

Seismic behaviour of post-tensioned concrete shear wall: a review.

Comportamiento sísmico de un muro de corte de hormigón postensado: una revisión

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ABSTRACT

Shear walls are specifically meant to withstand lateral forces exerted by either wind or earthquake loads on a structure. Due to their superior strength and stiffness, shear walls have been an integral feature of mid-rise and high-rise structures over the past two decades. Various studies have been performed in this field. Usage of post-tensioned tendons in the traditional shear wall is one of the major advancements in recent times so as to increase the stiffness and reduce the damage incurred by destructive earthquakes. The key advantage of post-tensioned shear walls is the potential to re-centre after a devastating earthquake which is lacking in conventional reinforced concrete (RC) shear walls that rely on yielding creating large deformations. Moreover, compared with conventional shear wall construction, post-tensioned shear walls can reduce the use of vertical mild steel reinforcement. This results in materials being used more effectively and eliminates congestion. This paper seeks to review and analyze the research studies based on post-tensioned shear wall focusing on works published within the last decade. Firstly, the benefits of using post-tensioned shear walls in seismically active areas are illustrated. The behaviour and parameters controlling the performance of post-tensioned shear walls are then studied. A critical study of the factors responsible for the performance of post-tensioned shear wall is the primary objective of this review.

Keywords- Shear Wall, Post-Tensioning, Energy-Dissipation, Self-Centering.

RESUMEN

Los muros de cortante están diseñados específicamente para resistir fuerzas laterales ejercidas por cargas de viento o terremotos en una estructura. Debido a su resistencia y rigidez superiores, los muros de corte han sido una característica integral de las estructuras de altura media y alta durante las últimas dos décadas. Se han realizado

varios estudios en este campo. El uso de tendones postensados en el muro de corte tradicional es uno de los principales avances en los últimos tiempos para aumentar la rigidez y reducir los daños ocasionados por terremotos destructivos. La ventaja clave de los muros de cortante postensados es el potencial de volver a centrarse después de un terremoto devastador que carece de los muros de cortante de hormigón armado (RC) convencionales que dependen de la fluencia creando grandes deformaciones. Además, en comparación con la construcción de muros de corte convencional, los muros de corte postensados pueden reducir el uso de refuerzo vertical de acero dulce. Esto da como resultado un uso más eficaz de los materiales y elimina la congestión. Este artículo busca revisar y analizar los estudios de investigación basados en muro de corte postensado con foco en trabajos publicados en la última década. En primer lugar, se ilustran los beneficios de utilizar muros de cortante postensados en áreas sísmicamente activas. A continuación, se estudian el comportamiento y los parámetros que controlan el comportamiento de los muros de cortante postensados. Un estudio crítico de los factores responsables del comportamiento de los muros de cortante postensados es el objetivo principal de esta revisión.

Palabras clave: muro de corte, postensado, disipación de energía, autocentrado.

INTRODUCTION

Shear walls are installed in buildings as part of the earthquake-resistant construction design to decrease lateral displacements under earthquake loads. The main purpose of building these special elements is to mitigate the effects of an earthquake, such as the loss of life, the degradation of infrastructure and the loss of economy. Shear walls are considered one of the most effective earthquake-resistant systems for seismic regions. The shear wall is primarily designed to withstand two kinds of forces: shear forces produced by ground movement and external forces and uplift forces due to the horizontal forces coming on top of the wall. Since earthquake mitigation is not feasible, there is a consensus to develop earthquake resistant structural systems with a high resilient ability and very limited post-earthquake structural damage. Numerous studies are taking place in this discipline in which the latest trend is to optimize the structures in order to create cost-effective buildings. One of the key drawbacks of using traditional construction is that the building is greatly weakened when a powerful earthquake hits, posing a danger to lives as well. With traditional constructions, substantial damage is likely to occur with large residual lateral displacements and wide residual cracks; thus, the cost and effects of damage during an earthquake may be significant to the occupant of the building (Holden et al. 2003). The use of post-tensioned (PT) tendons proves to be an efficient solution to resolve the shortcomings of conventional RC shear wall during an earthquake such as flexural and shear cracks, toe crushing, and

rebar failure because of their superior self-centering potential and higher energy dissipation capacity (Shatnawi et al. 2018).

Incorporating post-tensioned shear wall in a structure system is an efficient way to increase lateral resistance with minimal recovery and downtime costs (Taori et al. 2020). The behavior under lateral load of unbonded post-tensioned shear wall demonstrates that the use PT tendons provides a large and stable hysteresis loop, which accounts for good inelastic energy dissipation without loss of self-centering behavior (Perez et al. 1998). The findings of the study conducted (Erkmen et al. 2009) show that self-centering behaviour can be achieved even when the PT forces fully dies out by proper design of the end anchorages of PT tendons (Erkmen et al. 2009).

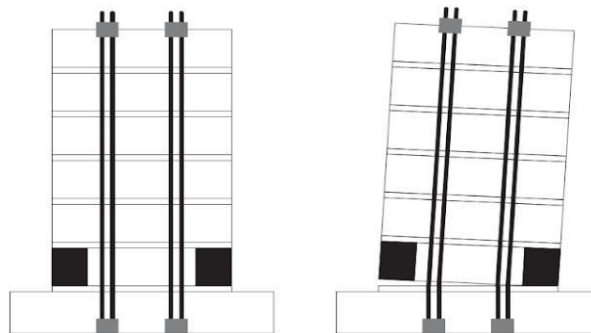


Fig 1. Schematic representation of self-centering PT shear walls (Gu A et al. 2019)

As the name implies, this system of shear wall uses post-tensioned tendons with desirable seismic characteristics, including self-centering capacity and resistance to significant nonlinear damages (Zareian et al. 2020). Recent researches and studies have shown that post-tensioned concrete shear walls have attractive features such as improved seismic load resistance, permanent deformation reduction, re-centering potential and higher dissipation of energy. The use of PT shear walls incorporates the benefit of the post-tensioned steel bars with self-centering ability in reinforced concrete shear wall. A schematic representation of PT shear wall is shown in Fig 1. Here, unbonded PT tendons are used to be vertically linked to the horizontal joints and supporting reinforcing stirrups are used to confine concrete at the wall toes. Unbonded PT tendons are able to give sufficient lateral resistance by the restoring force provided by PT steel bars which results in higher self-centering capacity upon unloading thus eliminating residual deformation after seismic activity (Meeval Bibin et al. 2019).

The advantage of using unbonded PT tendons is that unbounding allows the shear wall to undergo significant non-linear displacements without yielding of PT steel bars (Shatnawi et al. 2018). The residual storey drift amplitude is a critical factor as it leads to the economic loss of buildings after an earthquake. In order to find the efficacy of post-tensioned shear walls, several studies have been conducted. It has been found that incorporation of PT shear walls in a building is an optimal way of enhancing lateral resistance with minimal costs of regeneration and downtime. Priestley and Tao (Priestley et al. 1993)

first proposed the concept of using unbonded post-tensioned (PT) tendons in precast RC frame structures to provide the primary lateral force resistance to eliminate residual drift of traditional structural frameworks after earthquakes. Using unbonded PT tendons, (Kurama et al. 2004) proposed the concept of a self-centering shear wall and formulated the corresponding design method (Kurama et al. 2004).

Advantages of PT Shear Wall

50 percent of the vertical reinforcements in the post-tensioned shear wall are replaced by an equivalent number of tensioned high-strength tendons. The inclusion of post-tensioned tendons modifies the shear wall behavior as follows (Holden et al. 2003, Shatnawi et al. 2018, Taori et al. 2020)

- Increases total strength and rigidity of the wall, resulting in improved seismic efficiency.
- Allows nonlinear displacements without yielding of PT bars.
- Decreases rebar congestion, thereby improving the performance of building.
- Reduces residual deformation.
- The walls are much more compact, tough and damage resistant.
- Reduces lateral drift with its re-centering property upon any seismic activity.
- Reduces the tensile stress transferred to the concrete.
- Excellent behaviour in terms of deflection and cracking.
- Can achieve slender shear walls and can therefore substantially achieve savings in concrete and steel.

Behaviour of Post-Tensioned Shear Wall

Self-centering behavior is one of the key characteristics of post-tensioned shear wall. It is defined as a building's capacity to return to its original position after the external non-linear load has been removed. PT shear wall is governed by the opening of gaps along horizontal connection starting from the connection between the wall and foundation and proceeding upward to the connections between wall panels (Kurama et al. 1999). The self-centering potential of PT shear walls is attributed due to the post-tensioning force, which results in reduced residual deformation during an intensive earthquake (Shatnawi et al. 2018). It also relies on many other factors, such as the detail of the tendon end-anchorage, initial degree of tendon tension, tendon.

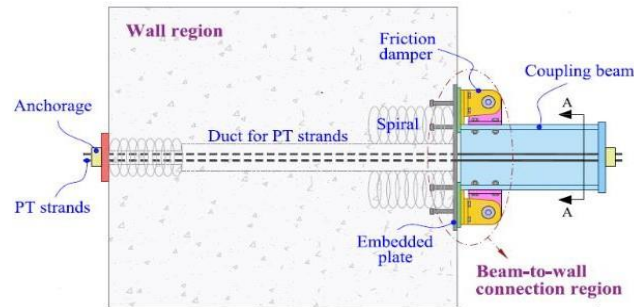


Fig 2. Subassembly equipped with friction dampers (Zareian et al. 2020)

layout and external axial load magnitude (Erkmen et al. 2009). Many researchers have been drawn to the use of PT tendons in shear walls and numerous experimental and analytical studies have been carried out to explore the behavior of post-tensioned shear wall under seismic activity.

Experimental Studies on Post-Tensioned Shear Walls

Conducted an analysis (Zareian et al. 2020) on post-tensioned hybrid coupled wall assemblies in which friction dampers were used at the beam-to-wall link area for energy dissipation as shown in Fig 2. Previous studies on PT coupled shear wall with steel angles demonstrated low stiffness and high yielding displacement, thereby restricting the potential of energy dissipation. Instead of steel angles, he used friction dampers to solve this issue and measured the behavior of friction dampers and their effect on the performance of hybrid coupled wall system. In addition, instead of concrete beam, steel coupling beam is proposed to mitigate the damage and to sustain self-centering capability. The hybrid specimen with frictional dampers were tested under quasi-static reverse-cyclic load and the results of the subassembly with steel angles were contrasted. It was noted that a flag-shaped hysteresis loop was created by subassembly fitted with frictional dampers produced and could be re-tested after test completion. It was observed that a residual drift greater than 0.5 % was beyond the acceptable range for all specimens with a damper moment ratio less than unity. For the specimen with damper moment ratio equals unity, the residual drift is considerable and it is advisable to use damper moment ratio less than unity in order to achieve beneficial self-centering ability. The study suggests that the use of post-tensioned coupled shear wall system without energy dissipation devices in seismic areas is not advisable.

To enhance the energy dissipation of post-tensioned shear walls, Gu et al. incorporated unbonded mild steel reinforcements and studied the behavior under cyclic loading tests. The findings of the test showed that while the hysteresis curve of self-centering hybrid shear wall with unbonded tendons (SW2) is not an ideally flag-shaped due to variation of gravity load during test, SW2 demonstrated improved self-centering ability and better deformation ability than conventional precast shear wall (SW1). SW1 experienced sliding effect during test and dissipated energy through formation of plastic hinges. Cracks

were formed at the base of the wall for specimen SW1. SW1 started to degrade at a drift of 1.6 %. For specimen SW2, rocking was observed around wall-foundation and PT tendons reached their yield stress at a drift of 2.4% (Gu A et al. 2019). The mode of failure in SW2 was by yielding of the strands as shown in Fig 3. This significance of PT shear wall system is illustrated in this study. It has been obvious from the conduct of parametric studies that wall aspect ratio, initial stress and area of PT tendon have a significant influence on post-effective stiffness. It should be remembered that the effective way of optimizing energy dissipation is to increase mild steel area and to limit the initial tension in PT tendons. PT shear walls suffered little damage during seismic activity, and damage happened in the form of spalling of concrete and crack formation.



Fig 3. Final damage state of SW2 (Gu et al.2019)

An attempt is made (Gu et al. 2019) to evaluate the residual drift capacity as it is a crucial problem associated after a seismic activity. Residual drift results indicate that SW2 experiences a small residual drift at peak displacements. The residual drift in SW1 was found to increase as the lateral displacements rose and reached a maximum value of 0.9%. With the increase of lateral displacements, the residual drift of SW2 does not change vastly. The results of cyclic loading test indicate that SW1 acted as a precast shear wall with an observed sliding effect induced by connections of grouted sleeves (Gu et al.2019). SW2 had a greater potential and displayed a better deformation ability and self-centering ability. An experimental study has been carried out (Zhu et al. 2014) on emulative hybrid precast concrete shear walls under reversed cyclic lateral loading. Grouted vertical reinforcements with unbonded high strength PT tendons is combined in the emulative hybrid shear wall and three different post-tensioned forces of 296.8 kN, 378 kN and 501.2 kN were established in the tendons and is the main variable considered in this experiment. During the test, the PT tendon remained elastic and the yielding of the binding reinforcements was delayed. In contrast to monolithic RC shear wall, PT walls were capable of achieving energy dissipation and retained high stiffness during the test compared. The results of the study indicate that increasing the PT forces can increase anti-crack capacity, initial stiffness and self-centering, but can decrease the capacity of energy dissipation and to some degree decrease the ductility capacity.

To comprehend the inter-storey shear response of a self-centering precast RC shear wall with unbonded post-tensioned tendons and mild steel reinforcements for flexural resistance across the base joint, Lu et al. conducted a shake table test on a 1/3-scale model of a five-story self-centering RC frame with shear walls under a sequence of earthquake excitations of rising severity. The hysteretic response of the test specimen between the base shear forces and roof displacement shows that, due to increasing lateral displacement, the area inside the hysteretic curves became gradually increased, showing an acceptable capacity for energy dissipation. Energy dissipation was achieved because of yielding of the energy- dissipating bars. The test results indicate that self-centering RC frame with shear walls has excellent seismic efficiency and the distribution of inter-story drifts was uniform with an overall inter-story drift ratio of 2.45%. It was also found that after the earthquake excitations, the sample re-centered with negligible residual drifts depicting its ability to be used in RC frames to minimize potential socio- economic damage after earthquakes.

Analytical Studies on Post-Tensioned Shear Walls

A parametric analysis on hybrid concrete shear wall combined with PT tendons was carried out to (Shatnawi et al. 2018) to analyze the lateral load response under cyclic loading. This study explores five prototype concrete shear walls. Wall PTWI represents purely unbonded PT shear wall, wall RCWI is ordinary reinforced concrete wall, and HWI, HWII, and HWIII are hybrid PT shear wall with a constant number of tendons but different values of the post-tensioning steel area (A_p) and mild steel area (A_s). HWI, HWII, and HWIII represent hybrid PT shear walls with varying A_p/A_s ratio – that are 0.3, 0.5 and 1.0 respectively. Fig 4. shows the graph of residual drift and A_p/A_s ratios and it has been found that displacement peaks reduce as A_p/A_s ratio increases. It has been found that displacement peaks reduce as A_p/A_s ratio increases. Residual drift is observed to be greatest for RCWI.

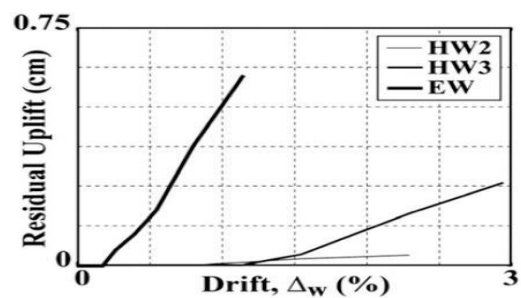
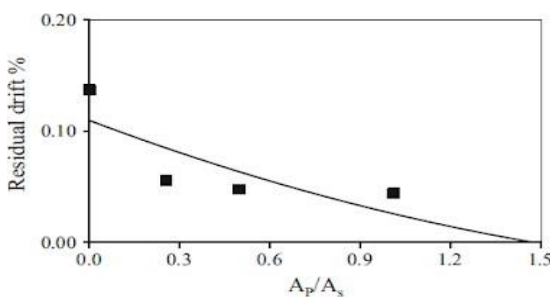


Fig 4. Residual drift v/s A_p/A_s ratio [2] Fig 5. Comparison of residual uplift of 3 models (Smith et al. 2013)

The peak drifts for HWII and HWIII are approximately identical, but was found to be even smaller than for HWI (Shatnawi et al. 2018). Peak displacement is found to be

minimum for PTWI whose A_p/A_s was infinity. This is because in PTWI, large restoring force is provided by the PT tendons that lets the shear wall swing back to its original position. The results from this study illustrates that increasing the A_p/A_s ratios in hybrid shear walls and reduce the permanent damage after loading. Smith et al. studied the influence of PT tendons in wall uplift by comparing two hybrid shear walls with PT tendons and a third specimen designed to emulate monolithic cast-in-place RC shear wall. Both the hybrid walls were kept stable in geometry, the only change being in the reinforcement details. Vertical displacement at the top of the wall was measured to assess the residual vertical uplift (Smith et al. 2013). Fig 5. shows the progression of residual wall uplift in both hybrid and emulative specimens. The residual uplift starts to accumulate in Specimens HW2 and HW3 only after $\Delta_W = \pm 1.55\%$ cycles. Initiation of losses in PT stress commenced at this stage. It was observed that since specimen EW didn't incorporate PT tendons, it accumulated larger residual uplift. The EW wall uplift leads to shear-slip failure with large degradation in strength and stiffness. The hybrid walls had a comparatively smaller uplift and had no undesirable impact on the performance.

To understand the effects of tendon location (Erkmen et al. 2009) examined a self-centering post-tensioned shear walls for varying tendon positions by developing computational models. Apart from the reference specimen consisting of six identical high-tensioned tendons which was uniformly distributed, two additional models were produced to research the influence of tendon location. For the first model, two outermost tendons were removed from both sides and the area of the remaining two tendons were tripled. For the second model, four tendons nearest to the middle of the wall were removed, tripling the area of the two outermost tendons. For both the models, the lateral load drift results indicated that the effective stiffness and energy absorption capacities of "centered tendon" were smaller compared to "edge tendon" and even reference specimen. This discrepancy was due to tendon arm reduction, which reduces the change in tendon strain per unit of gap opening. The response of the walls, however, shows that shifting the tendons towards the middle or the edge of the wall does not affect the wall's self-centering behaviour.

In an attempt to overcome the limitations of energy dissipation in conventional post-tensioned shear walls, Taori et al. studied the response of post tensioned hybrid shear walls with external energy dissipating reinforcement (EEDR) in the form of mild steel bars and compared its performance with an internally placed EEDR under seismic actions. Three specimens were analyzed numerically – (i) PT wall with external EDR (PTWE), (ii) PT wall with internal EDR (PTWI), and (iii) PT wall without EDR (PTW), were carried out. The comparison of the behavior of three models shows that in the presence of EDR in the PT shear walls, the energy dissipation is increased drastically (Taori et al. 2020). The energy dissipation is observed to be higher in PTWE than that of PTWI. At a design drift of 0.38%, the energy dissipation was twice in PTWE compared PTWI. From the graph, it has been

found that the overall energy dissipation was about 21% higher in PTWE as compared to PTWI at a drift of 1.04%. By positioning the EDR externally, the residual drifts have also been observed to be minimized. PTWE has the additional advantage of simple and easy placement and replacement. In terms of overall performance, the analysis indicates that the PTWE model is a favored model considering cost of rehabilitation post- earthquake as well.

To further analyze the effect of post-tensioned forces (Zhu et al. 2016) studied the stiffness degradation of three hybrids precast shear wall with different post-tensioned forces and one reference RC shear wall by numerical computational model in ABAQUS. The post-tensioned force considered for the samples were 296.8 kN, 378 kN and 501.2 kN respectively. The findings reveal that, relative to the conventional shear wall, all the three-hybrid specimen retained higher stiffness throughout the test. Moreover, when loaded into the inelastic range, the specimen with the largest post-tensioning force had higher initial stiffness and otherwise degraded fastest. With regard to displacement ductility, the average displacement ductility factor was observed to decrease by 14.4% indicating the negative affect of increasing post-tensioning force on the displacement ductility.

Area to be Addressed

The use of various tendon profiles and the interaction of unbonded PT walls with other building components needs a thorough study. The influence of unbonded PT shear walls in a building as a whole can be further analysed. The behavior of hybrid shears walls when coupled together has been least explored. The efficacy of various dampers when incorporated into coupled hybrid shear wall and effect of openings is a possible option for possible studies. The potential of partial replacement of concrete with sustainable materials and the effect of PT tendons can be considered as a possible study in this area.

CONCLUSIONS

Recent researches and studies indicate that post-tensioned reinforced concrete shear walls have superior features to withstand lateral loads followed by earthquake-related seismic forces. In this era, prior importance is assigned to building constructions to mitigate structural damage and the risk resulting from seismic activities. From the conduction of literature survey on post-tensioned shear wall, it has been noted that shear walls with PT tendons has the potential to minimise the structural damage along with improved safety. Increase in strength and stiffness in shear walls by incorporating PT tendons is found to be an effective way to increase the structures resilience toward permanent damage.

The conclusive outcomes drawn from the study are enlisted below:

- There are various benefits of integrating PT tendons into traditional shear walls, such as increased stiffness, strength, stability, damage control and reduced lateral

displacements.

- The lateral load capacity and effective stiffness are found observed to be increased in the post- tensioned shear wall system as the PT stress level increases.
- The overall reinforcement area can be reduced by using unbonded post-tensioned reinforcement and wall ductility is observed to be enhanced.
- It was noted that as the self-centering capability increases, the residual displacement decreases.
- The positioning of tendon has the least effects on the self-centering behavior of PT shear walls.
- Failure mode of hybrid shear wall with PT tendons is primarily controlled by the yielding of the PT strands.
- Increasing the post-tensioned forces can increase the initial stiffness but can negatively affect the displacement ductility and reduced energy dissipation.
- Comparing the performance of self-centering hybrid shear wall and conventional precast shear wall, the findings indicate that hybrid shear wall displayed improved deformation ability and self- centering ability.
- Absence of PT force can result in inadequate restoring, leading to excessive uplift, horizontal slip, and degradation of lateral strength and stiffness.

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