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HYBRID SHAPE MEMORY ALLOY AND STEEL REINFORCEMENT FOR EARTHQUAKE RESISTANT CONCRETE SHEAR WALLS

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ABSTRACT

This research examines the use of SMA reinforcement to enhance the seismic resilience of reinforced concrete shear walls. The efficacy of SMA reinforcement is assessed based on strength, ductility, energy absorption, stiffness, and minimisation of residual deformation. The outcomes and discoveries of this research suggest that utilising a blend of SMA and traditional steel rebars can yield a financially efficient design that markedly diminishes residual deformation and improves the seismic resilience of these structural systems.

Keywords: Reinforced concrete, Steel, Seismic, Walls, Earthquake.

I. INTRODUCTION

Reinforced concrete (RC) shear walls represent a highly efficient structural solution for counteracting lateral forces generated by seismic activity, wind, and other dynamic influences in mid- to high-rise edifices. Their elevated rigidity, durability, and capacity to manage lateral distortion render them a crucial element of contemporary seismic-resistant edifices. In the event of a powerful earthquake, reinforced concrete shear walls are anticipated to experience considerable cyclic lateral distortions while preserving sufficient strength and stability. Nonetheless, traditional reinforced concrete shear walls may suffer from significant cracking, concrete failure, reinforcement giving, and lasting deformations when exposed to high seismic forces. These deterioration processes may greatly compromise the structural soundness of edifices and may need expensive repairs or, in severe instances, destruction. Consequently, the advancement of novel reinforcing and retrofit methodologies that enhance the seismic performance, energy absorption, and post-earthquake operability of reinforced concrete shear walls has emerged as a significant focus in structural engineering research. Conventional seismic design methodologies often depend on the development of plastic hinges and the yielding of standard steel reinforcing to absorb seismic energy. While this ductile design approach can avert abrupt structural failure, it may also lead to significant permanent deformation and substantial impairment of structural elements. Residual drift poses significant challenges since it may undermine the use and operational capacity of structures post-earthquake, notwithstanding the structure's stability. Moreover, traditional steel reinforcement is prone to corrosion, potentially diminishing durability and long-term structural efficacy. These constraints have prompted scholars to explore sophisticated materials and intelligent structural systems that may provide improved strength, ductility, energy absorption, and self-centering properties. Shape Memory Alloys (SMAs) have surfaced as advantageous materials for enhancing the seismic resilience of structural systems. Shape Memory Alloys (SMAs) are distinguished by their remarkable capacity to experience significant inelastic deformations and later revert to their initial form under certain thermal or mechanical stimuli. Nickel-titanium (NiTi) alloys have garnered significant interest among various shape memory alloy (SMA) materials because to their remarkable superelastic properties, substantial recoverable strain potential, resistance to corrosion, and consistent cyclic performance. The extraordinary elastic characteristics of SMA reinforcement enable structural components to experience significant deformation during seismic events while minimising lasting residual deformation after the seismic forces are alleviated. This self-aligning behaviour is especially beneficial for reinforced concrete shear walls, since managing drift and averting significant residual displacement are essential for preserving functioning after an earthquake.

The integration of SMA reinforcement into reinforced concrete shear walls may provide several benefits compared to traditional steel reinforcement. SMA bars or wires may be judiciously positioned in essential areas of the wall, especially next to boundary elements and plastic hinge zones, where significant tensile stresses and cyclic deformations are anticipated. Under earthquake stress, the SMA reinforcement may experience reversible phase changes, enabling the wall to release energy while concurrently facilitating self-centering. The integration of traditional steel reinforcement with SMA elements may provide a hybrid structural framework that harmonises strength, ductility, energy absorption, and deformation recovery. These solutions possess the capability to diminish damage concentration, curtail residual drift, and enhance the robustness of structures exposed to recurrent seismic occurrences. Notwithstanding the advantageous traits of SMA-reinforced structural systems, several obstacles persist in their practical implementation in RC shear walls. These include the comparatively elevated expense of SMA materials, bonding and anchoring stipulations, the interplay between SMA and traditional reinforcement, thermal sensitivity, and the need to refine the placement and amount of SMA reinforcement. Furthermore, the intricate nonlinear response of SMA-reinforced RC shear walls subjected to cyclic pressure necessitates thorough experimental and computational analysis. Consequently, it is important to examine the impact of SMA reinforcement on critical seismic performance metrics such as load-bearing capacity, stiffness deterioration, ductility, energy absorption, hysteretic behaviour, crack formation, and residual deformation. The examination of SMA reinforcement for RC shear walls signifies a crucial advancement in creating more robust, damage-tolerant, and sustainable structural systems that can preserve functionality and enable swift recovery after substantial seismic occurrences.

II. REVIEW OF LITERATURE

Ningthoucha, Yumnam & Ningthoukhongjam, S.S.. (2022) This research uses non-linear static (pushover) analysis to examine how shear wall geometry affects seismic response of nine-storey moment resistant RC frames. The moment resisting RC frame is rectangular and has shear walls along the building's least lateral dimension. The study employed S, B, C, H, and E shear wall forms. SAP2000 FEM software was used to model the building frame and shear walls, and pushover curves (performance point, storey drift, top displacement, and base shear) were measured to determine seismic responses. The building frame performed best with S-shaped shear walls.

Hossain, Sadman & Bagchi, Ashutosh. (2021) This article examines the seismic performance of reinforced concrete shear wall structures utilising the National Building Code of Canada's seismic design standards and wall shear strength. We evaluated four-, six-, and eight-story structures with basic configurations and varying heights. Static and linear dynamic analyses show design robustness, but dynamic time history analysis shows plastic hinge region shear capacity deficiency. A dynamic amplification factor for shear on flexural walls controls shear demand. Here, a simple approach is presented to assess amplified shear demand and cheaply increase structural wall shear resistance to prevent unintentional shear failure.

Afzali, Anoushiravan et al., (2017) Skyscraper development is rising due to population increase and municipal expansion constraints. Thus, seismic behaviour of these structures must be examined. A recent research found that earthquake frequency content parameter strongly impacts building seismic resistance. This study studied frequency content's direct effects on high-rises. Thus, six Reinforced Concrete (RC) central core 10, 15, 20, 25, 30, and 35-story buildings were built in OpenSees and evaluated for seismic behaviour under various seismic frequencies. This study used non-linear dynamic Time-History to examine building drift, shear force, and maximum displacement. Time-History study found low-frequency content recordings affect structures more. Drift and displacement responses were mostly for low-frequency material in 10- and 15-story buildings. Story shear force increased with building height, although low-frequency contents had the most.

Ghassemieh, Mehdi et al., (2012) Recent civil engineering applications for smart materials are diverse. These materials include shape memory alloy (SMA), which has superelasticity and shape memory effect. These qualities have led to SMA research in civil structure control. This paper examines how SMA reinforcements improve shear wall behaviour, particularly under seismic excitations. ABAQUS modelled two reference structures, conventional and linked shear walls. Vertical SMA reinforcing bars were suggested to be used like conventional steel reinforcements across the structure's height and in every linked shear wall system connecting beam to improve seismic response. The program implemented the one-dimensional superelastic SMA material model using FORTRAN code. Under El-centro and Koyna records, time history analysis examined the dynamic response of shear walls to seismic loads. The residual displacement for ordinary and coupled shear walls was significantly reduced by using superelastic SMA material instead of steel bars. Additionally, SMA reinforcements might drastically reduce the linked shear wall system's maximum deflection.

III. EXPERIMENTAL SETUP

This research examines the performance of two varieties of concrete shear walls, namely single and linked, using varying quantities of additional shape memory alloys with conventional steel reinforcement. The models representing individual shear walls were 5.0 meters in width, 15 meters in height, and 0.3 meters in thickness. Furthermore, the models in the subsequent scenario comprised two shear walls linked by coupling beams measuring 2.4 m in length and 0.6 m in depth. ABAQUS was used for the finite element modelling and analysis of the shear walls. The models for single and linked shear walls are shown in Figures 1 and 2, correspondingly.

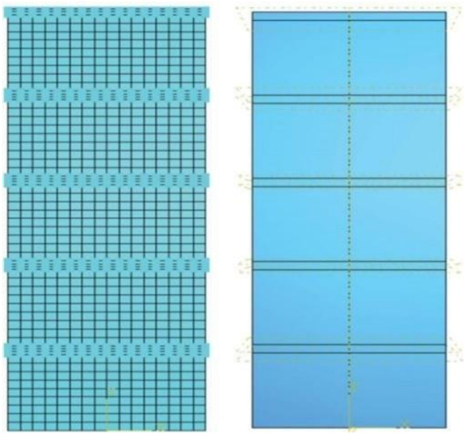

Figure 1: Finite element model of the ordinary shear wall without openings

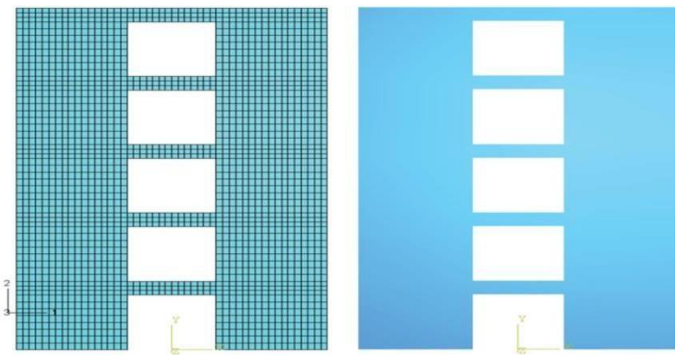

Figure 2: Finite element model of the coupled shear wall

The Concrete Damage Plasticity model, created by Lee and Fenves, was used across all models to accurately represent the deteriorated behaviour of concrete walls. The compressive strength was recorded at 35 MPa, with a specific weight of 25 kN/m³ and a Poisson's ratio of 0.2. The mechanical characteristics of the ASTM A615M steel used for the rebars are included in Table 1. To depict the story's inertial forces, a collection of discrete masses was positioned at the story-level nodes.

Table 1: Adopted ASTM A615M steel for rebars

Mechanical properties	**Grade 420**	**Grade 520**
Tensile strength (MPa)	620	690
Yield strength (MPa)	420	520

Before conducting the time history analysis, a modal analysis was executed on both models to enhance the comprehension of the shear walls' dynamic behaviour. Figures 3 and 4 illustrate the mode forms together with their corresponding periods derived from the modal analysis of the individual and interconnected shear walls, respectively. The out-of-plane degree of freedom of the walls was limited to confine any damaging movements to stay in-plane.

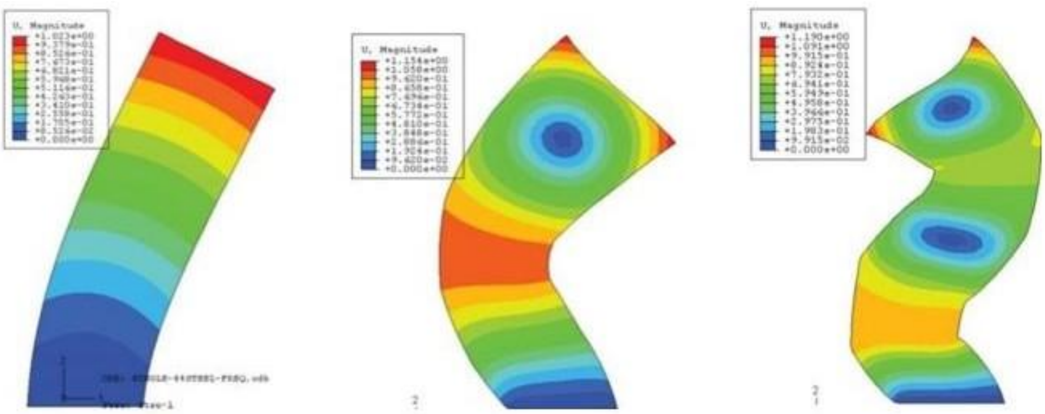

Fig. 3. Single shear wall mode shapes: (a) 1st (0.726 s), (b) 2nd (0.157 s), and (c) 3rd (0.073 s).

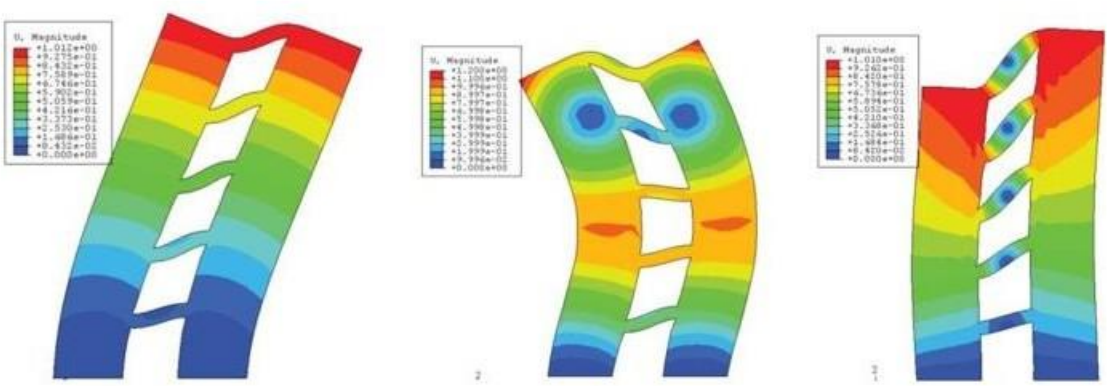

Fig. 4. Coupled shear wall mode shapes: (a) 1st (0.828 s), (b) 2nd (0.202 s), and (c) 3rd (0.131 s).

IV. RESULTS AND DISCUSSION

Employing the implemented user-defined material subroutine, the aforementioned two sets of models were examined to assess their responses to seismic stimuli and severe dynamic loads. The aim was to assess the efficacy of using SMA rebars in concrete shear walls. This was achieved by evaluating time history analysis data of the structures exposed to seismic accelerations in the computational models. Two seismic acceleration records, namely El Centro 1940 at 180 degrees NS and Koyna 1967 at 270 degrees NS, were chosen to evaluate the seismic resilience of these buildings. Displacements across all levels were selected as evaluation criteria to assess the efficacy of SMA rebars with varying reinforcement ratios alongside traditional reinforcements. The outcomes were then contrasted with those of traditional concrete shear walls without any SMA reinforcement. Figures 5 and 6 illustrate the contrasts in the reactions of shear walls reinforced just with steel rebars and those with shape memory alloys during the two examined seismic events.

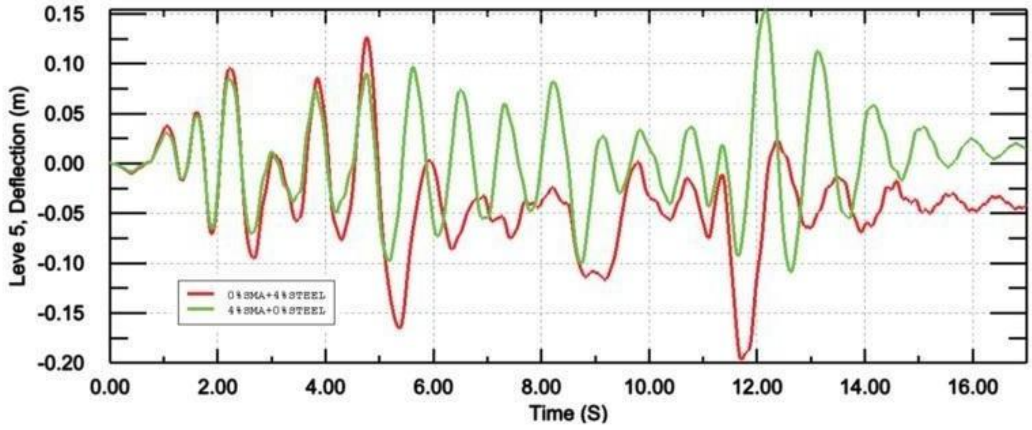

Figure 5. Shear wall deflections for the two reinforcements under El Centro earthquake

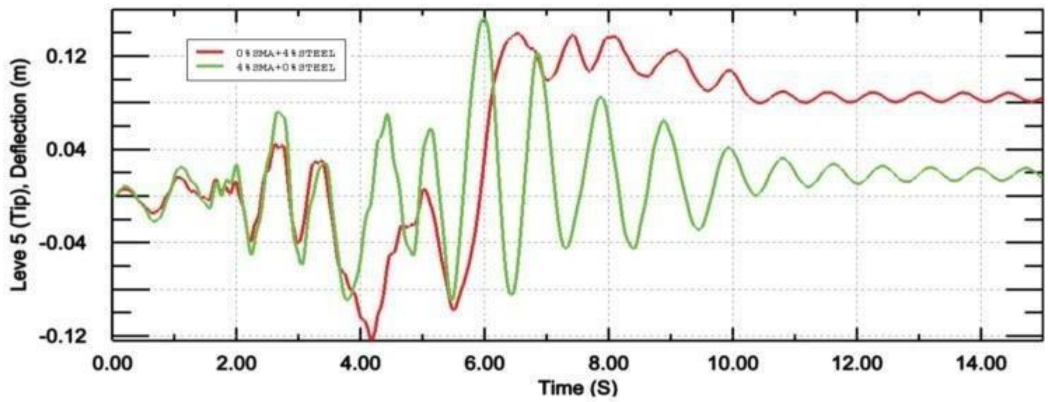

Figure 6. Shear wall deflections for the two reinforcements under Koyna earthquake

The data indicates that the use of SMA material exhibiting superelastic properties may significantly reduce the residual displacement after seismic events. The findings indicate that under the scenario of a traditionally reinforced shear wall, the remaining displacements were around 5 cm for the El Centro earthquake and 8 cm for the Koyna earthquake. Conversely, the SMA reinforced shear walls had permanent displacements of just 2 cm during the two seismic events. This suggests that the incorporation of SMAs results in a 60% and 75% decrease in residual displacements caused by the two earthquakes, respectively, despite no variations seen in maximum displacements.

Single Shear Walls

The residual deformations of the solitary shear wall reinforced with steel or SMA, when exposed to the El Centro earthquake, are shown in Figure 7. The residual deformations of the five separate stories have evidently diminished considerably as a result of the use of SMAs.

This improvement may be ascribed to the superelastic properties of SMA, since the alloy tends to revert to its initial undeformed configuration, hence preventing the buildup of residual displacements. Conversely, the yielding of traditional steel rebars throughout each cycle may lead to the accumulation of plastic deformations, resulting in significant and irreparable residual deformation after seismic loading.

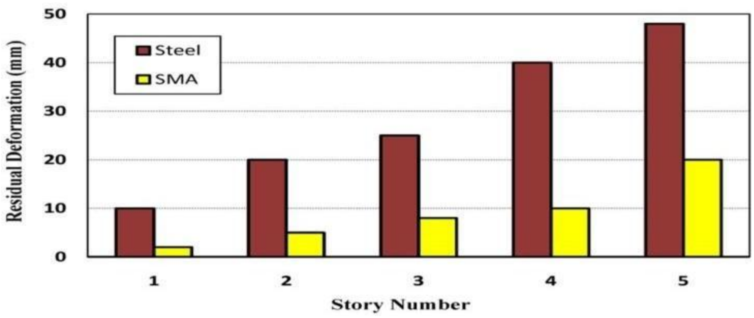

Fig. 7. Residual story deformation of the single shear wall (El Centro; steel vs. SMA).

Figure 8 illustrates the deflections of the fifth story single shear wall for two mixtures of SMAs with steel reinforcements, namely 4%SMA+2%steel and 6%SMA+2%steel, during the El Centro earthquake. An increase of two percent in SMAs, from 4% to 6%, resulted in a drop in the maximum tip displacement of the single shear wall from 140 mm to 89 mm, reflecting a 45% reduction, while the residual displacement decreased from 30 mm to 15 mm, indicating a 50% reduction.

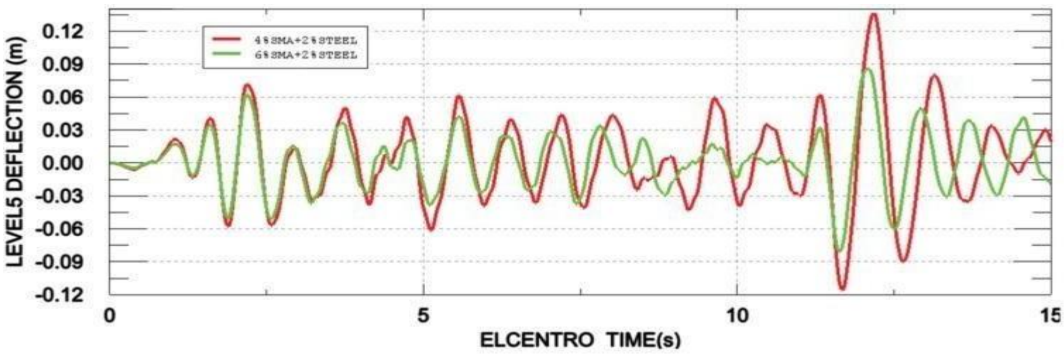

Fig. 8. Fifth-story deflection under the El Centro earthquake (SMA–steel combinations).

<u>Coupled Shear Walls</u>

The peak displacements of the coupled shear wall reinforced with steel or SMA during the Koyna earthquake are illustrated in Figure 9. The illustrated findings distinctly demonstrate that shear walls reinforced with SMA experienced markedly reduced maximum displacements.

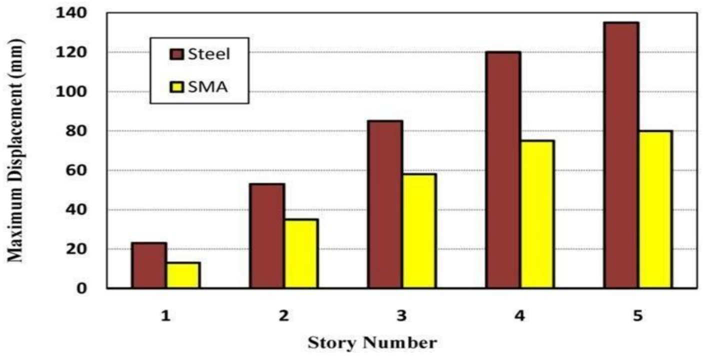

Fig. 9. Maximum displacement of the coupled shear wall (Koyna; steel vs. SMA).

In Figure 10, the deflections of the fifth-story coupled shear wall, reinforced with either SMA or steel, during the Koyna earthquake are shown. In the scenario with just steel reinforcement, the concrete wall exhibited a peak deflection of around 13 cm, but the SMA reinforced structure had a markedly decreased displacement of around 7 cm, reflecting an estimated 46% decrease in maximum displacement. Moreover, the incorporation of super elastic SMA reinforcement markedly decreased the residual displacement of the concrete wall to 1 cm, in contrast to the 6 cm seen without such reinforcement, representing an 83% decrease.

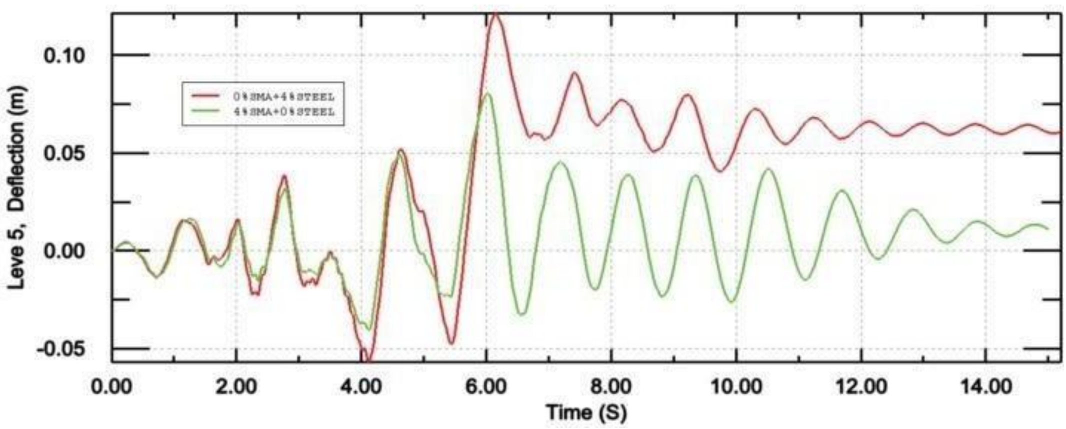

Fig. 10. Fifth-story coupled shear wall deflection (Koyna; SMA vs. steel).

Figure 11 depicts the temporal response outcomes for two scenarios of interconnected shear walls, one with a blend of 2.5% SMA and 1.5% steel reinforcement, while the other consists solely of 4% SMA reinforcement. The similarity between the two behaviours suggests that using reduced quantities of SMA reinforcement with traditional steel rebars is a more financially advantageous choice compared to the pricier SMA-only solution.

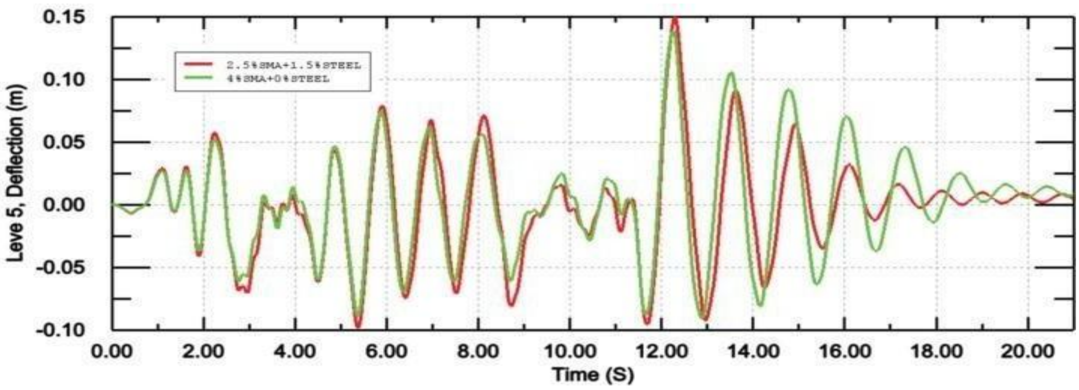

Fig. 11. Fifth-story coupled shear wall deflection (El Centro; SMA + steel vs. SMA).

V. CONCLUSION

SMA reinforcement represents a promising approach to enhance the seismic resilience of reinforced concrete shear walls. It has the potential to enhance strength, ductility, and energy absorption while minimising permanent deformation and residual displacement following seismic events. The self-aligning capability of SMA aids the structure in reverting to a location nearer its initial state after seismic stress. In general, SMA-reinforced RC shear walls may enhance the safety, durability, and post-seismic functionality of structures. Additional investigation is required to tackle financial, architectural, and practical building obstacles.

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