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SMA Reinforcement for Seismic Performance Improvement of RC Shear Walls

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Abstract

In recent years, considerable attention has been paid to the development of effective structural control devices, with particular emphasis on improving the seismic response of buildings. Shape Memory Alloy (SMA) wires have shown that their superelastic characteristics are well suited for seismic applications. This is mainly due to their recentering and energy dissipating capabilities. When buildings are subjected to earthquakes, it is vital to dissipate the input energy through predetermined and well-designed mechanisms. This study investigates the effectiveness of using SMAs as reinforcements to single and coupled concrete shear walls. To this end, ABAQUS was used to model the behavior of the shear walls, and a User Implemented Material (UMAT) was programmed in FORTRAN to represent the uniaxial superelastic behavior of the SMA reinforcement. Time-history analyses were performed to evaluate the seismic performances of the structures subjected to two earthquake ground motion records. The results and findings of this study indicate that employment of a combination of SMA and conventional steel rebars can result in a cost-effective design to significantly reduce the residual deformation and enhance the seismic performance of such structural systems.

Keywords: Concrete shear wall; SMA reinforcement; Seismic performance; Permanent damage; Energy dissipation

1. INTRODUCTION

It is common for reinforced concrete building structures to have concrete shear walls as their lateral force-resisting systems. Due to the inherent brittle nature of concrete, special measures are required to achieve ductile structural behavior in reinforced concrete buildings. Such brittle behavior has the tendency to result in structures sustaining permanent damages when subjected to seismic activity. If a mechanism were introduced to restore the initially undeformed shape of the reinforced concrete shear walls for instance, many problems regarding the permanent deformation of such vital building elements could be addressed. One effective energy dissipation approach is to introduce connecting beams in coupled shear walls, hence the name coupling beam. Coupling beams can dissipate energy and mitigate damage on shear walls by undergoing inelastic deformations. This is achieved through special detailing of reinforcement in such beams due to the limited space existing around connections. The recentering effect of Shape Memory Alloys (SMAs) can help restore such damaged structures and elements back to their undeformed shapes. One of the unique mechanical behaviors inherent to SMAs is their superelastic behavior, as depicted in Fig. 1.

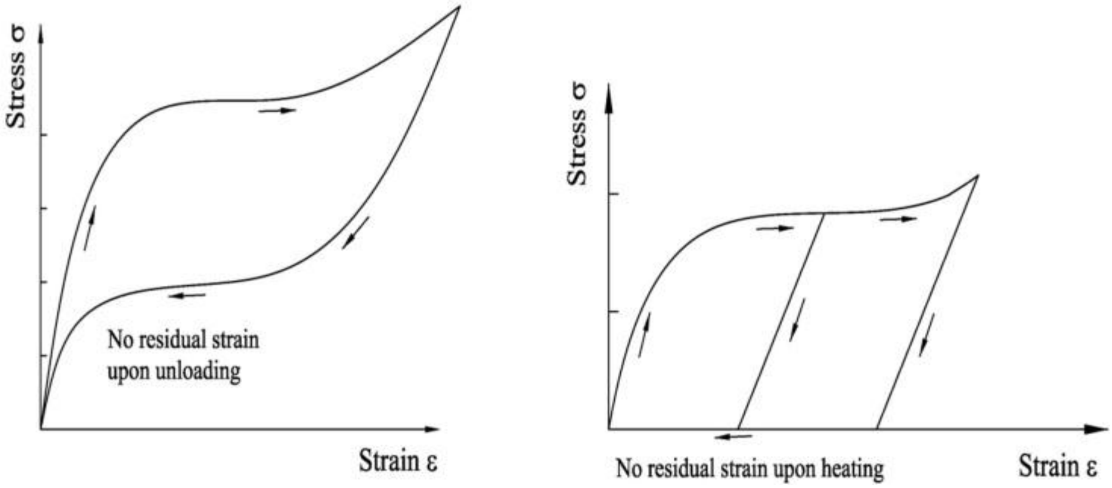

Fig. 1. Stress-strain curves for SMAs: (left) superelasticity effect; (right) shape memory effect

Dolce et al. [1] studied the effectiveness of SMA materials for use in seismic mitigation applications. Wilde et al. [2] performed an analytical study of base isolation systems employing SMAs. SMA-based seismic isolation system consisted of laminated rubber bearing and superelastic SMA bars. They conducted time history analysis with different excitations to compare SMA-based bearings with their conventional counterparts consisting of a lead core. DesRoches and Delemont [3] evaluated the efficiency of using SMA restrainers to reduce the response of decks in a multi span simply supported bridge. DesRoches et al. [4] experimentally evaluated the properties of superelastic Ni-Ti shape memory alloys under cyclic loading to assess their potential for applications in seismic resistant design and retrofit. Czaderski et al. [5] tested a reinforced concrete beam equipped with SMAs and compared it conventionally reinforced concrete beams. The possibility of producing an RC beam having variable stiffness and strength was shown through the application of SMAs. Li et al. [6] experimentally studied the behavior of smart concrete beams with embedded shape memory alloy bundles used as actuators to achieve a recovery force within the structural members. Sharabash and Andrawes [7] studied the application of SMAs as seismic passive damper devices for vibration mitigation of cable stayed bridges. Ghassemieh et al. [8] studied the behavior of concrete shear walls equipped with SMA reinforcements exhibiting pseudoelastic characteristics. The findings showed that the application of SMAs in this fashion resulted in major gains in seismic design by substantially improving the serviceability of the structures while reducing repair costs following a severe earthquake event. In another study, Ghassemieh et al. [9] showed that application of SMA reinforcements can improve the seismic response of shear walls. Qian et al. [10] conducted nonlinear time history analyses on a ten-story steel frame with and without SMA dampers that were subjected to ground excitation. The dampers used consisted of 0.5 mm diameter superelastic wires as an aid to recenter the structure following the earthquake loading. The simulation results indicated that the dampers were effective in mitigating the structural response of the model building, both in terms of energy dissipation as well as in recentering aspects. Yan et al. [11] tested four different configurations of SMA dampers on four-story frame structures that they denoted as A0, A1, A2, and A3. (Here the first configuration denotes that no dampers were implemented, i.e. the control case, and the next consisted of SMA wires in a cross-bracing configuration only on the bottommost floor; the A2 configuration had dampers placed on the first two floors, and the last, A3, configuration had damping on each floor.) As expected, displacements, velocities, and accelerations at the top of the frame structures were greatly reduced in the SMA damped structures as contrasted by the control case. Also as expected, the latter two configurations that were outfitted with more damping devices performed better in terms of overall energy absorption, even though the authors concluded that in practice, it is not necessary to provide full damping on each story based on the comparable performance as witnessed from the A2 case, for example. This, the authors noted, renders not only a sound alternative from an engineering perspective, but an economically more appealing solution as well. Tang and Lui [12] proposed a hybrid damping device that consisted of both SMA wires and a viscous fluid to recenter the structure following seismic excitation. Studies were performed on single-story as well as four-story steel frame model buildings. The frames outfitted with the hybrid dampers resulted in noticeably smaller peak displacements and residual story drifts. It was also noted that in cases where the recentering force exceeded the plastic limit force of the frame, the buildings were almost completely capable of being recentered in spite of having sustained inelastic deformations. Another noteworthy finding was that the viscous fluid dampers did not exert any appreciable residual forces on the frames that would otherwise compromise the effectiveness of the SMA wires. Sultana and Youssef [13] investigated the seismic performance of steel moment resisting frames using superelastic SMAs. It was shown that the seismic performance of these structures can be improved by using SMA connections at chosen locations, which will consequently result in minor increases in maximum inter-story drift, high reduction in maximum residual inter-story drift, and lower level of damage distribution. Morais et al. [14] reported a study on the development process and initial tests of a new energy dissipation damper based on SMA wires for earthquake response mitigation. The good performance of the dampers was demonstrated both in terms of their mechanical behavior as well as in dissipating energy during a seismic event.

In this study, the effectiveness of using SMAs as rebars or strands inside concrete shear walls is investigated. Both superelastic and shape-memory feature effects during and after earthquakes, respectively, are considered herein. Finite element simulations were performed using ABAQUS. In conjunction, a program was coded in FORTRAN to process the material behavior. The study focused on the performances of single and coupled shear walls. The responses of these two types of concrete shear walls was investigated under different seismic load scenarios as well as low and high frequency dominated earthquakes through time history analysis.

2. DETAILS OF NUMERICAL SIMULATION

This study focuses on the behavior of two types of concrete shear walls, i.e. single and coupled, with different amounts of added SMA as well as traditional steel rebars. The models simulating single shear walls were 5.0 m wide, 15 m tall, and 0.3 m thick. Moreover, the models in the second case consisted of two shear walls connected with coupling beams having 2.4 m length and 0.6 m depth. ABAQUS was used to for finite element modeling and analysis of the shear walls. The single and coupled shear wall models developed are shown in Figs. 2 and 3, respectively.

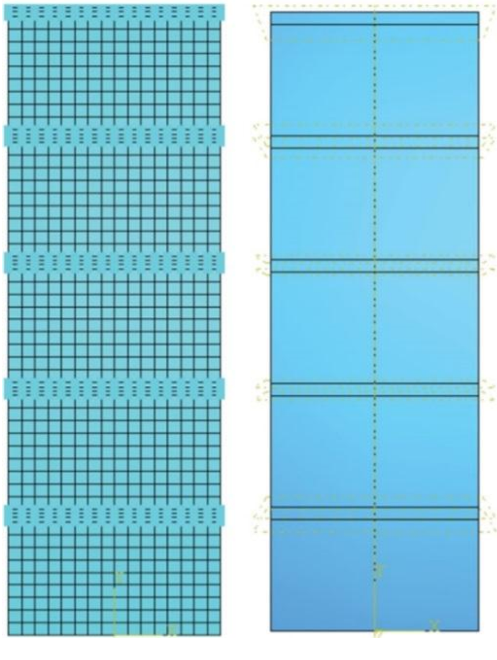

Fig. 2. Finite element model of the ordinary shear wall without openings

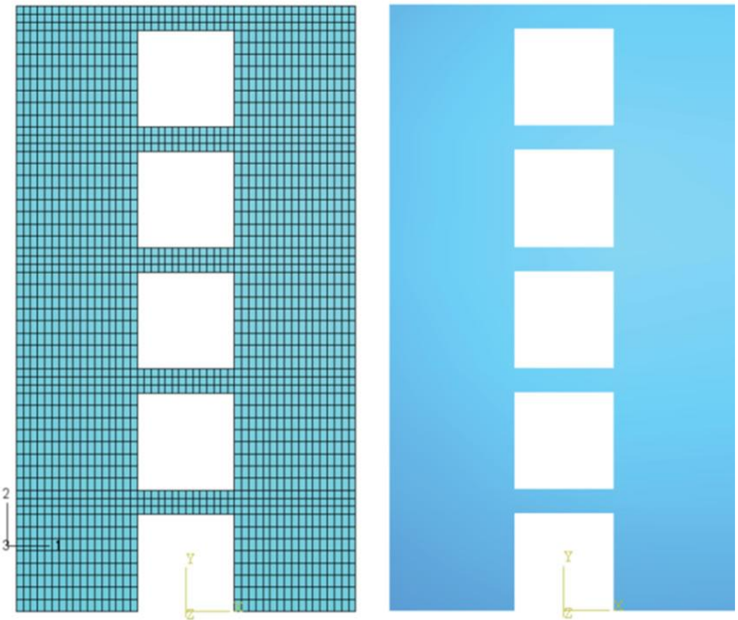

Fig. 3. Finite element model of the coupled shear wall

To simulate the material properties, the Concrete Damage Plasticity model developed by Lee and Fenves [15] was implemented and used in all models to better describe the damaged behavior of concrete walls. The compressive strength was taken as 35 MPa with a specific weight of 25 kN/m^3 and a Poisson's ratio of 0.2. The mechanical properties of the ASTM A615M steel material adopted for the rebars is summarized in Table 1. In order to represent the story inertial forces, a set of lumped masses were placed 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

Prior to the time history analysis and in order to have a better understanding of the dynamic behavior of the shear walls, modal analysis was performed on both models. Figs. 4 and 5 show mode shapes and their associated periods as obtained from modal analyses of the single and coupled shear walls, respectively. It is noted that the out-of-plane degree of freedom of the walls was constrained to restrict all damage causing motions to remain in plane.

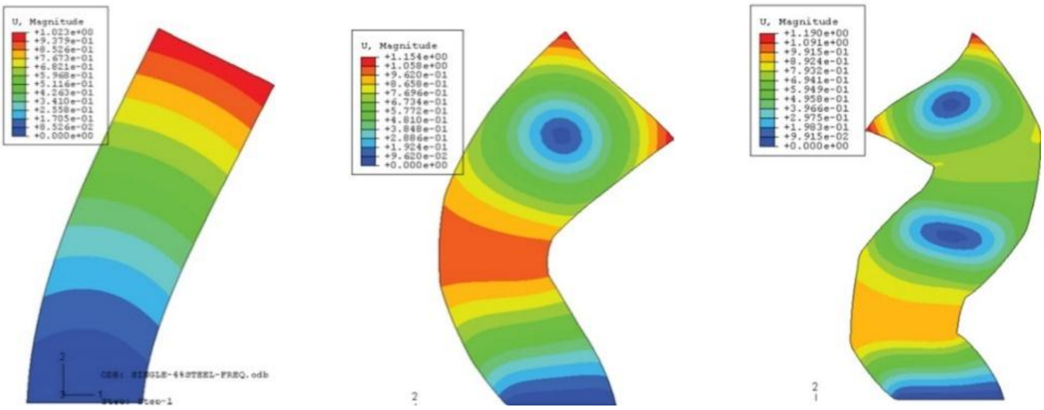

Fig. 4. Mode shapes of the single shear wall

(a) 1st (T_{n1} = 0.726 s), **(b)** 2nd (T_{n2} = 0.157 s), **(c)** 3rd (T_{n3} = 0.073 s)

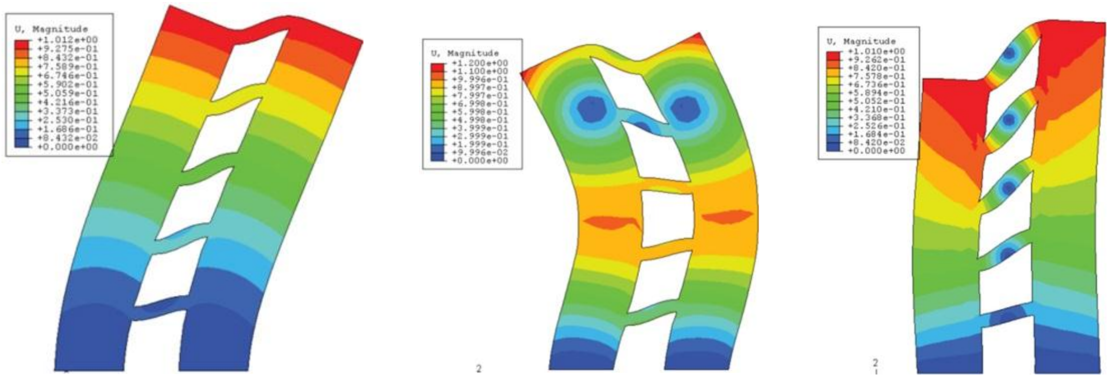

Fig. 5. Mode shapes of the coupled shear wall

(a) 1st (T_{n1} = 0.828 s), **(b)** 2nd (T_{n2} = 0.202 s), **(c)** 3rd (T_{n3} = 0.131 s)

3. DESCRIPTION OF THE CUSTOMIZED UMAT PATCH INTO ABAQUS

This study used SMAs as added rebars to the traditional steel rebars used in civil engineering. The incentive was to use the recentering effect of these alloys as preventive measures against damage in the shear walls. The goal was to see if using these smart alloys as rebars in the shear wall would serve the purpose of reducing the final permanent deformation as well as mitigating the destructive effects of earthquakes on the general building structure. Smart alloy shear walls were only added as vertical rebars, similar to their conventional steel rebar counterparts.

For the coupling beam the rebars were added horizontally again like the traditional longitudinal steel rebars. Since the material model for SMA was not provided as a possibility in the package mechanical behavior library, the superelastic behavior of this alloy was developed by the first author and implemented as a user-defined material subroutine. This was developed in FORTRAN and synchronized to the finite element package of ABAQUS. This user-defined material subroutine was introduced as a User Implemented Material, UMAT, to the main package in ABAQUS. Since this study proposes a method that is based on adding SMAs as supplemental rebars, the developed material model provides a representation of the uniaxial behavior of such alloys for their superelastic phase.

In most civil engineering applications unidimensional phenomenological models are adequate. Fig. 6 shows the generalized illustration for the proposed uniaxial superelastic numerical model that was implemented. Also temperature effects were neglected in the model.

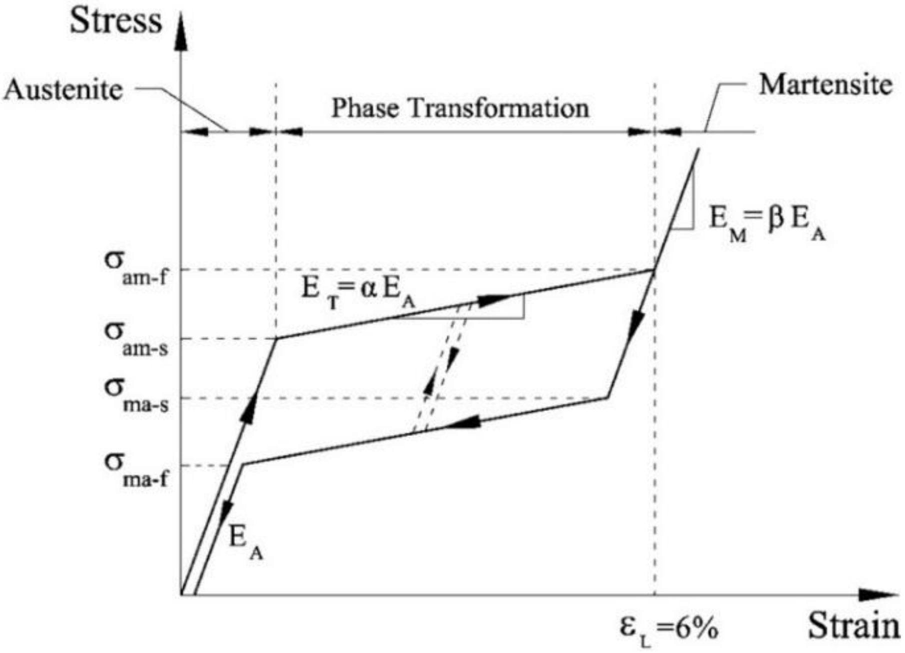

Fig. 6. Stress-strain relationship of the superelastic SMA material

The parameters used to define the material model are as follows: σ_{am-s} is the starting austenite to martensite stress; σ_{am-f} is the finishing austenite to martensite stress; σ_{ma-s}, is starting stress martensite to austenite; and σ_{ma-f} is the finishing stress martensite to austenite. The superelastic plateau strain length and the modulus of elasticity are denoted by ε_L and E_A, respectively. The idealized behavior for the SMA model being represented, neglects any strength degradation effects occurring per load cycles. Also, the permanent deformation was idealized to be zero at the start of each loading cycle with all Bauschinger effects neglected.

Furthermore, it was assumed that the loading and unloading branches have the same modulus of elasticity, namely when $\beta = 1$, as depicted in Fig. 6. Andrawes and DesRoches [16] have shown that these general idealizations have insignificant effects on the response. Table 2 summarizes the modeled SMA mechanical properties patched as UMAT into the ABAQUS software.

Table 2. SMA mechanical properties

SMA Material Properties	Value
Modulus of elasticity (GPa)	40
Austenite to Martensite starting stress (MPa)	400
Austenite to Martensite finishing stress (MPa)	500
Martensite to Austenite starting stress (MPa)	300
Martensite to Austenite finishing stress (MPa)	200
Superelastic plateau strain length (%)	6

4. DISCUSSION OF RESULTS

Using the introduced user defined material subroutine, the previously mentioned two groups of models were analyzed to see how they react to seismic excitations and extreme dynamic loadings. The objective was to evaluate the effectiveness of implementing SMA rebars in concrete shear walls. This was accomplished by assessing time history analyses data of the structures as subjected to earthquake accelerations in the numerical models. Two earthquake acceleration records, i.e. El Centro 1940, 180° NS, and Koyna 1967, 270° NS, were selected to assess the seismic performance of these structures.

Displacements of all stories were chosen as assessment parameters to evaluate the performance of the SMA rebars with different reinforcement percentages together with the conventional reinforcements. These results were subsequently compared with those of conventional concrete shear walls with zero percent SMA reinforcement. Figs. 7 and 8 show the comparisons between shear wall responses having steel rebars only to those with SMAs for the two considered earthquakes.

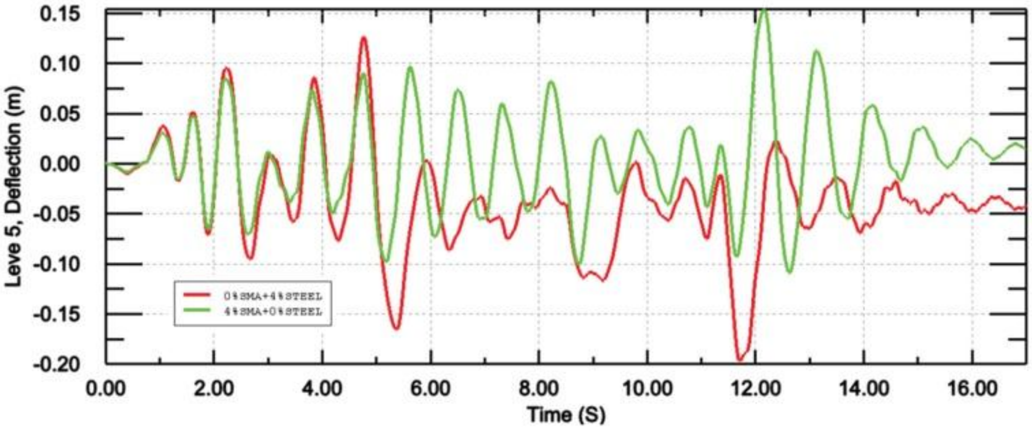

Fig. 7. Shear wall deflections for the two reinforcements under El Centro earthquake

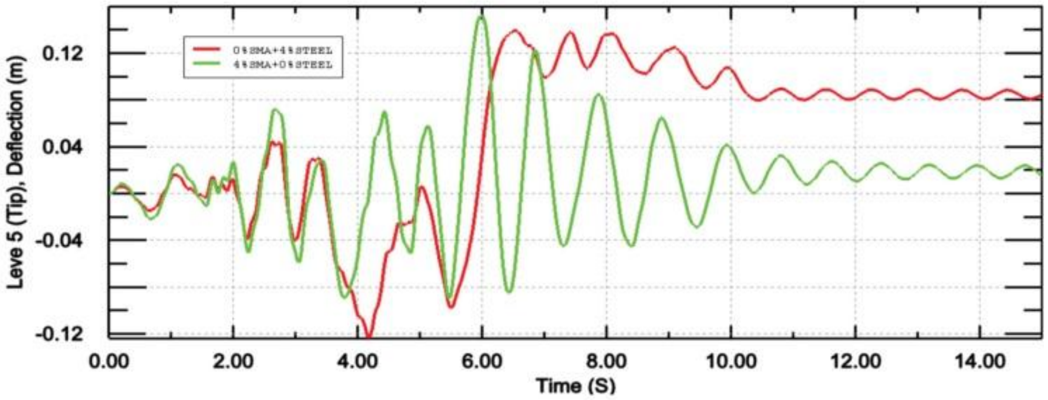

Fig. 8. Shear wall deflections for the two reinforcements under Koyna earthquake

From the figures it is found that application of the SMA material with superelastic behavior can effectively reduce the residual displacement following seismic activity. Specifically, results show that for the case of a conventionally reinforced shear wall, the residual displacements were approximately 5 cm for El Centro and 8 cm for the Koyna earthquakes. In contrast, the SMA reinforced shear walls experienced permanent displacements of merely 2 cm for the two earthquake cases. This indicates that addition of SMAs provides 60% and 75% reductions in residual displacements induced by the two earthquakes, respectively, in spite of no differences being observed in maximum displacements.

4.1. Results for Single Shear Walls

The story residual deformations of the single shear wall with the steel or SMA reinforcements as subjected to the El Centro earthquake are depicted in Fig. 9. It is obvious that the residual deformations of the five individual stories have been significantly reduced due to application of SMAs. Such an enhancement can be attributed to SMA’s superelastic behavior, since the alloy has the tendency to return to its originally undeformed state which can avoid the accumulation of residual displacements. In contrast, yielding of the conventional steel rebars at each cycle can accumulate plastic deformations and hence considerable and unrestorable residual deformation remains at the end of the seismic loading.

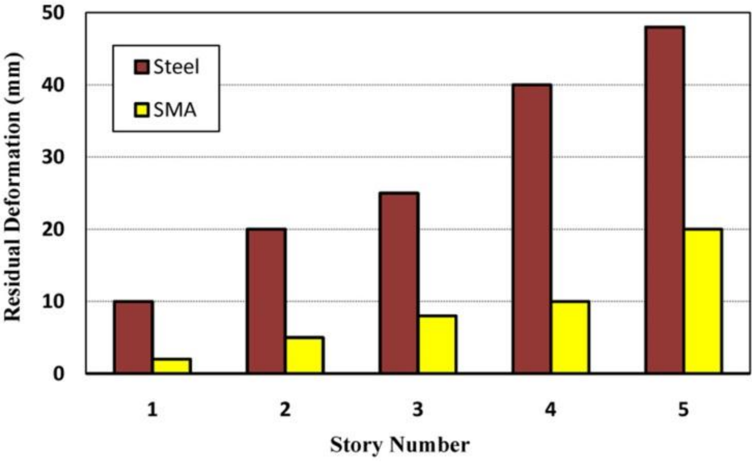

Fig. 9. Story residual deformations of the single shear wall with the steel or SMA reinforcements subjected to El Centro earthquake

Fig. 10 shows the fifth story single shear wall deflections for two combinations of SMAs with steel reinforcements, i.e. 4%SMA+2%steel and 6%SMA+2%steel, under the El Centro earthquake. It is observed that with an additional two percent of SMAs, i.e. 4% to 6%, the maximum tip displacement of the single shear wall was decreased from 140 mm to 89 mm, a 45% reduction, and the residual displacement was reduced from 30 mm to 15 mm, a 50% reduction.

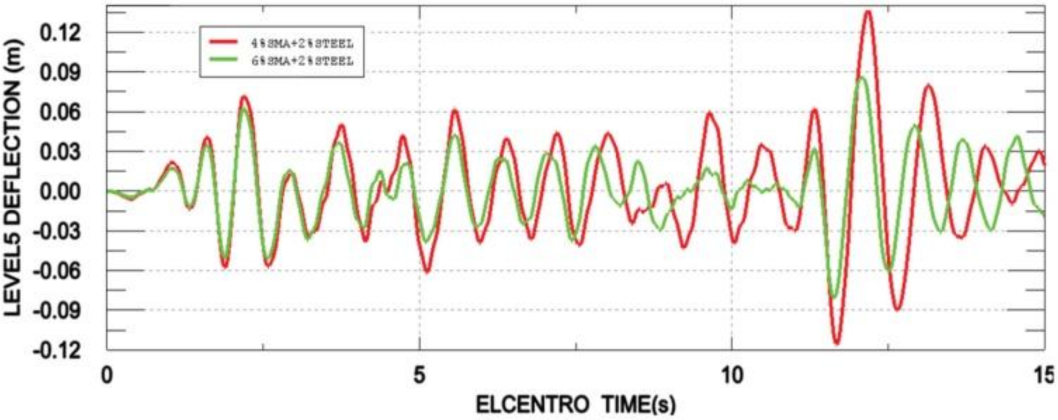

Fig. 10. Fifth story single shear wall deflections for two combinations of SMAs with steel reinforcements under El Centro earthquake

4.2. Results for Coupled Shear Walls

The maximum displacements of the coupled shear wall with the steel or SMA reinforcements as subjected to the Koyna earthquake are shown in Fig. 11. The depicted results clearly indicate that shear walls with SMA reinforcements underwent significantly lower levels of maximum displacements.

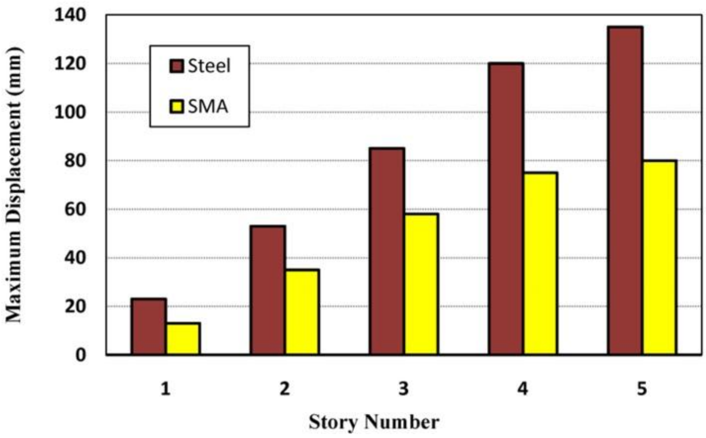

Fig. 11. Maximum displacements of the coupled shear wall with the steel or SMA reinforcements subjected to Koyna earthquake

In Fig. 12, the fifth story coupled shear wall deflections having either SMA or steel reinforcement as subjected to the Koyna earthquake are shown. In the case involving only steel reinforcement, the concrete wall had a maximum deflection of approximately 13 cm, while in the SMA reinforced case, the structure experienced a significantly reduced displacement of about 7 cm, indicating an approximate 46% reduction in the maximum displacement. In addition, superelastic SMA reinforcement significantly reduced the residual displacement of the concrete wall to 1 cm as contrasted to the 6 cm not involving such reinforcement, an 83% reduction.

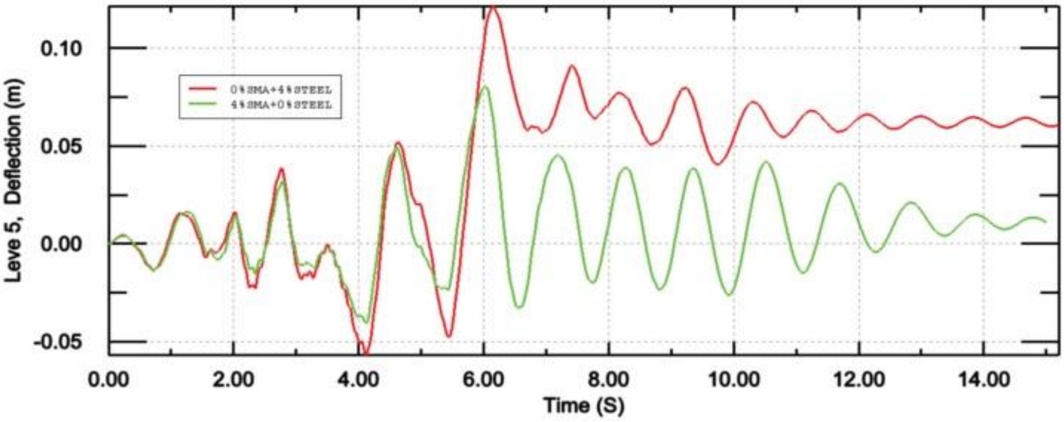

Fig. 12. Fifth story coupled shear wall deflections having either SMA or steel reinforcement under Koyna earthquake

Fig. 13 illustrates the time history results for two cases of coupled shear walls, one having a combination of 2.5%SMA+1.5%steel reinforcement, and the second involving only 4%SMA reinforcement. It can be seen that the two behaviors are very nearly alike making the case for implementing lower levels of SMA reinforcement in combination with conventional steel rebars a more lucrative alternative to that of the more costly SMA only option.

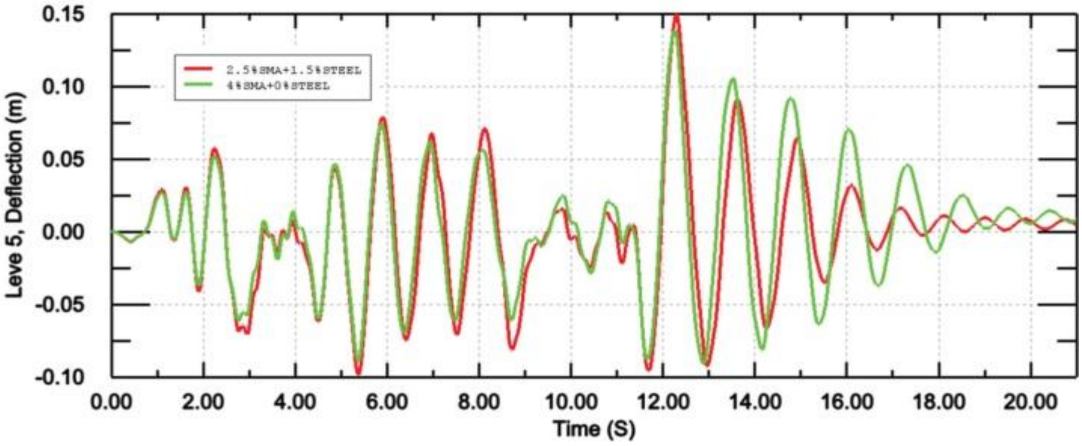

Fig. 13. Fifth story coupled shear wall deflections having SMA+steel or only SMA reinforcements under El Centro earthquake

5. CONCLUSION

In this paper, the effectiveness of using varying levels of SMAs in improving the seismic performances of single and coupled concrete shear walls was investigated through detailed numerical simulation. ABAQUS was used to model the behavior of the shear walls, and a User Implemented Material (UMAT) was programmed in FORTRAN to treat the uniaxial superelastic behavior of the SMA reinforcement. Two earthquake records, i.e. El Centro and Koyna, were chosen to study the dynamic response of the shear walls.

This study showed that using SMAs in combination with conventional steel rebars can be quite effective in reducing the story maximum displacements and residual deformations in single and coupled shear walls. It was found that using less SMA reinforcement in conjunction with conventional steel rebars resulted in comparable performances to situations with higher levels of SMAs alone, posing a lucrative and sound engineering option to mitigating permanent damage and enhancing the drift response of such lateral force-resisting systems following seismic activity.

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