# Seismic Performance of RC Frame-Shear Wall Structure with Novel Shape Memory Alloy Dampers in Coupling Beams

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### SUMMARY:

Frame-shear wall system is widely adopted in high rise buildings. According to the concept of ductility seismic design, coupling beams in shear walls are required to yield prior to the damage of wall limbs. However, damage in coupling beams results in high repair cost post earthquake and even in some cases it is difficult to repair the coupling beams if the damage is severe. In order to solve this problem, a novel passive SMA damper was proposed in this study. After earthquakes deformation of the dampers can recover automatically because of the pseudoelasticity of austenite SMA material. In order to verify the validity of the proposed dampers, seismic responses of a planar 18-story frame-shear wall structure with such passive SMA dampers in coupling beams was investigated. Analytical results indicate that the displacement responses of the frame-shear wall structure with such dampers can be reduced remarkably.

Keywords: Shape memory alloy, Passive damper, Frame-shear wall, Coupling beam, Seismic performance

# **1. INTRODUCTION**

Frame-shear wall system is widely adopted in high rise buildings because of its double lateral force resisting system and high lateral stiffness in resisting earthquakes. According to the concept of ductility seismic design, coupling beams in shear walls are required to yield and dissipate seismic energy prior to the damage of wall limbs. But in shear walls, coupling beams are formed because of the openings on RC walls and their span-depth ratio is usually small (usually <5), therefore their failure is brittle. This kind of damage mode has small energy dissipation capability because the strength of the components decreases rapidly once it is damaged. So it will be helpful to improve energy dissipation capability of the coupling beams if their energy dissipation mode is designed to be ductile. Much effort has been devoted for changing damage mode of RC coupling beams in the past three decades. Such effort includes changing reinforcement arrangement (the beams are reinforced with diagonal (Wei and Ai, 2006; Paulay and Binney, 1974) or rhomboidal reinforcement (Dai and Sun, 1993)), assembling steel (Wang and Sang, 1995) or making splits (horizontal or vertical splits (Yuksel, 2008)) in the beams or even replacing the RC beams with steel beams (Park and Yun, 2006; Gong and Shahrooz, 2001). The brittle damage mode of RC coupling beams is changed to some extent by such works but there is still another problem. The beams are inevitably seriously damaged after earthquake. They need to be repaired and the building cannot be used immediately. Also, the repair is usually costly. Some other researchers then attempted to add passive energy dissipation devices in coupling beams (Teng et al., 2007; Madsen et al., 2003). Most seismic energy is dissipated by the dampers and then the damage in RC beams is alleviated. The passive dampers that were used in these studies include friction dampers and metallic dampers. However, residual deformation will be remained in these dampers and they need to be replaced after earthquake.



In this study, we suggest using shape memory alloy (SMA) dampers in coupling beams. The austenite SMA wires are adopted in the dampers, so the seismic energy will be dissipated because of the pseudoelastic property of these wires. At the same time, residual deformation will not be remained in the damper after earthquake. From 1990s, SMA has been developed as passive dampers in mitigating structural seismic responses due to its special pseudoelastic property. Corresponding researches can be found in literatures (Li et al., 2008; Han et al., 2003; Dolce et al., 2001; Dolce and Cardone, 2001). Even, Indirli (2001) used SMA dampers in rehabilitation of a real structure (the S. Georgio church bell tower). But SMA has not been used yet in structural seismic response mitigation of frame shear wall structure.

In this study, the RC coupling beam is first vertically split in the middle and then become two cantilevers. The SMA damper is then installed between the cantilevers and connects them to be a complete beam again. The dampers can be considered as a special energy dissipation element in the beam. The axial force in the beams can still be transferred through the dampers, thus the wall limbs on the left and right sides of the coupling beams can still work as a complete system in resisting lateral earthquake force.

The conceptual design of the SMA damper is described first in this paper. After that, the appropriate characteristic parameters of the dampers for their seismic design are proposed. Impact analysis of the characteristic parameters of the dampers to structural seismic response is conducted through a planar 18-story frame shear wall structure.

### 2. CONCEPTUAL DESIGN OF SMA DAMPER IN COUPLING BEAMS

SMA damper is a type of deformation sensitive passive device, thus it should be placed at the locations on structures which have relative large deformation. As for coupling beams in shear walls, if the passive damper is incorporated at the middle rather than the ends of the beam, the deformation of the damper will be much larger. Similar viewpoint has been verified by Chung et al. (2009).

As above mentioned, in this study, the coupling beam between wall limbs is vertical split in the middle. The novel SMA damper is incorporated between the cantilever ends, as shown in Fig. 2.1 (a). The assembly parts of the damper are shown in Fig. 2.1 (b). The damper is composed with four steel components (assembly parts I-IV) and two groups of SMA wires (group A and B). As depicted in Fig. 2.1 (b), parts I to IV are all welded by steel plates with various shape and thickness. Parts I and II are pre-embedded in the left and right side cantilever ends (Fig. 2.1 (c)) and are welded with the reinforcement in the beam through tie bars. Parts III and IV are connected with Part I from the front and offside of the beams through bolts. Part II has two elliptic "ears" while Parts III and IV have two holes at the exact corresponding positions. The "ears" on part II drill through the holes on parts III and IV. They can freely move up and down in the holes, but along horizontal direction they can only move in a very small space. So the axial force in the beam can be transferred through the damper when the relative displacements between the two cantilever ends are big (bigger than the gaps between the "ears" and the holes along the horizontal direction). Also, four small "ears" are welded, respectively, beside the upper and lower edges of the holes on parts III and IV. SMA wires are wound around the ears on part II and III (or on part II and IV). As shown in Fig. 2.1 (b), group A SMA wires wound around the upper ends of the "ears" on part II and the lower "ears" on parts III and IV. While group B wires are wound around the lower ends of the "ears" on part II and the upper "ears" on parts III and IV. Austenitic NiTi wires are adopted in the dampers so they will exhibit pseudoelastic behaviour. Under earthquake forces, bending and axial deformation are dominant in the wall limbs. In this situation, the cantilevers will rotate as well as move vertically along the deformation direction of the walls. Then relative vertical displacement will occur between cantilever ends and this displacement will transfer to SMA wires through components I to IV. Once the SMA wires are tensioned, energy will be dissipated due to phase transformation inside SMA. A schematic deformation map is given in Fig. 2.2 to help

readers better understand the work mechanism of the dampers. Always, one group of SMA wires will be tensioned whichever direction (left or right) the wall limbs vibrate along.



**Figure 2.1.** The location and assembly parts of the SMA damper in the coupling beam: (a) location of the SMA damper; and (b) assembly parts of the damper



**Figure 2.2.** Schematic deformation diagram of the SMA damper: (a) initial state; (b) group A SMA wires are tensioned when structure vibrates to left; and (c) group B SMA wires are tensioned when structure vibrates to right

Large number of experiments on mechanical properties of austenitic NiTi SMA wires were ever conducted by the authors and relative results can be found in our previous works (Li et al., 2008). A simplified flag-like model was proposed in this study to fit the experimental stress-strain curves of SMA wires, as shown in Fig.2.3 (a). In this figure,  $\sigma_y$  and  $\varepsilon_y$  respectively represent yield stress and strain of SMA wires, and  $\sigma_u$  and  $\varepsilon_u$  are respectively elastic unloading stress and strain.  $E_0$  and E' are the initial elastic modulus and post-yield modulus of SMA wires, respectively. The values of these key parameters were obtained through fitting of the experimental curves and also were given in Fig.2.3 (a). These values are the basis in subsequent design of the SMA dampers. Therefore the simplified force-deformation relationship of the SMA damper is symmetric when it is tensioned or compressed, as shown in Fig.2.3 (b). In this figure,  $F_{dy}$  and  $\Delta_{dy}$  are yield force and deformation of SMA damper, and  $F_{du}$  and  $\Delta_{du}$  are respectively elastic unloading force and deformation.  $K_d$  and  $K_d'$  are the initial and post-yield stiffness of the damper.



**Figure 2.3.** Simplified model of NiTi wires and the SMA damper: (a) simplified model describing stress-strain curve of SMA wires; and (b) simplified model describing force-deformation curve of SMA damper.

#### **3. DESIGN PARAMETERS OF THE SMA DAMPER**

Design parameters of the SMA damper should be the parameters that affect structural seismic responses apparently. Then the values of these parameters should be assigned within an appropriate range. For the seismic design of the SMA dampers in RC coupling beams, three parameters are to be considered:

### (1) Yield displacement ratio (YDR)

As mentioned above, our SMA dampers are installed in the coupling beams, they are naturally hoped to yield before the yielding of wall limbs. Then the first design parameter of SMA damper should be the ratio of yield displacement of the damper to that of the wall limes in this story. However, the deformation of SMA dampers is along vertical direction but structural interstory drift is horizontally. They should be unified.

If the ratio of yield forces between SMA dampers and the coupling beams are appropriate (the damper is designed as a fuse element), then we can hope that the deformation of coupling beams mainly occur in the dampers. The following relationship can be obtained under such hypothesis,

$$\Delta_{by} = \frac{l_c + l_w}{h} \Delta_{sy} \tag{3.1}$$

where  $\Delta_{sy}$ =minimum yield displacement of the structural story in which the SMA dampers are installed;  $\Delta_{by}$ =the relative vertical displacement between cantilevers at the moment  $\Delta_{sy}$  occurs;  $l_c$ =clear span of coupling beam;  $l_w$ =width of wall limb; h=story height. Fig. 3.1 shows such relationship between displacements of coupling beam and wall limb in Eqn. 3.1. This is only a simplified calculation method because the wall limbs and coupling beams are all considered as rigid body without bending deformation.



Figure 3.1. Relationship of displacements between coupling beams and wall limbs

Then the first design parameter of the SMA damper is converted to the ratio of yield displacement of the damper to  $\Delta_{by}$ , as given in Eqn. 3.2. The damper will yield before the yielding of wall limbs if  $\Delta < 1$ .

$$\Delta_{by} = \frac{l_c + l_w}{h} \Delta_{sy} \tag{3.2}$$

#### (2) Yield force ratio (YFR)

To guarantee the yield force of the SMA damper is appropriate, that is, the RC beams will not damage before the dampers work, the yield force ratio is defined as the second parameter. That is the ratio of yield force of SMA damper to the shear force in coupling beam of the yielding story corresponding to  $\Delta_{sv}$ , as shown in Eqn. 3.3.

$$\Gamma = F_{dv} / F_{bv} \tag{3.3}$$

 $F_{by}$  can also be obtained through pushover analysis of the bare structure and it is the shear force in coupling beam of the yielding story corresponding to  $\Delta_{sy}$ .

(3) Beam to wall stiffness ratio (BWSR)

The stiffness of the coupling beams will be changed due to the addition of SMA dampers. Therefore the ratio of stiffness between coupling beams to wall limbs is changed. In Chinese seismic design code for shear wall, this ratio is referred to as "working coefficient of the whole structural system" (usually represented by the letter  $\alpha$ ). Failure mode of shear wall differ greatly when the value of  $\alpha$  is in various range. For example, the coupling beams are thought too weak thus can't connect wall limbs as a whole system when  $\alpha < 1$ . While if  $\alpha > 10$ , the coupling beams will become too strong and damage will be concentrated in wall limbs. So  $1 < \alpha \le 10$  is appropriate.

Calculation of  $\alpha$  for the coupling beams with SMA dampers is not the same as that of conventional RC coupling beams. The novel coupling beam can be simplified as a beam with such support and connection condition as shown in Fig. 3.2. The  $\alpha$  for this case can be calculated as

$$\alpha^{2} = \frac{\frac{6E\tilde{I}_{b}\cdot k_{d}\cdot c^{2}}{k_{d}\cdot a^{3} + 3E\tilde{I}_{b}}}{Th\frac{\sum EI_{wi}}{H^{2}}}$$
(3.4)

where E =elastic modulus of concrete used in the beam;  $k_d$  =initial stiffness of SMA damper in the middle of beam; 2c =distance between centroid of two adjacent wall limbs; 2a =calculation length of coupling beam and is equal to 2c minus the length of rigid link at two ends of coupling beam;  $\tilde{I}_b$  =moment of inertia of the RC beam considering the shear deformation; T =influence coefficient considering axial deformation which indicates how much the wall is weakened due to openings; h =story height; H =height of the structure;  $I_{wi}$  = moment of inertia of wall limbs corresponding to the wall limbs' centroid respectively.

$$\widetilde{I}_{b} = \frac{I_{b}}{1 + \frac{3\mu E I_{b}}{GA_{b} \cdot a^{2}}}$$
(3.5)

where  $I_b$  =moment of inertia without considering shear deformation;  $\mu$  =modified coefficient induced by uneven cross section shear stress which is equal to 1.2 for beams with rectangular cross section; G =shear modulus of concrete used in beams;  $A_b$  =cross section area of coupling beam.



Figure 3.2. Simplified model of the coupling beam with SMA dampers in the middle

#### 4. ANALYTICAL MODEL OF FRAME SHEAR WALL AND SMA DAMPER

A 18-story frame-shear wall structure is selected as the model structure (as shown in Fig. 4.1). The site soil can be classified as type II according to the code for seismic design of buildings in China (GB50011-2010). The level of design earthquake is 10% probability of exceedance in 50 years and the corresponding PGA of earthquake input is 0.2g.

The height of each story is 3.6m except for the first story (4.5m). Total height of the structure is 65.7m. Thickness of walls is 0.3m and the size of columns at the ends of walls is 0.6m×0.6m. Cross section of frame columns, frame beams and coupling beam are 0.7m×0.7m, 0.3m×0.7m and 0.3m×1.5m, respectively. Fig.4.1 shows the bare and damped structures. Compressive strength of concrete used in coupling beams and frame beams is 20.1MPa. In columns and walls, compressive strength of concrete are 26.8MPa (stories1-9) and 23.4MPa (stories10-18). Tensile strength of bars used for hoops is 235MPa. For longitudinal reinforcement in frame beams, coupling beams and wall limbs, the strength of steel is 335MPa, while tensile strength of longitudinal bars used in frame columns and end columns of shear walls is 400MPa. The reinforcement ratio of horizontal and vertical distributed bars in wall limbs is 0.3%.



**Figure 4.1.** The bare and damped structures: (a) plan of shear wall in the bare structure; (b) finite element model of the SMA damper; (c) schematic map of the bare structure; (d) finite element model of the bare structure; and (e) schematic map of structure with SMA dampers at each floor

Finite element models are established for the bare and damped structures by using the software ABAQUS. Longitudinal reinforcement in beams and columns, as well as distribution reinforcement in walls, are considered in the finite element models, but hoops in all components are ignored.

SMA dampers are placed in the middle of coupling beams at each floor, as shown in Fig. 4.1 (e). Each coupling beam is split vertically into two L-shaped cantilevers (Fig. 4.1 (b)) which are connected each other by four horizontal hinged link elements. Thus axial force can be transferred between the two cantilevers at each floor. Also, the two cantilevers are connected vertically by a three-dimensional truss element to model SMA damper. Constitutive model in Fig. 2.3 (b) is used to describe

force-displacement relationship of SMA dampers.

The SMA dampers with various YDR and YFR are incorporated into the coupling beams to address the effects of dampers' design parameters on structural seismic response. Thus appropriate values of the design parameters for the novel SMA dampers can be given. Three YDRs (0.4, 0.6 and 0.8) and three YFRs (0.6, 0.9 and 1.2) are considered respectively. For each scenario, the SMA dampers are installed at each floor and have the same design parameters. In the design of these dampers, the parameters  $\Delta_{by}$  (relative vertical displacement between cantilevers at the moment  $\Delta_{sy}$  occurs, =1.67mm) and  $F_{by}$  (shear force in coupling beam of the yielding story corresponding to  $\Delta_{sy}$ , =451.1kN) at the first story of the bare structure are used as the design basis. The resulted yield displacement and yield force for these dampers are given in Table 4.1, together with corresponding BWSR and initial stiffness for these dampers (the ratio of YFR to YDR, represented by  $K_d$ ). The BWSR of all structures with SMA dampers is smaller than the bare structure ( $\alpha = 11.5$ ).

YDR	$\Delta$ =0.4	$\Delta = 0.6$	$\Delta = 0.8$
YFR	$(\Delta_{dy} = 0.7 \text{mm})$	$(\Delta_{dy} = 1.0 \text{mm})$	$(\Delta_{dy} = 1.4 \text{mm})$
Γ=0.6	α=5.971	<i>α</i> =5.114	<i>α</i> =4.544
$(F_{dy} = 270.7 \text{kN})$	$K_d = 4.052 \times 10^5 \text{N/mm}$	$K_d = 2.701 \times 10^5 \text{N/mm}$	$K_d = 2.026 \times 10^5 \text{N/mm}$
Γ=0.9	<i>α</i> =6.860	α =5.971	<i>α</i> =5.358
$(F_{dy} = 406.0 \text{kN})$	$K_d = 6.078 \times 10^5 \text{N/mm}$	$K_d = 4.052 \times 10^5 \text{N/mm}$	$K_d = 3.039 \times 10^5 \text{N/mm}$
Γ=1.2	<i>α</i> =7.483	α =6.601	<i>α</i> =5.971
$(F_{dy} = 541.3 \text{kN})$	$K_d = 8.104 \times 10^5 \text{N/mm}$	$K_d = 5.402 \times 10^5 \text{N/mm}$	$K_d = 4.052 \times 10^5 \text{N/mm}$

**Table 4.1.** Parameters of SMA dampers in coupling beams

The Northridge earthquake (the CWC270 component recorded at the 90009 N. Hollywood-Coldwater Can station during the Northridge earthquake of January 17, 1994) is selected as excitation input for the bare and damped structure. The absolute peak acceleration is adjusted to 0.40g, which corresponds to large earthquake for the site and earthquake resistance level of the structure specified in Chinese seismic design code. Fig. 4.2 gives time history and elastic response spectrum (under large earthquake) of Northridge earthquake.



Figure 4.2. Earthquake input: (a) time history of Northridge earthquake; and (b) response spectrum of Northridge earthquake

### 5. ANALYTICAL RESULTS

Fig.5.1 shows maximum interstory drift and story shear force at each floor of the bare structure and the structures with various SMA dampers. Note that both YDR and YFR have significant influence on structural responses. In the three scenarios that SMA dampers have various YDRs (with the same YFR), the case  $\Delta = 0.4$  gets smaller structural interstory drifts than other cases, as shown in Fig. 5.1 (a). That is because a damper with smaller YDR means the dampers can yield and dissipate seismic energy earlier.

For the three scenarios that SMA dampers have various YFRs (with the same YDR), the case  $\Gamma = 1.2$  gets the best control effects on structural interstory drifts, as shown in Fig. 5.1 (b). The story shear forces of the structures with various SMA dampers are almost reduced compared with the bare structure. Also, there is no obvious difference between the story shear forces of the structures when they are installed with various dampers (Fig. 5.1 (c)).



**Figure 5.1.** Maximum interstory drift and story shear at each floor of the bare and damped structures: (a) maximum interstory drift of structures with various SMA dampers (with various YFRs but the same YDR); (b) maximum interstory drift of structures with various SMA dampers (with various YDRs but the same YFR); and(c) maximum story shear force of structures with various SMA dampers (with various YFRs but the same YFR).



**Figure 5.2.** The properties of damper with  $\Gamma = 1.2$  and  $\Delta = 0.4$ : (a) maximum strain of dampers at each floor; and (b) stress-strain curve of the damper in story4; and(c) force-deformation curve of the damper in story4

The maximum strain of dampers at each floor ( $\Gamma$ =1.2 and  $\Delta$ =0.4) is shown in Fig. 5.2 (a). The stress-strain curve and force-deformation curve of the SMA damper at the fourth story are also given in Fig. 5.2. It can be found that all the maximum strain of dampers is within recoverable strain of pseudoelasticity under large earthquake, which indicates that residual deformation does not remain in the damper after earthquake.

The mean control effects on structural interstory drift and story shear force of all stories are calculated and shown in Fig. 5.3. It is noted that the following conclusion can be obtained: for the SMA dampers in shear walls similar to the model structure in this study,  $\Gamma = 1.2$  and  $\Delta = 0.4$  are appropriate to get better control effects.



**Figure 5.3.** Mean control effects of 18 storys with various YDR and YFR dampers: (a) mean control effect on structural interstory drift ; and (b) mean control effect on structural interstory drift

### 6. CONCLUSIONS

In this study, a novel SMA damper that is installed in coupling beams of frame-shear wall structures was developed. Nonlinear time history analysis was conducted for an 18-story frame-shear wall structure with such SMA dampers to verify seismic response control effect of this damper.

(1) It is noted that the vertical displacement in the middle of coupling beams due to the flexural deformation in shear walls is sufficient to induce the hysteretic behavior of the SMA dampers. Seismic responses of frame-shear wall structures with such type of SMA dampers can be reduced effectively.

(2) For the novel SMA dampers, the coefficients include yield displacement ratio (YDR), yield force ratio (YFR) and coupling beam to wall limbs stiffness ratio (BWSR) should be considered as the design parameters.

(3) The BWSR of all structures with SMA dampers should be assigned within an appropriate range. It should not differentiate from the working coefficient (ratio of stiffness between coupling beams to wall limbs) of the bare structure too much. Structural displacements will be amplified significantly if BWSR is too large, but poor control effects on structural displacements will be observed if BWSR is too small.

(4) Smaller YDR will make SMA dampers yield earlier and dissipate seismic energy. And for the SMA dampers in shear walls similar to the model structure in this study,  $\Gamma = 1.2$  and  $\Delta = 0.4$  are appropriate to get better control effects.

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