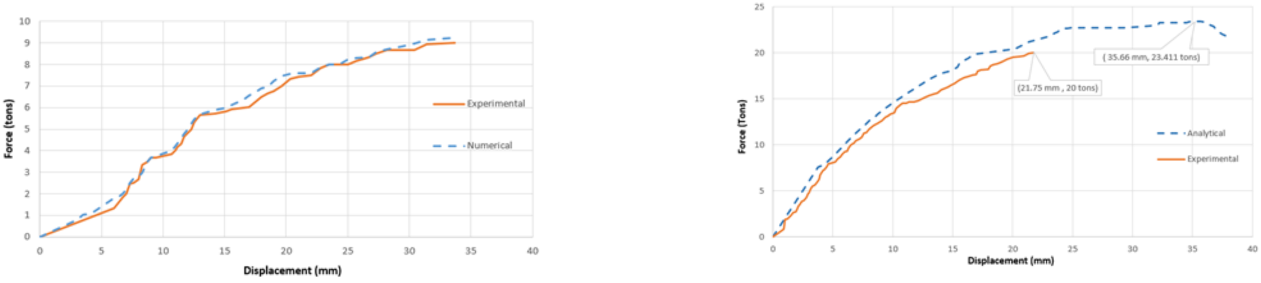
(a) (S12) in PTW

(b) (S11) in PTW

Figure 10: Distribution of stress

Figures 9 and 10 highlight the tension damage and stresses occurring in each specimen at failure. In PTW, figure 9-a highlights a tension failure with the appearance of cracks at the junction between the upper and lower portions of the wall in addition of stress distribution, in figure 10 (a-b), that is focused primarily on the lower section of the wall, originating from the junction point between the upper and lower portions of the wall and extending further into the lower part, especially around the mid-span of the lower portion, as previously discussed. Moving to Figure 9-b, it highlights a tension failure occurring in the upper part of the wall, along with the appearance of cracks at the junction between the upper and lower portions of the wall.

5.2 Pushover curves



(a)PTW

(b) SPTW

Figure 11: Pushover curve (load- displacement)

Figure 11 shows the numerical and analytical displacement-load curve in addition of the percentage of error in ultimate load capacity for each specimen.

Moving to post tensioned wall, figure 11 (a and b) indicates that both curves the PTW have a displacement of 33.7 mm with maximum load of 9 tons for experiment and 9.24 tons from numerical outputs.

While for SPTW and as mentioned before, the hydraulic jack has a maximum capacity of 21 tons, for this reason when the load reached 20 tons with 21.75 mm displacement, the experiment was stopped.

The curve of numerical outputs shows that the ultimate load of this strengthened specimen was 23.411 tons with 35.66 mm displacement.

7. Conclusions

The study's findings are as follows:

- In the strengthened walls, SPTW, cracks are evenly distributed along the entire wall length, as opposed to being concentrated in a small section in PTW, which means that the failure mode was transformed from brittle to ductile.
- The ultimate load-bearing capacity of the strengthened reinforced wall increased by approximately two times for the strengthened post-tensioned wall as compared to the control walls (PTW).
- The failure mechanism transformed from shear failure to a combination of bending and shear failure after strengthening the post-tensioned wall.
- These strengthening techniques enhanced the confinement level.
- Analytical model provided using ABAQUS software has provided excellent validation of the behavior of these walls and can be relied on in further investigation while doing parametric study.

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Declarations
Conflict of interest: The authors declare that there is no conflict of interest regarding the publication of this paper.

References

[1] (Sas, G.; Hansen, C.; Taljsten, B. FRP strengthening of RC walls with openings. In Proceedings of the Advanced Composites in Construction, ACIC, Edinburgh, UK, 1 September 2009.)

[2] Elnashai, A. S. and Pinho, R., “Repair and retrofitting of RC walls using selective techniques”, Journal of Earthquake Engineering, 2(04), pp. 525–568 (1998).

[3] Taghdi, M., Bruneau, M., and Saatcioglu, M., “Seismic retrofitting of low-rise masonry and concrete walls using steel strips”, Journal of Structural Engineering, 126(9), pp. 1017–1025 (2000).

[4] Christidis, K. I., Vougioukas, E., and Trezos, K. G., “Strengthening of non-conforming RC shear walls using different steel configurations”, Engineering Structures, 124, pp. 258–268 (2016).

[5] Kheyroddin, A. and Naderpour, H., “Nonlinear finite element analysis of composite RC shear walls”, Iranian Journal of Science and Technology, 32(B2), p. 79 (2008)..

[6] Holden, T., Restrepo, J., and Mander, J. B. (2003). "Seismic performance of precast reinforced and prestressed concrete walls." J. Struct. Eng., 10.1061/(ASCE)0733-547 9445(2003)129:3(286), 286-296.

[7] Kurama, Y. (2002). "Hybrid post-tensioned precast concrete walls for use in seismic regions." PCI J., 47, 36-59

[8] Nakaki, S., Stanton, J., and Sritharan, S. (1999). "Overview of the presss five-story precast test building." PCI J., 44, 26-39.

[9] Priestley, M. N., and Tao, J. R. (1993). "Seismic response of precast prestressed concrete frames with partially debonded tendons." PCI J., 38(1), 58-69.

[10] Lee, W., Jeong, H., Billington, S., Mahin, S., and Salkai, J. "Post-tensioned structural concrete bridge piers with self-centering characteristics." Proc., Structural Engineering Research Frontiers Session of the 2007 Structures Congress.

[11] Marriott, D., Pampanin, S., and Palermo, A. (2009). "Quasi-static and pseudo-dynamic testing of unbonded post-tensioned rocking bridge piers with external replaceable dissipaters." Earthq. Eng. Struct. D., 38(3), 331-354.

[12] Ou, Y.-C., Chiewanichakorn, M., Aref, A. J., and Lee, G. C. (2007). "Seismic performance of segmental precast unbonded posttensioned concrete bridge columns." J. Struct. Eng., 10.1061/(ASCE)0733-9445(2007)133:11(1636), 1636-1647. 580

[13] Palermo, A., Pampanin, S., and Marriott, D. (2007). "Design, modeling, and experimental response of seismic resistant bridge piers with posttensioned dissipating connections." J. Struct. Eng., 10.1061/(ASCE)0733-9445(2007)133:11(1648), 1648-1661.

[14] Priestley, M. N., Sritharan, S., Conley, J. R., and Pampanin, S. (1999). "Preliminary results and conclusions from the presss five-story precast concrete test building." PCI J., 44(6), 42-67.

[15] Holden, T., Restrepo, J., and Mander, J. B. (2003). "Seismic performance of precast reinforced and prestressed concrete walls." J. Struct. Eng., 10.1061/(ASCE)0733- 9445(2003)129:3(286), 286-296.