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What is This?
Seismic control of concrete shear wall using shape memory alloys

Mehdi Ghassemieh, Mahnaz Mostafazadeh and Maryam Saberdel Sadeh

Abstract
Shape memory alloy is a new functional material, which has found increasing applications in many engineering areas. Research efforts have been extended to use shape memory alloy in controlling civil structures. In this article, both pseudoelastic and shape memory effect properties of Nitinol shape memory alloy are implemented for control of concrete shear wall structure when subjected to seismic excitation. First, the behavior of the concrete shear walls equipped with shape memory reinforcements in its pseudoelastic characteristics is assessed, and the results are compared with the behavior of the ordinary concrete shear wall utilizing steel reinforcements. A finite element time history analysis is employed, and the results indicate that the proposed enhancement of the concrete shear wall with shape memory alloy reinforcements is able to reduce the permanent residual strain in the structure and hence attain reasonable improvement in seismic response. Then, the memory effect characteristics of shape memory alloys by imposing pretension in SMA rebar in concrete shear wall are evaluated. The results show that the concrete shear wall equipped with pretension rebars is much stiffer than either the concrete shear wall equipped with pseudoelastic shape memory alloy rebars or the ordinary concrete shear wall with steel.

Keywords
shape memory alloy, seismic control, concrete shear wall, pseudoelasticity

Introduction
Today, a significant number of existing structures utilize the concrete shear walls as lateral resisting system. For the concrete shear wall systems, it is difficult to satisfy the very ductile behavior conditions. Therefore, such structures have often suffered failure caused by earthquake events. Damage assessment has become more important than ever since structural designers have started to employ performance-based design methods, which require structural and member behaviors at different limit states to be predicted precisely. Shearing, bending, sliding, and overturning damages are usually the four kinds of damage that occur in concrete shear wall during earthquake. If concrete shear walls could attain their initial shape to some extent after an earthquake, then problems associated with permanent damage could be mitigated.

Several passive control devices, for either seismic isolation or energy dissipation, have been utilized to mitigate the seismic response. They are based on different concepts and materials, leading to different mechanical behaviors. Shape memory alloys (SMAs) are one example of smart materials that can be used for passive control of structures. SMAs have found applications in many areas due to their high power density, high damping capacity, durability, and fatigue resistance. To this day, one of the main applications of SMAs is using them for passive structure control such as damper. The passive structural control using SMAs takes advantage of the SMA’s damping property to reduce the response and consequently plastic deformation of the structures subjected to severe loadings. SMAs can be effectively used for this purpose via two mechanisms: ground isolation system and energy dissipation system. In a ground isolation system, SMA-made isolators, which are installed between a superstructure and the ground to assemble an uncoupled system, filter the seismic energy transferred from the ground motion to the superstructure so that the damage of the superstructure is attenuated. On the other hand, via the energy dissipation mechanism, martensite or austenite SMA elements integrated into structures absorb vibration energy based on the hysteretic stress–strain relationship. Although the two mechanisms are based on the damping capacity of...
SMAs, they are different in arrangement and function. The SMA isolator provides variable stiffness to the structure according to the excitation levels, in addition to energy dissipation and restoration after unloading. On the other hand, the SMA energy dissipation element mainly aims to mitigate the dynamic response of structures by dissipating energy.

SMA has remarkable properties, such as memory effect (free recovery effect), superelastic effect, changes of the mechanical and electrical properties due to temperature changes, and the constrained recovery effect. Shape memory effect (free recovery effect) means that a large (pseudo-)plastic deformation can be reversed by heating. If the going back is prevented by (e.g. concrete), stress in the SMA will be resulted (constrained recovery effect). The background of these effects is the fact that the crystal lattice structure of SMA consists either of martensite phases in low temperatures or of austenite phases at high temperatures. The described remarkable effects are caused by these two phases and their special transformations. The phase transformations are triggered by temperature changes or mechanical action.

There have been some studies that attempted to evaluate the effectiveness of the use of SMAs in passive control of structures subjected to seismic excitations. Dolce et al. (2000) in a series of publications studied the effectiveness of SMA materials for the use in seismic applications; they also studied the implementation of various states of SMA material for the use of special dampers in structures. They proposed different recentering and/or dissipating devices based on experimental results. Wilde et al. (2000) performed an analytical study to evaluate the behavior of base isolation systems with SMA material for elevated highway bridges. In recent studies on SMA materials, Ozbulut and Hurlebaus (2011) explored effectiveness of SMA/rubber-based isolation systems for protecting bridges against seismic loads by performing a sensitivity analysis. Johnson et al. (2008) determined the effects of SMA restrainer cables on the seismic performance of in-span hinges of a representative multiple-frame concrete box girder bridge subjected to earthquake excitation. They compared the performance of SMA restrainers to that of traditional steel restrainers as restraining devices for reducing hinge displacement and the likelihood of collapse during earthquakes. Dolce and Cardone (2001) experimentally investigated the proper choice of alloy, the effect of temperature, SMA size and loading rate, and number of cycles. Bruno and Valente (2002) showed the effectiveness of the use of SMA materials by analytical measures using simple pseudoelastic constitutive model for SMAs using damage index approach. DesRoches and Delemont (2002) studied the effectiveness of the use of SMA materials as restrainers for control of bridge displacements. They employed a constitutive model adapted directly from experimental data. Baratta and Corbi (2002) analyzed the dynamics of a structural elastic–plastic frame, endowed with pseudoelastic SMA tendons. Masuda and Noori (2002) investigated the optimization of hysteretic characteristics of damping devices based on pseudoelastic SMAs. DesRoches et al. (2004) experimentally evaluated the properties of superelastic Ni–Ti SMAs under cyclic loading to assess their potential for applications in seismic-resistant design and retrofit. Black et al. (2006) studied the behavior of large-diameter SMAs experimentally. Abolmaali et al. (2006) compared the energy dissipative characteristics of bolted T-stub connections using steel and SMA fasteners. Czaderski et al. (2006) tested a reinforced concrete (RC) beam equipped with SMA material and compared it with conventional RC beam; the results proved that by using SMAs, it was possible to produce a RC beam that had variable stiffness and strength. Li et al. (2007) experimentally studied the behavior of smart concrete beams with embedded SMA bundles. They used SMA bundles as actuators to achieve recovery force. Rahman et al. (2008) during a numerical study investigated the effect of cross-sectional geometry on the bending of a beam and also buckling of a column made of SMA. A multilinear constitutive model developed by Motahari and Ghassemieh (2006) is adopted to capture the most common behaviors of SMA. Motahari et al. (2007) also introduced a special SMA damper to have both recentering and energy-dissipating characteristics simultaneously.

The specific objective of this study is to investigate the behavior of a concrete shear wall reinforced with SMA rebars in its two different material characteristics separately. Finite element program, Abaqus, was used in order to evaluate the behavior of the structures subjected to seismic loading. The damaged plasticity model for concrete was used in order to carry out the static nonlinear analysis of concrete shear wall structures. Two different concrete shear walls, one reinforced with SMA together with steel rebar and the other with just steel rebars, have been analyzed. The seismic behavior of the two concrete structure models has been compared in terms of their load displacement behavior. Also, the behavior of two different concrete shear walls, one reinforced with ordinary SMA rebars (memory effect characteristic) and the other with pretension SMA rebar, is investigated. The concrete shear walls with SMAs considered in this study are only subjected to the conventional lateral loadings, and therefore, the effect of loading rate and speed of loading is not considered in this study. The mechanical stress–strain constitutive model similar to the model proposed by Motahari and Ghassemieh (2006) was adopted for this study.

**SMA**

SMAs are a class of new alloys that display multiple incomparable characteristics, including shape memory effects, pseudoelasticity, and high damping characteristics. During deformation, SMAs will undergo phase
transformations instead of intergranular dislocations as typically found in metals. These phase transformations refer to spontaneous shifts between martensitic and austenitic crystal forms. The material properties of the martensite and austenite phases depend upon the temperature and external stress applied to the crystal (see Figure 1(a)). At temperatures slightly above $A_f$ (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 $M_f$ (martensite finish temperature), the material is in its martensitic form and exhibits the shape memory effect. The crystallographic change during a shape memory effect cycle is illustrated in fully twinned martensite forms into alternating layers of rhombic-shaped crystals (see Figure 1(b)). After loading the SMA beyond a certain strain threshold, the twinned martensite begins to shift slightly along twin boundaries to accommodate deformation, in what is commonly referred to as the detwinning process; once the crystal has been detwinned, a residual deformation will remain until the load is removed. However, upon heating the SMA above the $A_f$ temperature, a phase transformation from martensite to austenite occurs, and any residual deformation is recovered. The austenitic crystal form is a planar arrangement where the atoms align themselves in squares. Upon cooling, the material returns to the twinned martensite form, thus completing the shape memory effect cycle. Shape recovery can either be free or constrained. Free recovery allows the material to recover its original shape completely, whereas constrained recovery can develop large internal forces useful for actuator applications or for posttensioning applications.

In recent years, many types of SMAs have been discovered. Among them, Nitinol (Ni–Ti) possesses superior thermomechanical and thermo-electrical properties and is the most commonly used SMA for structural applications because of its large recoverable strain, superelasticity, and exceptionally good resistance to corrosion. In this article, the SMAs are referred to as Nitinol SMAs.

**Modeling SMAs**

This section provides an outline on the modeling aspects of SMA, which is an integrated part of a comprehensive discussion of material properties. Since most civil engineering applications of SMA are related to the use of bars and wires, one-dimensional phenomenological models are often considered suitable. In order to attain the numerical behavior of the structure, finite element computer program (Abaqus) was used in this study. Since in the most finite element programs, the SMA mechanical behavior does not appear by default, the SMA material has been implemented in the computer program by using Fortran as a subroutine material module.

Several researchers have proposed uniaxial phenomenological models for SMA. Figures 2 and 3 show the 1D-superelastic and shape memory effect model (Brocca et al., 2002) implemented in the computer model, where SMA has been subjected to multiple stress cycles at a constant temperature and undergoes stress-induced austenite-to-martensite transformation. The parameters used to define the material model are austenite-to-martensite starting stress, austenite-to-martensite finishing stress, martensite-to-austenite

![Figure 1](image-url)

**Figure 1.** (a) Stress–strain properties of SMA with its pseudoelasticity and shape memory effect. (b) Crystallographic changes through shape memory effect

Source: Brocca et al. (2002).

SMA: shape memory alloy.

![Figure 2](image-url)

**Figure 2.** Superelastic model of SMA incorporated in FEM computer program.

SMA: shape memory alloy; FEM: finite element method.
starting stress, martensite-to-austenite finishing stress, superelastic plateau strain length or maximum residual strain, and modulus of elasticity.

Here in this article, Nitinol SMAs are used as structural reinforcement in the shear walls. Tables 1 and 2 show the mechanical properties with superelastic and shape memory effect characteristics, respectively, defined in Abaqus software as “User Implemented Material.”

### Concrete shear wall model

Before implementing SMA material in concrete shear wall model, first material implemented in the computer program was verified with an experimental concrete shear wall model conducted by Ghorbani-Renani et al. (2009). Figure 4 shows the geometry of experimental shear wall model in section “A-A”, and reinforcement details are also presented. Here the height, length, and thickness of the wall are 2.7, 1.3, and 0.2 m, respectively. The number of longitudinal reinforcements is six 15-mm steel rebars being placed through the width at both sides and four 20- and 25-mm steel rebars confined at the boundaries by 10-mm steel rebars at 100-mm distance. The lateral shear reinforcements are 15-mm steel rebars located at every 300-mm distance. Mechanical properties of material used in the experimental model are given in Table 3.

Figure 5 shows the geometry of finite element model. Analysis was undertaken on a concrete shear wall model with similar mechanical properties of the experimental model.

Figure 6 shows the normalized lateral response of experimental and computer model subjected to increasing monotonic loading. The load was applied at the top of the wall in the lateral direction; $D$ is the lateral displacement of wall measured at the top and $h_w$ is the height of concrete shear wall.

As it is shown, with the nonlinear analysis, finite element model managed to predict the behavior relatively similar to the experimental model.

### Validation of SMAs

In order to verify the SMA material model behavior, material subroutine is implemented in the computer program. Then the numerical material model was tested against the experimental model used by Czaderski et al. (2006), in which they experimented a RC beam with SMA wires (memory effect) and compared its behavior with a conventional concrete beam. The concrete beam section and method of loading implemented on the beam are illustrated in Figures 7 and 8, respectively. The concrete for the test beams had cube strength of 44.3 MPa, tensile strength of 3.1 MPa, and an elastic modulus of 24,200 MPa after 28 days (Czaderski et al., 2006).

Figure 9 shows the comparison of the results obtained from concrete beam with steel reinforcement subjected to the loading protocol given in Figure 8 modeled in the computer program with the results

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**Table 1.** Superelastic mechanical properties.

<table>
<thead>
<tr>
<th>Superelastic properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus of elasticity (GPa)</td>
<td>68</td>
</tr>
<tr>
<td>Austenite-to-martensite starting stress (MPa)</td>
<td>435</td>
</tr>
<tr>
<td>Austenite-to-martensite finishing stress (MPa)</td>
<td>535</td>
</tr>
<tr>
<td>Martensite-to-austenite starting stress (MPa)</td>
<td>335</td>
</tr>
<tr>
<td>Martensite-to-austenite finishing stress (MPa)</td>
<td>170</td>
</tr>
<tr>
<td>Superelastic plateau strain length (%)</td>
<td>8</td>
</tr>
<tr>
<td>Specific weight (kN/m³)</td>
<td>5</td>
</tr>
</tbody>
</table>

Source: Brocca et al. (2002).

**Table 2.** Shape memory effect mechanical properties.

<table>
<thead>
<tr>
<th>Shape memory effect properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus of elasticity (GPa)</td>
<td>70</td>
</tr>
<tr>
<td>Austenite-to-martensite starting stress (MPa)</td>
<td>285</td>
</tr>
<tr>
<td>Austenite-to-martensite finishing stress (MPa)</td>
<td>380</td>
</tr>
<tr>
<td>Specific weight (kN/m³)</td>
<td>65</td>
</tr>
</tbody>
</table>

Source: Brocca et al. (2002).
obtained from experiment (Czaderski et al., 2006). As can be seen, the results indicate relatively good correlation between numerical model and the experimental beam equipped with ordinary steel reinforcement.

Figure 10 shows the comparison of the results obtained from concrete beam with SMA reinforcement subjected to loading arrangement illustrated in Figure 8 modeled in the computer program with the results obtained from experiment (Czaderski et al., 2006). The numerical results are fairly close with the experimental results.

As it was presented, both the numerical models of the ordinary concrete shear wall structure with steel reinforcement as well as the concrete beam with SMA reinforcement are verified with the experimental results. Now, the behavior of the concrete shear wall with SMA reinforcement subjected to lateral load is studied.

**Shear wall with SMA reinforcement**

After verifying the concrete and SMA material model, the behavior of concrete shear wall equipped with SMA with its superelastic and shape memory effect is assessed separately. The physical and mechanical properties of concrete shear wall selected are approximately similar to the experimental model used by Ghorbani-Renani et al. (2009). For reducing the excessive computational time, the so-called boundary reinforcements were omitted and only the 15-mm longitudinal and transverse rebars were kept as reinforcements throughout the concrete wall. This time the concrete shear wall is modeled with SMA rebars and the structure is...
subjected to lateral monotonic loading and then unloads. It must be noted that when the concrete wall utilizes the SMAs with memory effect, after unloading takes place, the SMA rebars are heated in order to recover the residual deformations. Figures 11 and 12 show the behavior of concrete shear wall equipped with different percentages of SMA with two different characteristics.

Figure 11 shows the response of concrete shear wall equipped with different percentages of superelastic SMA reinforcements. As shown, replacing steel reinforcement by SMA caused reduction in residual displacement, slight degradation in wall’s stiffness, and increase in strength of concrete shear wall to some extent. The residual displacement ratio and percentage of its reduction as well as primary stiffness and percentage of its degradation are given in Table 4. The main reason for choosing such parameters is to show the tendency of the stiffness, strength, and permanent deformations to be altered as the percentage of the SMA is changed with respect to the steel reinforcements.
As it is shown, placing SMA with its superelastic characteristic as reinforcement caused an increase in strength of the wall and a decrease in the residual displacement and stiffness, especially when percentage of SMA becomes more than 50%. For instance using 40% steel and 60% SMA, the residual displacement and percentage of reduction are 0.0057 and 82.8%, respectively, and the primary stiffness and percentage of degradation are 150 and 42.5%, respectively; using 20% steel and 80% SMA, the residual displacement and percentage of reduction become 0.0026 and 92.1%, respectively, and the primary stiffness and percentage of degradation become 124 and 52.5%, respectively. Therefore, using SMA material with superelastic characteristic instead of steel in concrete wall can reduce damage implemented to concrete shear wall during a relatively heavy earthquake, if the steel and SMA reinforcements are well proportioned.

Figure 12 shows the response of concrete shear wall equipped with different percentages of SMAs with memory effect characteristic (from 0% to 100% in 20% range). As shown, replacing steel by SMA caused reduction in residual displacement, stiffness, and strength of concrete shear wall partly. The residual displacement ratio and reduction percentage as well as primary stiffness and percentage of its degradation are given in Table 5.

As it is shown, placing SMA with memory effect characteristic as reinforcement caused a reduction in the strength of wall, stiffness, and residual displacement, especially when percentage of SMA reinforcement becomes more than steel reinforcement. For instance using 40% steel and 60% SMA, the residual displacement and percentage of reduction are 0.0305 and 10.6%, respectively, and the primary stiffness and percentage of degradation are 185 and 29.1%, respectively; using 20% steel and 80% SMA, the residual displacement and percentage of reduction become 0.0055 and 82%, respectively, and the primary stiffness and percentage of degradation are 146 and 44.1%, respectively.

### Table 4. Residual displacement, primary stiffness, and percentage of their reduction in concrete wall.

<table>
<thead>
<tr>
<th>Percentage of rebar</th>
<th>Residual displacement ($\Delta/h_w$)</th>
<th>Percentage of reduction</th>
<th>$V/(b_w l_w)$ (MPa)</th>
<th>$\Delta/h_w$</th>
<th>Primary stiffness (MPa)</th>
<th>Percentage of degradation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% steel</td>
<td>0.0341</td>
<td>0</td>
<td>1.305</td>
<td>0.005</td>
<td>1.305/0.005 = 261</td>
<td>0</td>
</tr>
<tr>
<td>80% steel and 20% SMA</td>
<td>0.0323</td>
<td>3</td>
<td>1.159</td>
<td>0.0049</td>
<td>236</td>
<td>9.6</td>
</tr>
<tr>
<td>60% steel and 40% SMA</td>
<td>0.0225</td>
<td>32.4</td>
<td>1.095</td>
<td>0.0052</td>
<td>210</td>
<td>19.5</td>
</tr>
<tr>
<td>40% steel and 60% SMA</td>
<td>0.0057</td>
<td>82.8</td>
<td>1.305</td>
<td>0.0087</td>
<td>150</td>
<td>42.5</td>
</tr>
<tr>
<td>20% steel and 80% SMA</td>
<td>0.0026</td>
<td>92.1</td>
<td>1.335</td>
<td>0.0108</td>
<td>124</td>
<td>52.5</td>
</tr>
<tr>
<td>100% SMA</td>
<td>0.0004</td>
<td>98.7</td>
<td>1.336</td>
<td>0.0121</td>
<td>110</td>
<td>57.8</td>
</tr>
</tbody>
</table>

SMA: shape memory alloy.

### Table 5. Residual displacement, primary stiffness, and percentage of their reduction in concrete wall.

<table>
<thead>
<tr>
<th>Percentage of rebar</th>
<th>Residual displacement ($\Delta/h_w$)</th>
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<tr>
<td>100% steel</td>
<td>0.0341</td>
<td>0</td>
<td>1.305</td>
<td>0.005</td>
<td>1.305/0.005 = 261</td>
<td>0</td>
</tr>
<tr>
<td>80% steel and 20% SMA</td>
<td>0.0339</td>
<td>0.58</td>
<td>1.221</td>
<td>0.0051</td>
<td>239</td>
<td>8.4</td>
</tr>
<tr>
<td>60% steel and 40% SMA</td>
<td>0.0322</td>
<td>2.6</td>
<td>1.205</td>
<td>0.0061</td>
<td>197</td>
<td>24.5</td>
</tr>
<tr>
<td>40% steel and 60% SMA</td>
<td>0.0305</td>
<td>10.6</td>
<td>1.108</td>
<td>0.006</td>
<td>185</td>
<td>29.1</td>
</tr>
<tr>
<td>20% steel and 80% SMA</td>
<td>0.0055</td>
<td>82</td>
<td>1.025</td>
<td>0.007</td>
<td>146</td>
<td>44.1</td>
</tr>
<tr>
<td>100% SMA</td>
<td>0.00014</td>
<td>95</td>
<td>0.941</td>
<td>0.0068</td>
<td>138</td>
<td>47.1</td>
</tr>
</tbody>
</table>

SMA: shape memory alloy.
From the results obtained, one can see that using superelastic instead of memory effect in concrete shear wall causes strength of shear wall to increase and more degradation in stiffness and residual displacement. However, the ability of the SMA rebars in the concrete shear wall with memory effect to dissipate energy showed to be more than the superelastic SMA rebars.

If one could improve the strength through the memory effect, then a better behavior in the overall system when subjected to lateral loads such as seismic loading can be observed. Thus, in the second approach, the SMA rebars with the shape memory effect were subjected to pretensioning force, which can normally be accomplished through the thermal process. Then the displacements are applied, and the behavior of the new system is evaluated. In order to apply the pretensioning in SMA rebars, deformation was dictated to SMAs before using them in concrete shear wall. Then through thermal process or anchoring techniques, the deformations of the SMA rebars may be brought down to zero. Figure 13 shows the result of concrete shear wall behavior equipped with regular and pretensioning SMA rebars.

In order to see the ultimate variations in the behavior of such a system, the maximum pretensioning based on the ultimate strength of SMA as well as concrete material was applied. As it is illustrated, a concrete shear wall with pretension SMA rebars is much stiffer and stronger than a concrete shear wall with ordinary SMA rebars. As it was expected, increasing the percentage of pretension SMA rebars in a concrete shear wall results in decreasing the residual displacement of concrete shear wall. Also, using memory effect with pretensioning absorbs more energy in comparison with ordinary SMA during earthquake, and this means more safety, thereby reducing the maintenance wall.

**Conclusion**

This article examined a novel approach to reduce the vulnerability of RC shear wall structures by utilizing a smart SMA material. The effectiveness of two different characteristics of SMA rebars in concrete shear wall was assessed separately. As illustrated, replacing more than 50% of steel rebars with SMAs that have superelastic behavior caused unexpected reduction in residual displacement, reduction in initial or primary stiffness, and increase in strength of the concrete shear wall. Replacing steel rebars with SMAs that have memory effect behavior result in reduction of the strength in the shear wall, a drop in residual displacement, and decrease in initial stiffness, but not as much as SMA with superelastic case. However, the energy dissipation in the memory effect case is more than in the superelastic case when subjected to loading and then unloading. It was shown that the overall behavior of the wall system was improved by pretensioning the SMA rebars with the memory effect. Increasing wall strength and capability of wall for dissipating energy as well as decreasing the residual permanent displacements are such improvements attained when the SMA rebars are pretensioned.

Excessive residual displacements have been identified as one of the major causes that make the rehabilitation of damaged structures difficult and costly after an earthquake. SMAs are unique materials that can recover most of its large inelastic deformations. If SMA can be used as reinforcement in concrete walls, it can initiate a major progress in seismic design, whereby the repair cost may be substantially reduced and the structure may remain serviceable even after a severe earthquake.

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**References**


