Seismic Enhancement of Coupled Shear Walls Using Shape Memory Alloys

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Abstract- This paper investigates the effectiveness of Shape Memory Alloys (SMAs) in enhancing the seismic behavior of coupled shear walls. First, SMA braces or strands are implemented in the shear wall openings for repairing and retrofitting purposes. A finite element program, SeismoStruct, is used to evaluate the seismic behavior of the controlled structure. For retrofitting purpose, a multi story concrete shear wall building with and without SMA elements is exposed to El-centro earthquake record for 15 seconds, followed with 25 seconds of damped free vibration. For repairing purpose, the structure in the first 40 seconds, is excited with El-centro earthquake and in the second stage, after adding the SMA braces, the same record is applied in second of 40 to simulate the aftershock. Results indicate that the proposed enhancement can successfully reduce the maximum displacements and permanent residual deflections of the existing shear wall structures. In the second part, as new designing technique, shear wall is reinforced with SMA reinforcement bars instead of conventional steel bars and/or with combination of SMA and steel reinforcement. ABAQUS finite element program is used to capture the seismic behavior of the concrete wall and the SMA material is implemented in the computer program by using FORTRAN as a subroutine material module. The structure is evaluated through nonlinear static as well as dynamic time history analyses. The results show that SMA reinforcement can significantly restore the residual displacement in the shear wall.

Keywords- Shape Memory Alloy; Coupled Shear Wall; Seismic Behavior; Seismostruct Software; ABAQUS Software

I. INTRODUCTION

When buildings are subjected to earthquakes or shock waves from explosions, it is essential to provide mechanisms for energy absorption in order to avoid the damaging effects caused by such unpredictable loads. During recent earthquakes, it has been found that lack of energy absorption avenues is one of the causes of poor building performance [1, 2]. Many multi storey buildings are enclosed by shear walls around the elevator shafts and stairwells. These walls provide considerable lateral stiffness to the structure in order to enable it to resist horizontal loadings such as earthquakes and winds. There will usually be several openings in these shear walls and if two such openings are on opposite sides, deep beams are used to interconnect the walls. These coupling beams are generally used as a mean of providing framing action to the core elements. In order to dissipate energy during earthquakes, they must undergo inelastic yielding and form plastic hinges which are usually positioned in beams near beam column joints. Therefore, due to their small span to depth ratio, coupling beams require highly congested reinforcement in order to achieve ductile behavior. They are difficult to construct due to the need for this complex detailing. Although dissipating energy through plastic hinging is a common practice in the design of multi-storey buildings, this practice usually results in significant residual displacements and the need to repair the structural elements after the earthquake. To address the shortcomings of current practices, a new retrofit and design approach using shape memory alloy (SMA) is proposed.

SMA is one example of smart materials that display several remarkable characteristics such as shape memory effect, pseudoelasticity (self centering), and energy dissipation features. Due to these characteristics, shape memory alloys have widely attracted attentions in passive control of systems in recent years. In a series of publications studied the effectiveness of SMA materials for the use in seismic applications is presented in [3]. The implementation of various states of SMA materials for the use of special dampers in structures is also illustrated. Different recentering and/or dissipating devices based on experimental results are also suggested. An analytical study of SMA-based seismic isolation system that consists of laminated rubber bearing and superelastic SMA bars is performed in [4]. Time history analyses with different excitation to compare the SMA-based bearing with conventional bearing with lead core is conducted. Experimental investigation on the proper choice of alloy, the effect of temperature, SMA size and loading rate and number of cycles is presented in [5]. The effectiveness of the use of SMA materials by analytical measures is shown using simple pseudoelastic constitutive model for SMAs using damage index approach [6]. The efficiency of using SMA restrainers to reduce the response of decks in a multi span simply supported bridge is evaluated in [7]. Experimental evaluation of superelastic Ni-Ti shape memory alloys under cyclic loading to assess their potential for applications in seismic resistant design and retrofit is presented in [8]. Energy dissipative characteristics of bolted t-stub connections using steel and SMA fasteners is shown in [9]. A multilinear constitutive model developed in [10] is adopted to capture the most common behaviors of SMA. A reinforced concrete beam equipped with SMA material is tested in [11] and the results are compared with conventional reinforced concrete beam.. The results proved that by using shape memory alloys it was possible to produce a reinforced concrete beam which had a variable stiffness and strength. Application of SMA bars instead of steel bars in plastic hinge zone of reinforced concrete bridge piers is investigated in [12]. Special SMA damper to have both re-centering and energy dissipating characteristics simultaneously is introduced in [13]. Experimental study on the behavior of smart concrete beams with embedded shape memory alloy bundles is given in [14]. In this study, SMA bundles are used as actuators to achieve recovery force. Efficiency of SMA restrainers with three other retrofit devices including conventional steel restrainers, metallic dampers and viscoelastic dampers is compared in [15]. Large scale testing program is conducted in order to evaluate the effect of SMA restrainer cable on the seismic performance of in-span hinges of multiple-frame concrete box girder bridge subjected to strong ground motion [16]. Application of SMAs as seismic passive damper devices for vibration mitigation of cable stayed bridges is studied in [17]. The feasibility of superelasticity in increasing ductility capacity and decreasing residual displacement of concrete bridge column is investigated in [18]. Effectiveness of SMA-rubber based isolation systems is explored for seismic protection of bridges against near-field earthquakes [19]. Performance of SMA-rubber based isolation systems with SMA-based sliding isolation system is also compared. Effectiveness of a new dual bracing system for improving the seismic behavior of steel structures is evaluated in [20].

In this study, it is taken advantage of the superelastic behavior of the shape memory alloy for enhancing the concrete coupled shear wall system. First, SMA in the form of bracings were implemented in the wall openings for repairing and retrofitting purposes. SeismoStruct finite element program, is used in order to evaluate the behavior of the controlled structure compared to the as-built wall. In the second part of this paper, as a new proposing design technique, steel rebars in the concrete wall are replaced by SMA reinforcements. ABAQUS computer software is also used to assess the seismic behavior of the reinforced concrete wall.

II. SHAPE MEMORY ALLOY

Shape Memory Alloys are new class of metallic alloys that exhibit unique characteristics, based on solid-solid martensitic phase transformation. SMA can be categorized as either superelastic austenite (the high temperature phase) which can recover its original shape when unloaded or martensite (the low temperature phase) which exhibits shape memory effect and hence recovers its original shape when heated (Fig. 1). During deformation, SMAs will undergo phase transformations between martensitic and austenitic crystal forms instead of intergranular dislocations as typically found in metals. The material properties of the martensite and austenite phases depend upon the temperature and external stress applied to the crystal. At temperatures slightly above Af (austenite finish temperature), the material is austenitic. However, the martensitic phase can be stress-induced, resulting in what is commonly referred to as the superelastic, or pseudoelastic effect. At temperatures below Mf (martensite finish temperature), the material is in its martensitic form and exhibits the shape memory effect.

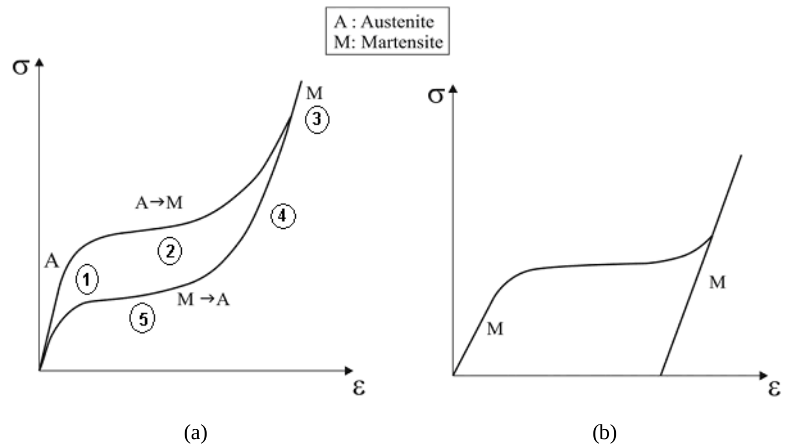


Fig. 1 Stress-strain curves for SMAs: (a) superelasticity effect; (b) shape memory effect [13]

In recent years, many types of shape memory alloys have been discovered. Among them Nitinol shape memory alloy possesses several superior thermo mechanical properties that make it ideal for structural applications. Nitinol SMA characteristics comprise: (1) large elastic strain range; (2) hysteretic damping; (3) reliable energy dissipation through repeated solid state phase transformation; (4) strain hardening at strain above 6%; (5) excellent low- and high-cycle fatigue properties; (6) excellent corrosion resistance; and (7) formation of stress plateau during phase transformation which controls the forces transmitted to the structure [7,17]. This study will concentrate on this type of SMA.

III. MATERIALS MECHANICAL PROPERTIES

Mechanical properties of SMA as well as some of the critical stresses used for the material in the analyses are presented in Table 1. The data given in Table 1 correspond to some of the metallurgical phases of the SMA which is explained as follows. As shown in Fig. 1, schematic of superelastic SMA stress-strain curve can be characterized almost by five branches [5]. Branches 1 and 4 correspond to the elastic deformation of the two stable phases of SMA, respectively, called Austenite and Martensite. Branches 2 and 3 correspond, respectively, to the forward (from Austenite to detwinned Martensite) and inverse (from detwinned Martensite to Austenite) phase transformation. Branch 5 corresponds to the onset of plastic deformation of the detwinned martensite.

TABLE ISMA 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
Specific weight (kN/m3)	65

Since shear wall and coupling beam structures are constructed using reinforced concrete, the material properties of the concrete used, are compressive strength of 32 MPa, Young's modulus of 30 GPa, poisson ratio of 0.2, and density of 25 kN/m^3.

IV. USING SMA BRACES AS NEW RETROFITTING AND REPAIRING ELEMENTS

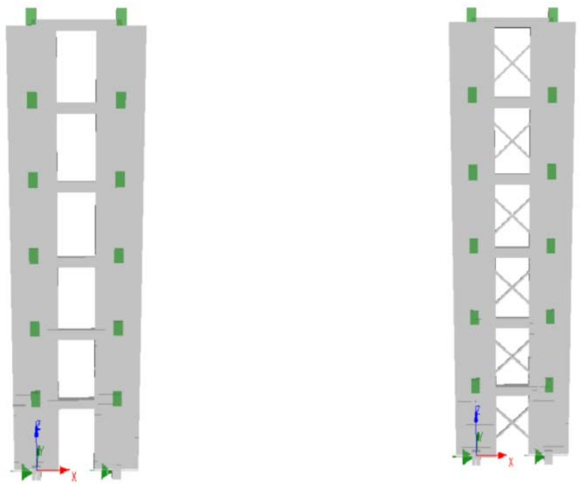
In this section, superelasticity feature of the alloy was employed for enhancing the concrete shear wall system. The proposed method uses SMAs as wire strand bracings (or dampers) in the concrete shear wall openings, at the coupling beam location particularly for repairing and retrofitting purposes. SMA bracings can be anchored to the structural component by simply bolting them to plates adhered on the surface of concrete. Similar repairing or enhancement of the concrete structure is normally required after damages induced by the earthquakes.

To assess the effectiveness of the new damping system, finite element program, SeismoStruct [21], was chosen in order to evaluate the behavior of the structures subjected to earthquake excitations. The response of the structure is obtained for selected time steps of the input earthquake accelerogram. To show the value of adding the SMA braces in mitigating the seismic response, the tip displacements at each floor level were obtained in the controlled and as-built structures from the time history analyses and the result were compared.

A. Structural Model Description

Analyses were undertaken on six storey coupled shear wall model to evaluate the effectiveness of the SMA bracing or damper placement [22]. The structure had two interconnected concrete walls. Each wall was 3 m wide with 0.5 m thickness, and each coupling beam was 0.6 m deep with 0.3 m width. Lumped masses were placed at each node where the coupling beam intersected the shear wall to represent the lateral inertial loads induced from the floor to the walls in time of earthquake excitations. The distance between the shear walls was fixed at 2.4 m and height between each level was fixed at 3.0 m.

For the upgraded structure, double diagonal SMA bracing wires are proposed to be placed as repairing or retrofitting members throughout the height of the structure. Analytical models of the structure in SeismoStruct software are presented in Fig. 2. Diameter of 100 mm is chosen for the SMA wire strands.



(a) As-built Shear wall (b) Shear wall with SMA Braces

Fig. 2 Analytical models of the shear wall in SeismoStruct software

B. Analyses

To assess the effectiveness of new system as a new damping device, an as-built structural model of two shear walls coupled with link beams were subjected to El-centro excitations and results were compared with the enhanced system which had additional SMA members.

Analyses were fragmented into two stages. In the first stage, a 15 second acceleration of the earthquake was imposed to the model followed by a 25 seconds of damped free vibration (inducing no acceleration). SMA wires as retrofitting elements were evaluated in this stage. In the second stage, the former procedure was repeated without shape memory alloy and the SMA elements as repairing elements were automatically added to the running analysis at the exact time of 40 second. In the second stage the same acceleration record of El-centro was used as a strong aftershock. As it happens in real vibrations, due to the natural damping of the system, real structures damp the perturbed fluctuation and finally come to stop vibrating. Therefore, in the analyses, the members were defined to have 2% of Rayleigh's damping property.

C. SMA Braces as Retrofitting Elements

In the first stage, the concrete shear wall building was exposed to El-centro earthquake record, for 15 seconds, followed with 25 seconds of damped free vibration to permit the system going back to its initial position, if possible. Results showed that parts of the structural system experienced the inelastic behavior and thus some residual deformations remained in the structure. It was showed that after earthquake and free vibration period, the structure had 22 mm lateral residual displacements, measured at the tip of the structure (Fig. 3). In the time history analysis of the structure, maximum displacement of 162 mm was obtained on the tip of the roof.

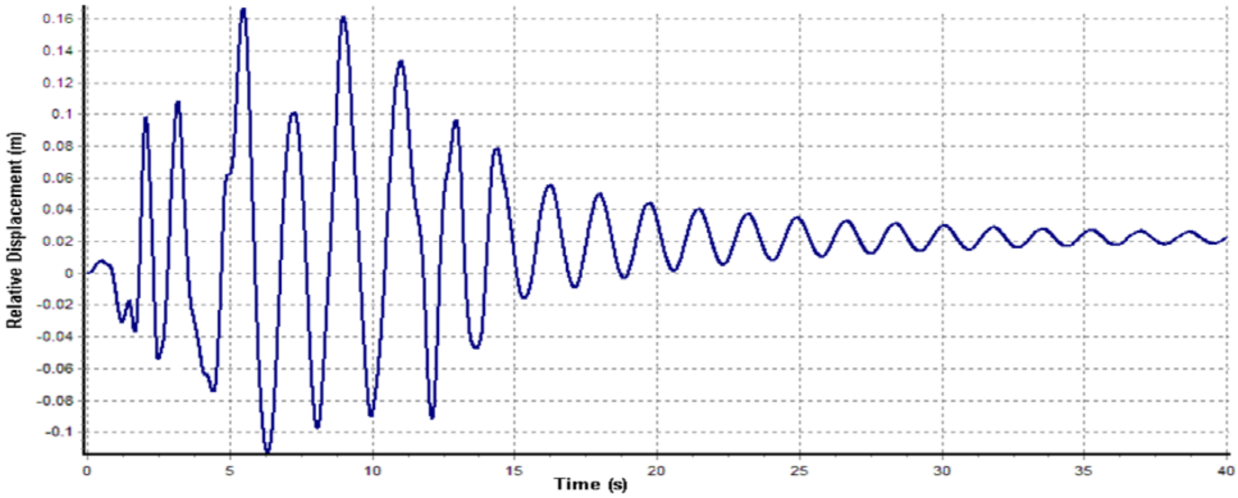


Fig. 3 Tip deflection response of original structure

However, in the same structure with the SMA bracings, it was found that some parts of the structural system became inelastic but insignificant residual deflection was detected at the tip of the structure. This was mostly due to fact that implementation of the SMA elements in the shear wall could efficiently restore the residual displacement. The analysis showed that after seismic excitation and free-vibration of the structure, only 1.5 mm of residual deflection was observed at the tip of the structure (Fig. 4) and this illustrated 93% reduction in the residual displacement of the shear wall. Besides, maximum displacement of 140 mm was observed during the seismic excitation which showed 16% decrease compared to the response of the as-built structure. This result is

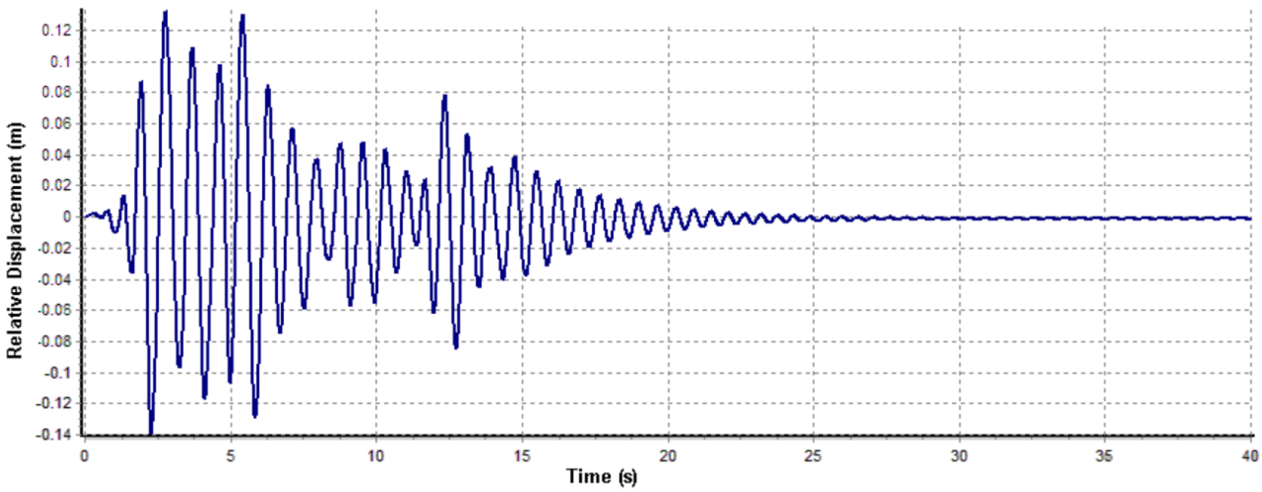


Fig. 4 Tip deflection response of structure with SMA bracings

interesting in the sense that although the as-built shear wall has a very high stiffness (due to dimensions of the concrete shear wall), in the retrofitted structure, SMA elements could manage to control the very high stiffness structure even further.

D. SMA Braces as Repairing Elements

In the second stage, the structure was excited with two earthquake accelerograms. First 15 seconds of El-centro earthquake followed by 25 seconds of damped free vibration was imposed to the structure. Then to simulate the aftershock, the same record was applied in second of 40. This was done intentionally in order to see how the response of the damaged structure would change in time of large magnitude aftershock. As it was expected, due to some inelastic behavior in the first excitation, the structural system did not respond in the same way during the aftershock. Results indicated that structural characteristics affected by the first seismic activity (Fig. 5). As illustrated, the maximum tip displacement of the structure was increased up to 220 mm due to the inelastic changes of the first excitation. The time history analysis also showed that after the second excitation, the structure had residual deflection of 45 mm measured at the tip of the structure.

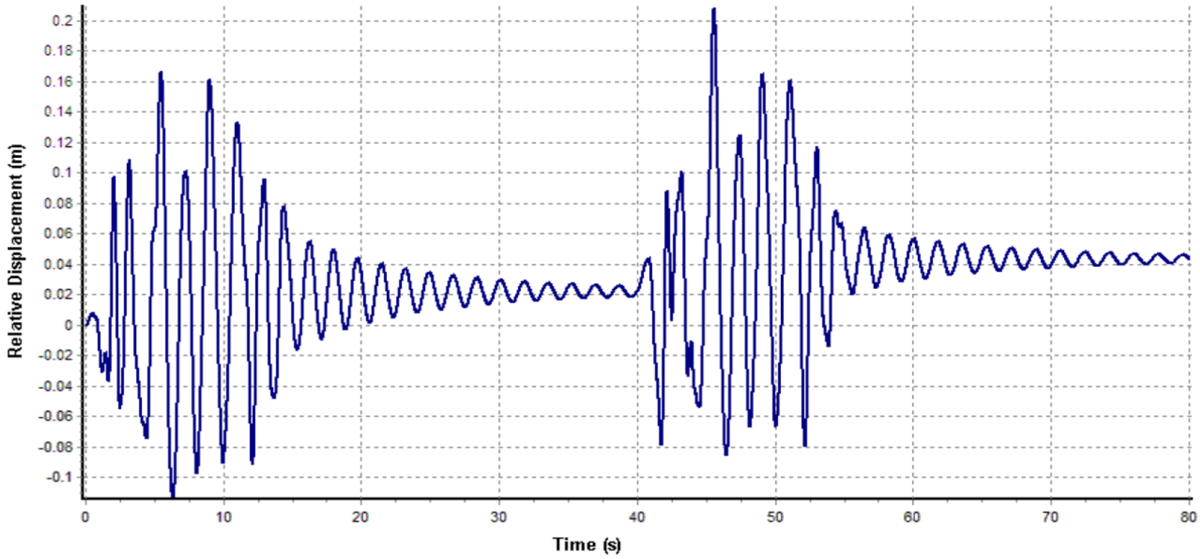


Fig. 5 Tip deflection response of original structure in two stages

For repairing the damaged structure, the SMA bracing members were installed after the first excitation. To implement the repairing SMA elements into the model, the SMA bracing element was automatically added to the model at the 40th second of the analysis. Results showed that there was nearly no residual deflection at the end of last excitation compared to the end of first excitation. They also showed that in the second excitation, the maximum response of the structure was totally mitigated (Fig. 6). As it can be observed, the maximum tip displacement of the structure was decreased to 150 mm and this showed 32% reduction compared to the response of unrepaired structure. In addition, SMA wires were able to reduce the residual displacement by 56% from 45 mm to 20 mm.

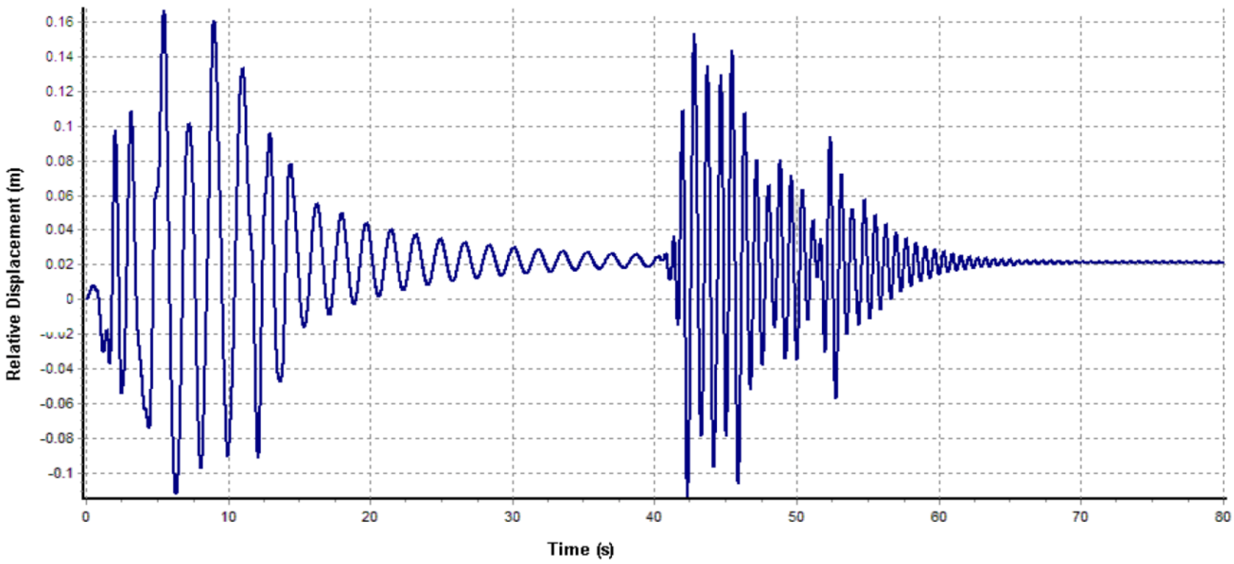


Fig. 6 Tip deflection response of structure with SMA repairing members in two stages

V. PROPOSING SMA REINFORCEMENTS AS NEW DESIGNING TECHNIQUE

The proposed method uses SMAs as reinforcement in concrete shear walls for the purposes of eliminating the residual displacement and converting the shear walls to self centering systems (Fig. 7). In order to attain the numerical behavior of the structure, finite element computer program ABAQUS [23] was used in this study. Since in the most finite element programs, the SMA mechanical behavior does not appear by default, thus the SMA material was implemented in the computer program by using FORTRAN as a subroutine material module. In order to find the behavior of the structures subjected to earthquake shockwaves or other loadings with cyclic behaviors, two general types of analyses were examined on the numerical models, namely the nonlinear static and the dynamic time history analyses. For dynamic analysis, the response of the structure was obtained against the selected main part of earthquake accelerograms as the input load, and for the nonlinear static monotonic analysis, the half cycle loadings were applied to the numerical models. To show the value of the SMA reinforcements in alleviating the seismic response, the tip displacements at each floor level were obtained in the controlled structure from time history analyses. The result of the new proposed system subjected to seismic excitations is then compared with those of the original concrete structure (without SMAs) and also assessed against models with different percentages of SMA reinforcements.

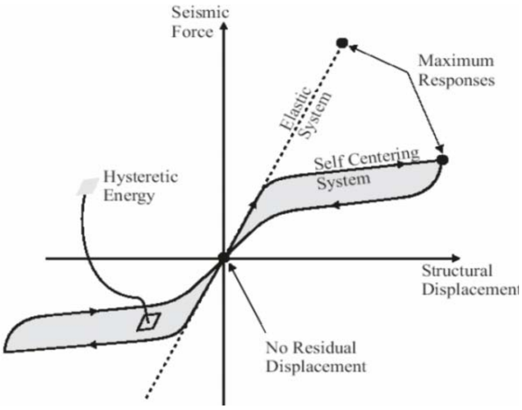


Fig. 7 Idealized Seismic Response of Self-Centering Structures [24]

A. Model Description

In this section, analyses were undertaken on multi-storey coupled shear walls to evaluate the effectiveness of the SMA rebars in comparison with conventional steel reinforcement. Again the structure had two interconnected concrete walls. Each wall had the width of 3.0 m and thickness of 0.3 m and each coupling beam was 0.6 m deep, 2.4 m length with 0.3 m width. Height between each level was fixed at 3.0 m. Lumped masses were placed at all nodes intersecting the floor slab level where the coupling beam intersected the shear. Concrete damage plasticity, developed by [25] was utilized for a proper material modeling of the concrete behavior in the numerical analyses.

For the upgraded structure, vertical SMA reinforcing rebars are proposed to be implemented like conventional steel reinforcements, throughout the height of the wall structure and in the all five connecting beams which are to couple the two shear walls. No diagonal rebars were studied in this research. For reaching the different percentages of reinforcements, the SMA and steel rebars were studied to posses various diameters and spacings. Finite Element models of the shear wall in ABAQUS software are presented in Fig. 8.

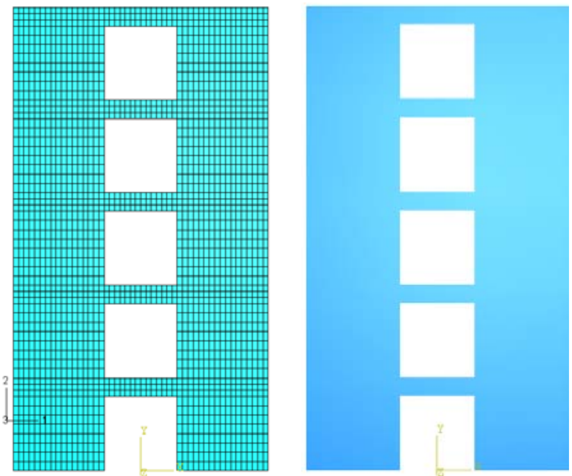
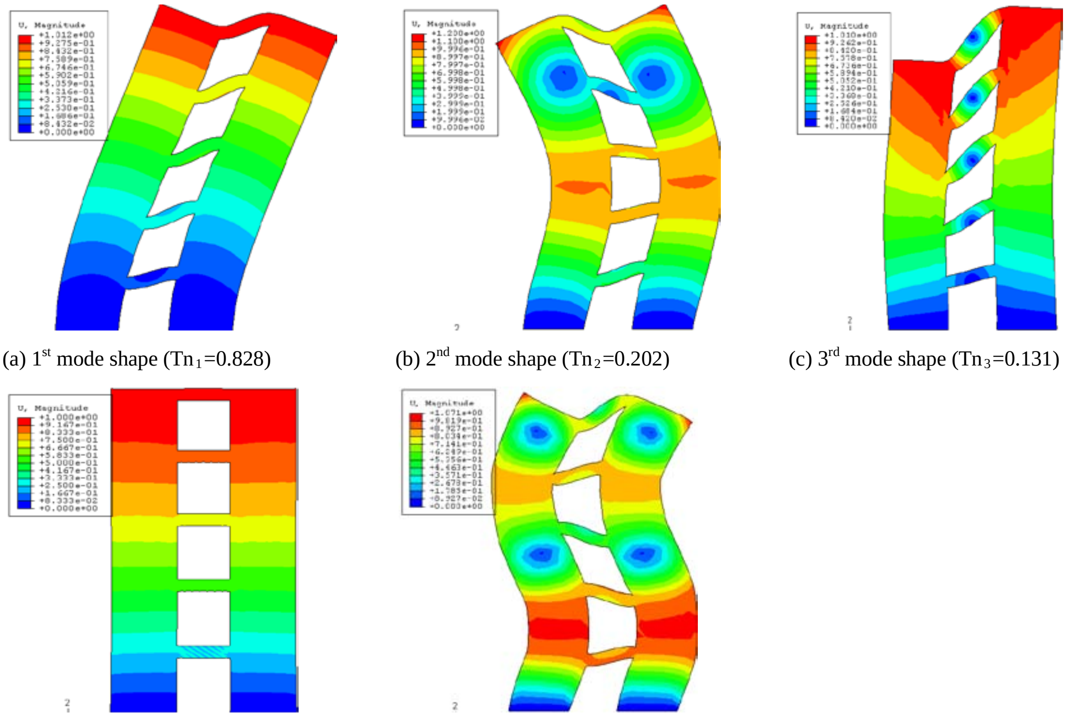


Fig. 8 Finite Element model of the reinforced concrete shear wall

In order to provide better understanding of the dynamic behavior of the shear wall, a modal analysis is conducted for the as-built structure by the ABAQUS software. Mode shapes and natural period of each mode are presented in Fig. 9. As illustrated, the first three fundamental modes of the shear wall had the periods of 0.828, 0.202 and 0.131 sec, respectively.



(a) 1st mode shape (Tn_1=0.828) (b) 2nd mode shape (Tn_2=0.202) (c) 3rd mode shape (Tn_3=0.131)

(d) 4th mode shape (Tn_4=0.144) (e) 5th mode shape (Tn_5=0.091)

Fig. 9 Mode shapes of the shear wall

B. Static and Dynamic Analyses

Two types of analyses on the numerical model were examined, which are to be nonlinear static monotonic analysis and dynamic time history analysis. At first, concrete shear wall equipped with SMA rebars was subjected to lateral monotonic loading and then unloaded. The goal was to evaluate the residual displacement for different percentage of SMA reinforcement. Then, the effectiveness of the SMA rebars in seismic enhancement of the concrete shear wall was investigated through time history analyses. The structure was exposed to El-centro and Koyna earthquake records and tip deflections were recorded.

C. Static Monotonic Analysis

Fig. 10 shows the response of concrete shear wall equipped with different percentage of superelastic SMA from 0% to 12% and in combination with 3% steel reinforcement. It can be observed that, increasing the percentage of shape memory alloy reinforcement caused reduction in residual displacement, slight increase in wall's stiffness and significant increase in strength of concrete shear wall. Specifically, residual displacement decreased from 130 mm to 81 mm and strength of the shear wall increased from 4.3 MN to 11.9 MN as the percentage of SMA reinforcement is changed from 0% to 12%. These meant 38% reduction in the residual displacement of the controlled shear wall compared to the response of the as-built structure.

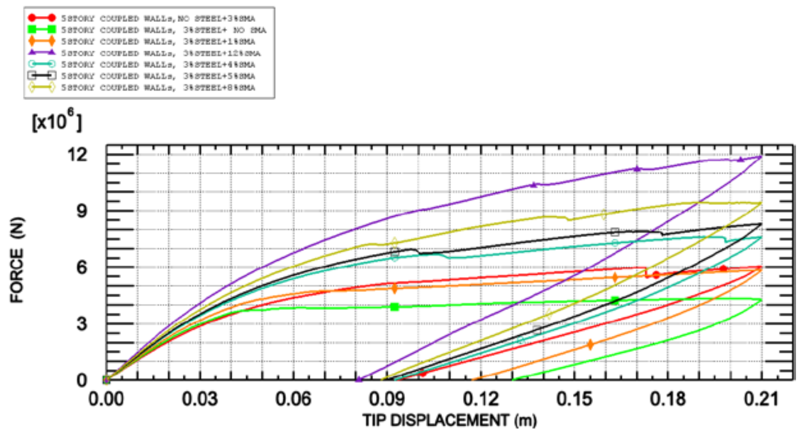


Fig. 10 Behavior of concrete shear wall with different percent of SMA reinforcements

D. Dynamic Time History Analysis

Fig. 11 compares the seismic response of the structure with steel or SMA reinforcement. The result showed that the shear wall with SMA reinforcement experienced much lower level of deflection than the shear wall with steel reinforcement. In particular, in the case of steel reinforcement, the concrete wall had maximum deflection of 0.13 m; while in the case of SMA reinforcement, the structure just experienced the displacement of 0.07 m (i.e. 46% reduction in the maximum displacement). Besides, using superelastic SMA material instead of steel in concrete wall can significantly reduce the residual displacement. Specifically, the residual displacement of the structure was reduced from 0.06 m in the original wall to 0.01 m in the controlled structure (i.e. 83% reduction in the residual displacement).

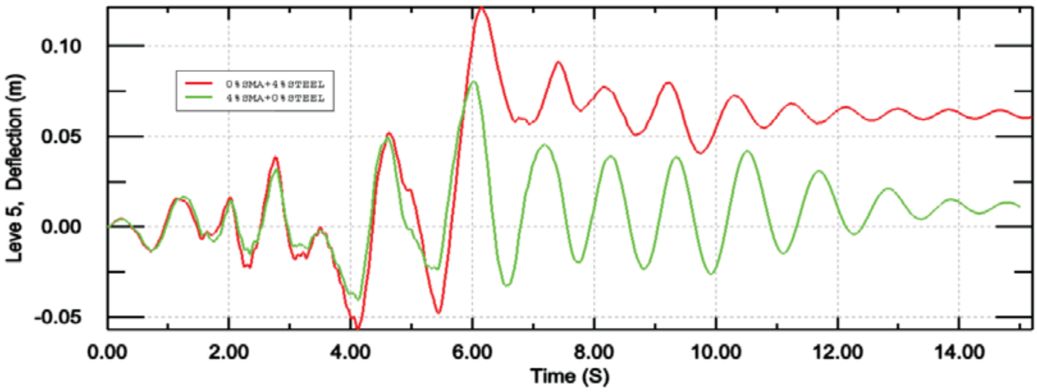


Fig. 11 Tip deflection of the shear wall subjected to Koyna earthquake for steel or SMA reinforcement

Fig. 12 displays the time histories of tip deflection for 0% steel and 4% SMA reinforcement and 1.5% steel and 2.5% SMA reinforcement. It can be observed that replacing 1.5% of shape memory alloy rebars by steel rebars did not affect the seismic response significantly and two concrete walls behave similarly under El-centro earthquake. However, since SMA is a very expensive material compared to steel, it may be economical to use it when the steel and SMA reinforcements are well proportioned.

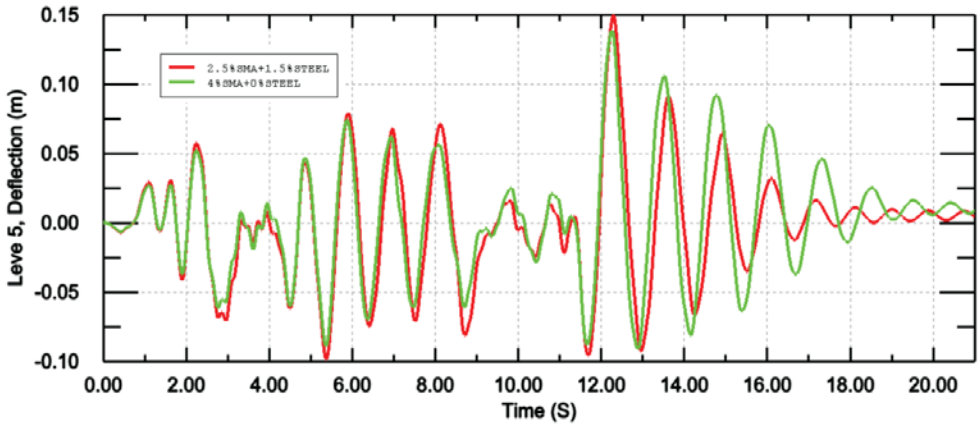


Fig. 12 Tip deflection of the shear wall subjected to El-centro earthquake for two different percentages of steel and SMA reinforcement

VI. CONCLUSIONS

In this paper, an analytical study is conducted to evaluate the effectiveness of shape memory alloys in improving the seismic behavior of coupled shear walls. First, SMA braces are implemented in the shear wall openings for repairing and retrofitting purposes. Finite element program, SeismoStruct, is used to assess the behavior of the controlled structure. Using SMAs as retrofitting elements, a multi story concrete shear wall building with and without SMA elements is exposed to El-centro earthquake record for 15 seconds, followed with 25 seconds of damped free vibration. The analysis showed that the SMA braces could decrease the maximum displacement and residual displacement of the wall by 16% and 93% respectively, compared to the response of the as-built structure.

Using SMA braces as repairing elements, in the first excitation, the structure is excited with 15 seconds of El-centro earthquake followed by 25 seconds of damped free vibration. Then in the second place, the SMA braces are added and to simulate the aftershock the same record is applied in second of 40. Results indicated that the maximum tip displacement and the residual deflection are reduced from 220 mm to 150 mm and 45mm to 20 mm, respectively during the aftershock in the repaired structure compared to the original shear wall.

In the second part, as new designing technique, shear wall is reinforced with SMA reinforcement bars instead of conventional steel bars or with combination of SMA and steel reinforcement. ABAQUS finite element program was used to attain the numerical behavior of the structure and the SMA material is implemented in the computer program by using FORTRAN as a subroutine material module. The structure is evaluated through static-monotonic and dynamic-time history analyses. The results showed that SMA reinforcement could reduce the residual displacement up to 83%. However, due to economical consideration, the steel and SMA reinforcements must be proportioned properly.

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