# CYCLIC PERFORMANCE OF SHAPE MEMORY ALLOY REINFORCED CONCRETE WALLS

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## ABSTRACT

Concrete walls are commonly used to resist lateral loads. Their relatively high stiffness limits the inter-story drifts and minimizes damage to other structural and non-structural elements. However, significant structural damage to the walls is expected during seismic events. This study investigates numerically the effectiveness of using Superelastic (SE) Shape Memory Alloy (SMA) bars to improve the seismic performance of moderate and squat concrete walls. The used analytical model was validated using experimental results by others. It was then utilized to investigate the cyclic load-displacement response of one-intermediate and two-squat walls while incorporating SMA bars. Results of this study led to identifying the location of SMA bars that result in best seismic performance.

**KEYWORDS:** Concrete shear walls, analytical model, SE SMA, cyclic loading, drift ratio.

## INTRODUCTION

Design codes ensure that civil structures achieve the life safety level during seismic events. However, they allow for non-structural and structural elements to be damaged. Such damage was observed during many earthquakes including the 2010 Chile earthquake [1]. Significant amount of recent research has been focusing on reducing seismic damage and achieving sustainable structures. Researchers have utilized damping deceives and/or advanced composite materials to reach this goal.

The uniqueness of superelastic SMAs lies in their ability to undergo large deformations and return to their undeformed shape through stress removal [2], Figure 1. In conventional seismic design of RC structures, reinforcing bars are expected to yield to dissipate seismic energy, resulting in permanent deformations. These deformations complicate post-earthquake retrofitting efforts. Youssef et al. [3] developed and experimentally tested beam-column joints that utilize superelastic SMAs as reinforcing bars in the plastic hinge regions. Steel bars were used at other locations to minimize the cost. Analytical models capturing the behaviour of SMA reinforced joints were

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developed by Alam et al. [4]. The performance of full-scale frames reinforced with SMAs under dynamic load was analytically investigated by Youssef and Elfeki [5]. It was concluded that utilizing SMA bars results in sustainable structures that are repairable following strong seismic events leading to significant cost savings and reduced downtime. Yamen et al. [6, 7] proposed formulations to accurately predict the flexural capacity and deformations of SMA RC members. Meshaly et al. [8] identified potential uses for SMA bars in concrete braced frames. Tazarv and Saiidi [9] tested a full scale SMA-Reinforced bridge column. The results showed that SMA bars not only reduce the residual drifts but also limit the damage in the plastic hinge of the column. Abdulridha [10] conducted a large-scale test on an intermediate wall that utilized SMA bars in the plastic hinge region. Significant recovery of deformations and increase in ductility were observed throughout the test. Effendy et al. [11] used external shape memory alloy (SMA) bars to improve the seismic performance of existing squat walls. They concluded that the use of SMA bars increased the maximum shear strength of the walls by 16% to 26%. They also observed significant reduction in the residual displacements.

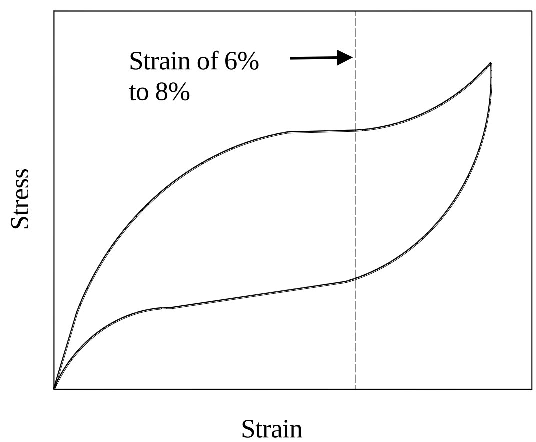
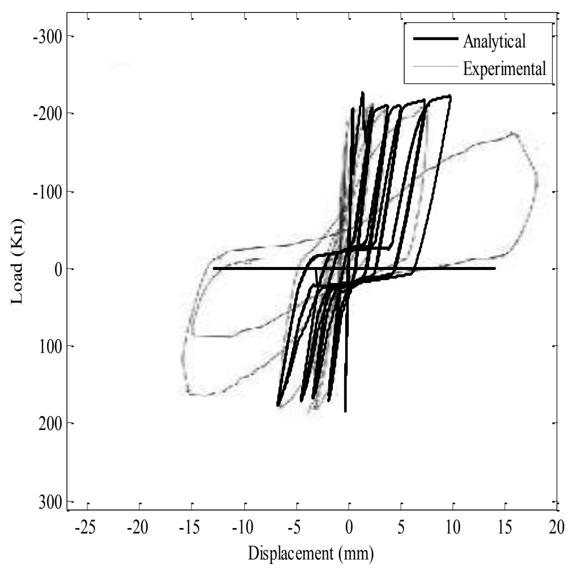



Figure 1. Typical Stress-Strain Response of SMA Reinforcement

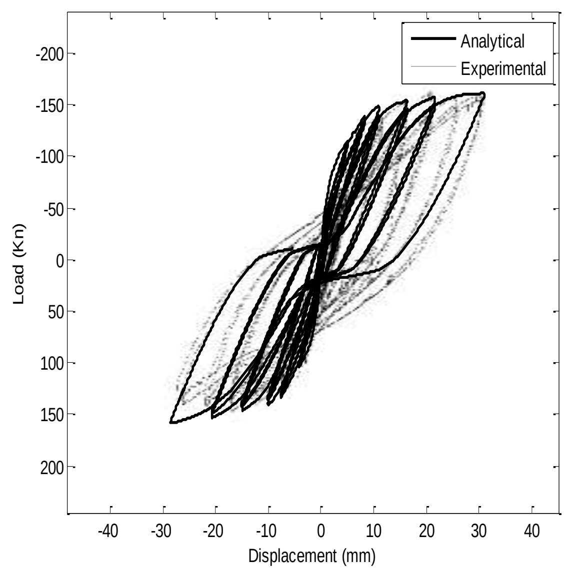
Although many experimental and analytical research examined the use of SMA bars in RC elements, research in this area is still in its infancy and specifically research addressing concrete walls. This paper investigates numerically the effect of SMA bars on the seismic performance of squat and intermediate concrete walls. The used analytical model is first presented. This is followed by a parametric study that evaluated different arrangements for SMA bars in squat and intermediate RC walls.

## ANALYTICAL MODEL

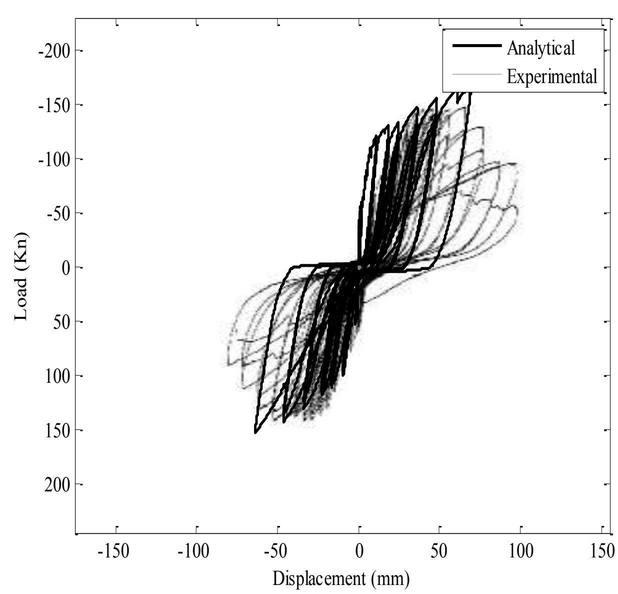
To predict the wall's behavior under lateral load, a model capable of predicting the shear-flexural interaction, the overall response, and the location of the neutral axis is required. Panagiotou et al. [12] developed and validated a truss model that utilizes nonlinear vertical, horizontal, and diagonal elements. Additional validation for this model was conducted in this paper using experimental studies by others. Figure 2 shows comparisons between the experimental results and the analytical model predictions. Figure 2a shows the comparison for a typical squat RC wall that was tested by Greifenhagen and Lestuzzi [13]. Comparisons for intermediate steel-RC and SMA-RC walls that were tested by Abdulridha [10] are shown in Figures 2b and 2c, respectively. The analytical model can clearly predict the behaviour of the walls including the maximum load capacity, residual deformations, ductility, energy dissipation, and failure mechanism (shear failure for squat wall and flexural failure for intermediate walls)




(a) Squat Wall




(b) Steel RC Intermediate Wall




(c) SMA RC Intermediate Wall

Figure 2. Analytical Model Validation

## PARAMETERIC STUDY

Two-squat concrete walls and one-intermediate wall were selected for this study. Dimensions of the walls are shown in Figure 3. The corresponding aspect ratios are 0.6, 0.9 and 2.2. Gravity loads were varied from 2.6% to 10.0% of $(f_c' A_g)$. All walls were subjected to reversed displacement cyclic loading. The concrete compressive strength and steel yielding stress were assumed 32 MPa and 425 MPa, respectively.

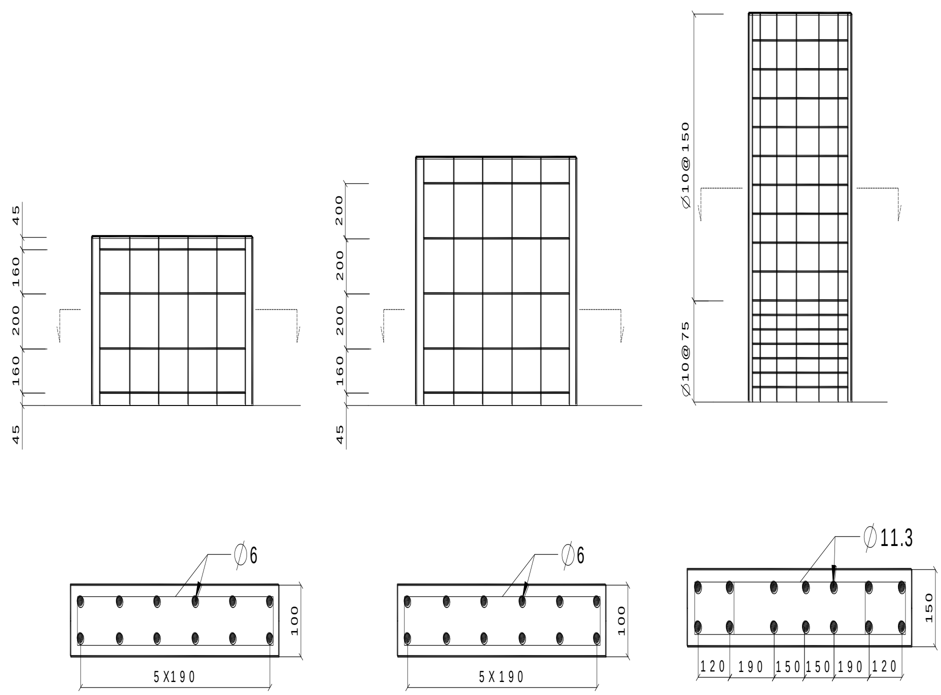



Figure 3. Reinforcement Details for Squat and Intermediate Walls (Dimensions in mm)

## SQUAT SHEAR WALLS

Four arrangements of reinforcing bars were analyzed in this section: SW1 (conventional steel RC wall), SW2 (all longitudinal steel bars were replaced with SMA bars), SW3 (SMA bars with a length of 1/3 of the wall height were used at the plastic hinge location of the wall) and SW4 (four SMA bars replaced the steel bars located at the corners of the walls).

A typical load-displacement curve for the studied squat walls is shown in Figure 4. All walls had similar performance and failed in shear when axial load ratio <5.0%. The final residual and failure drifts were recorded for each of the studied cases.

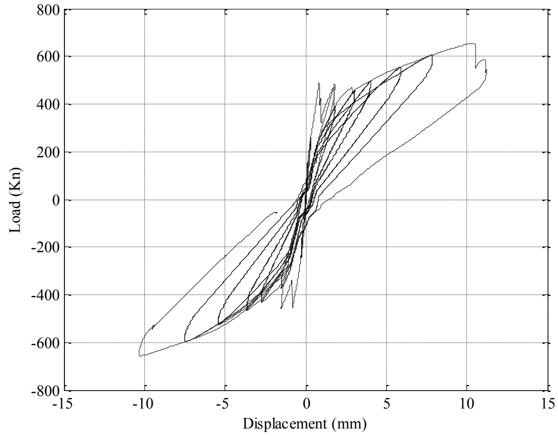
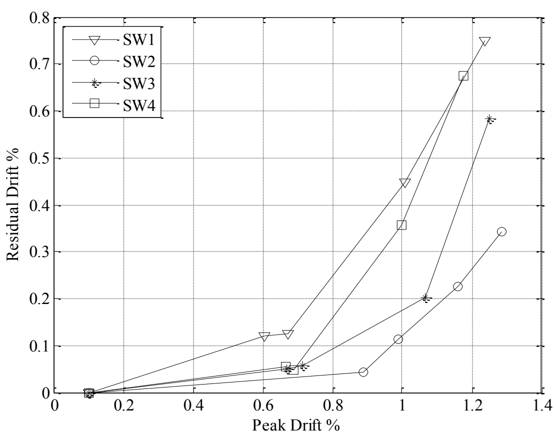
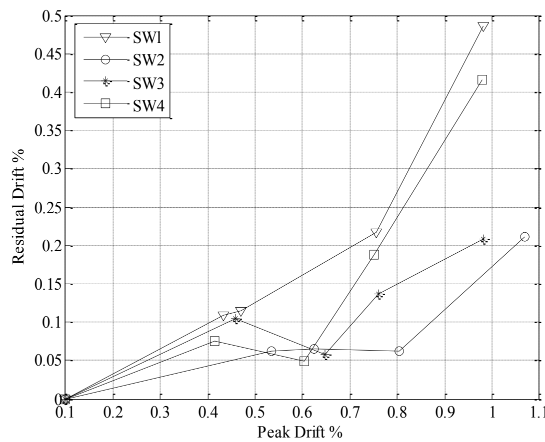



Figure 4. Cyclic Response of SW2 at Axial Load Ratio of 5%

Figures 5a and 5b show the peak drift versus the residual drift for aspect ratios of 0.6 and 0.9, respectively. Each point on each curve represents a unique axial load ratio. For aspect ratio of 0.6 and peak drifts less than 0.7%, the residual drift of SW2, SW3, and SW4 were lower than SW1 by 34%, 18%, and 18%, respectively. For drifts >0.7%, the reduction in residual drifts were 73%, 60%, and 21% for SW2, SW3, and SW4, respectively. Increasing the wall aspect ratio from 0.6 to 0.9, the reduction changed to 65%, 57%, and 15% for SW2, SW3, and SW4, respectively.



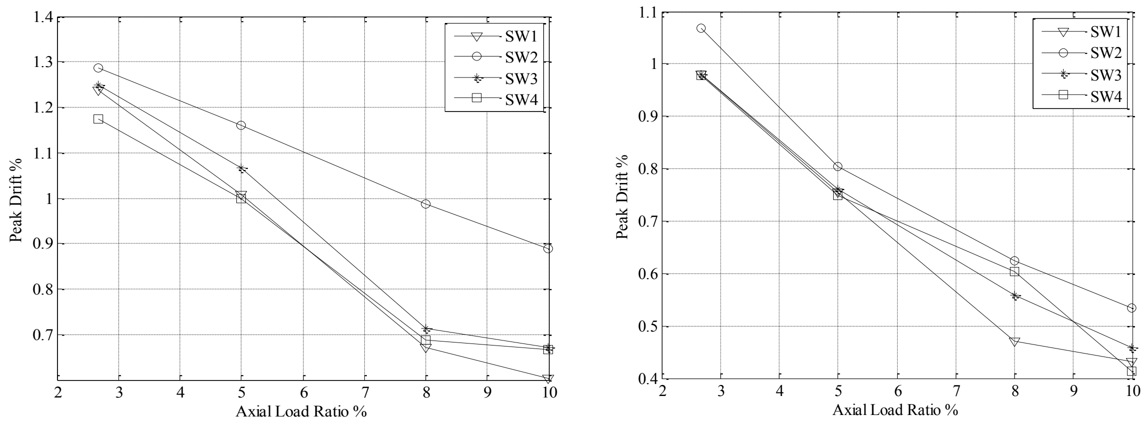

(a) Aspect Ratio of 0.6




(b) Aspect Ratio of 0.9

Figure 5. Squat Wall Peak Drift versus Residual Drift at Different Axial Load Ratio

Figures 6a and 6b show the relationship between the peak drift and the axial load ratio. Replacing all the longitudinal steel bars with SMA bars (SW2) increased the peak drift by 22% as compared to SW1. Increasing the axial load ratio from 2.6% to 10.0% for SW4 (aspect ratio of 0.6) had no effect on the peak drift. Increasing the wall aspect ratio from 0.6 to 0.9 reduced the peak drift ratio by 50% and 53% for SW2 and SW3, respectively. Increasing the axial load ratio from 2.6% to 5% transformed the dominate failure mode from shear to flexure.




(a) Aspect Ratio of 0.6 (b) Aspect Ratio of 0.9

Figure 6. Squat Wall Peak Drift versus Axial Load Ratio

## INTERMEDIATE SHEAR WALL

The study covers using of SMA bars in the wall's plastic hinge region (IW2) and the wall's boundary (IW3). The results are compared with a conventional wall (IW1).

Figure 7 illustrates the cyclic response of IW2 and Figure 8a shows the peak drift versus axial load ratio. SMA bars increased the peak drift by 110% and 93% for IW2 and IW3, respectively. Increasing the axial load ratio from 2.6% to 10.0% reduced the drifts by 26% and 47% for IW2 and IW3, respectively. The corresponding reduction for IW1 was 52%.

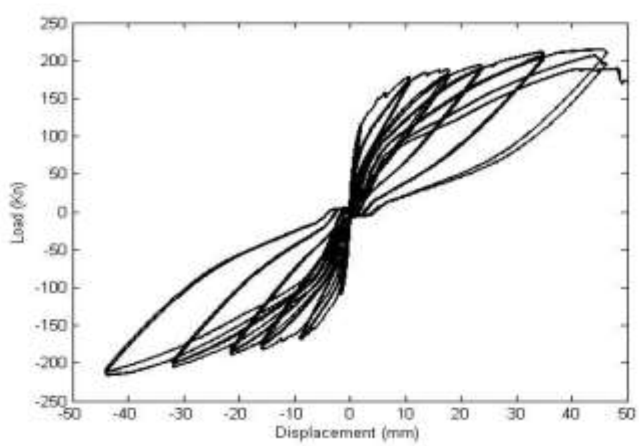
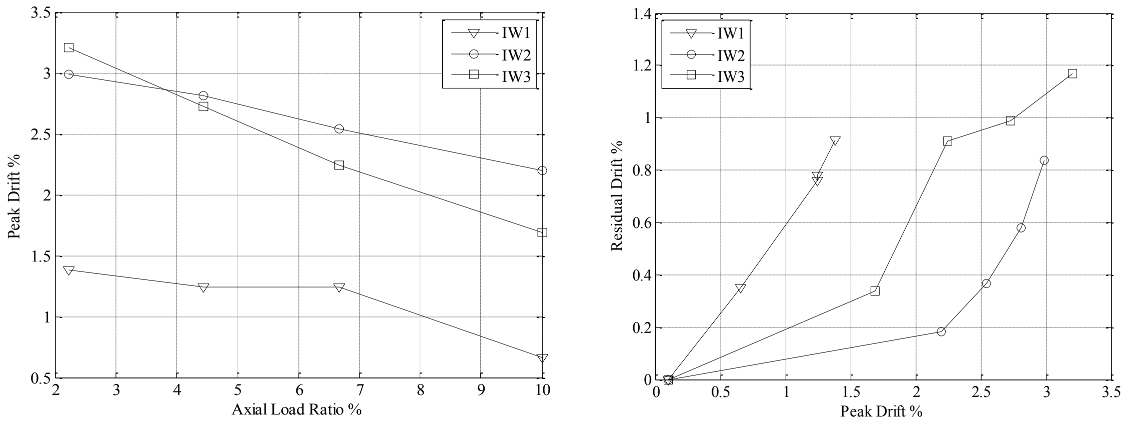



Figure 7. Cyclic Response of IW3 at Axial Load Ratio of 5%

Figure 8b shows the residual drift ratio versus the peak drift ratio. Each point on each curve represents a unique axial load ratio. For peak drifts, less than 1.4%, placing the SMA bars in the boundary or the plastic hinge region reduced the residual drift by 85% and 94%, respectively.




(a) Peak Drift versus Axial Load Ratio

(b) Peak Drift versus Residual Drift at Different Axial Load Ratio

Figure 8. Intermediate Wall Results

## CONCLUSIONS

This paper investigated the preferred location for SMA bars in squat and intermediate concrete walls to achieve minimum seismic residual drifts. The associated increase in inter-story drifts will increase the demand for other structural and non-structural elements and need to be further investigated.

For low-rise concrete walls, the preferred location of SMA bars is over the full wall height while for intermediate walls, the preferred location for SMA bars is in plastic hinge region.

1- For squat walls with low aspect ratios, using SMA bars at the wall boundary does not change the wall behaviour. The effect of using SMA bars in the plastic hinge zone becomes noticeable for aspect ratio of 0.9.
2- 50% lower residual drifts are expected for intermediate walls when SMA bars are used in the plastic hinge region.
3- SMA bars allowed recovery of 85% and 94% of intermediate wall’s drift when SMA bars are utilized in the boundary and plastic hinge region, respectively.
4- For squat walls, the recovery of wall’s drifts were 60% and 70% when SMA bars were used in the plastic hinge and over the wall full height, respectively.
5- Increasing the axial load ratio for squat walls transformed the dominate failure mode from shear to flexure.

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