The Seismic Response Analysis of Isolation Structure with Shape Memory Alloy Re-centring Dampers

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ABSTRACT :

Shape memory alloy (SMA) is provided with preferable damp capacity at pseudo-elasticity state, applying this property, a SMA re-centring damper is introduced by some scholars. In this paper, the new isolation system combining the above damper with laminated rubber bearing is proposed, so as to obtain preferable isolation character and re-centring capacity. To illustrate the feasibility and effectiveness of the proposed system, the following work is done: First, according the constitution model of SMA at pseudo-elasticity state the program is compiled, then the mechanical behavior of damper is simulated and the hysteretic curve is obtained. Based on the above, a linear restoring model for SMA re-centring damper is put forward. And then, the program based on the theory of story model for shear tape is compiled to conduct elasto-plastic time history analysis of practical structure examples, According to the results, the seismic response of structure is significantly reduced, and the fully re-centring capacity after earthquake is obtained by this isolation system.

KEYWORDS: SMA re-centring damper, laminated rubber bearing, base isolation, elasto-plastic time history analysis

1. Introduction

To provide the systems with adequate dissipation capacity, the hysteretic curves of the above isolation devices are usually rectangular shaped or shuttle shaped, which may cause permanent deformation of isolation layer in the horizontal direction. Because the smart materials have excellent mechanical performance, the structure vibration control applied them is focused on recently. One class of such material is shape memory alloy (SMA). Mauro Dolce introduces a new type of SMA re-centring damper making use of the pseudo-elasticity property, which can provide with considerable energy dissipation capacity and return to its original state after unloading. In this paper, the new isolation system combining the above damper with laminated rubber bearing is proposed to provide the isolation structure with re-centring capacity. To illustrate the feasibility and effectiveness of mentioned system, the following research work is done.

2. The constitutive model for pseudo-elasticity of SMA

The pseudo-elasticity is one of properties of SMA. If the material temperature is greater than A_f (the temperature at which the inverse transformation finishes), the large strain attained on loading is completely recovered at the end of unloading. This remarkable process gives rise to energy-absorbing capacity with zero residual strain. A variety of constitutive laws have been developed, but engineering applications emphasize Brinson laws based on phenomenological theory, which avoid difficult-to-measure parameters and can be easily utilized in structure analyses such as finite element procedure. Brinson laws for pseudo-elasticity analyze can be expressed as:

$$\sigma - \sigma_0 = D(\xi)\varepsilon - D(\xi_0)\varepsilon_0 + \Omega(\xi)\xi - \Omega(\xi_0)\xi_0 \qquad (2.1)$$

$$D = D_A + \xi(D_M - D_A) \tag{2.2}$$

$$\xi = \xi_s \tag{2.3}$$

$$\Omega = -\varepsilon_L \cdot D \tag{2.4}$$

where, D_A and D_M respectively stands for elasticity modulus on austenite and martensite, ε_L is maximum resumable strain, ξ is martensitic percent, ξ_s and ξ_T respectively stands for martensitic percent induced by stress and temperature, they can be calculated by phase change equation as follow.

When the stress decrease, also $C_A(T - A_f) \le \sigma \le C_A(T - A_s)$, the interior crystal lattice changes from martensite to austenite and phase change equation is:

$$\xi_s = \frac{\xi_{s0}}{2}\{\cos[\frac{\pi}{A_f - A_s}(T - A_s - \frac{\sigma}{C_A})] + 1\} \tag{2.5}$$

When the stress increase, also $\sigma_s^{cr} + C_M(T - M_s) \le \sigma \le \sigma_f^{cr} + C_M(T - M_s)$, the interior crystal lattice changes from austenite to martensite and phase change equation is:

$$\xi_s = \frac{1 - \xi_{s0}}{2}\cos\{\frac{\pi}{\sigma_s^{cr} - \sigma_f^{cr}}[\sigma - \sigma_f^{cr} - C_M(T - M_s)]\} + \frac{1 + \xi_{s0}}{2} \tag{2.6}$$

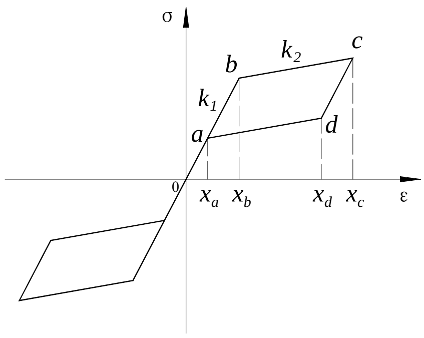

Figure 1 the subsection linear constitutive model

The detailed parameter of the model is expressed in figure 1. Here, segment $0ab$ and cd is respectively in austenitic state and martensitic state, the slope is k_1, and segment bc and da is respectively in process of martensitic transformation and austenitic transformation, the slope is k_2. Then the restoring force $F(x)$ of SMA in pseudo-elasticity process is expressed as follow:

$$F(x) = \begin{cases} k_1 x & (0ab, a0) \\ (k_1 - k_2)x_b sign(x) + k_2 x & (bc) \\ (k_1 - k_2)(x_b - x_c)sign(x) + k_1 x & (cd) \\ (k_1 - k_2)x_a sign(x) + k_2 x & (da) \end{cases} \tag{2.7}$$

3. Research on SMA re-centring damper

3.1 Configuration and functioning principle of SMA re-centring damper

Mauro Dolce introduced a unique SMA re-centring damper in MANSIDE（Memory Alloys for New Seismic Isolation and Energy Dissipation Device）project. Making use of pseudo-elasticity property of SMA, the damper is provided with considerable energy dissipation and fully re-centring capacity. The specific configuration of damper is showed in figure 2.

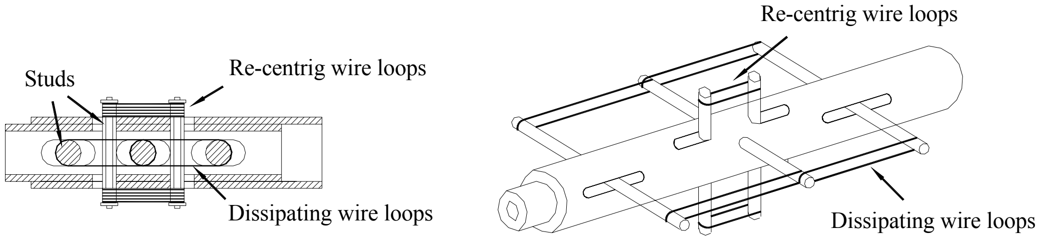

Figure 2 Specific configuration of the SMA re-centring damper

Because the re-centring group has infinite initial stiffness, it can be realized a non-linear rigid-elastic behavior when omitting its energy dissipation capacity. The dissipation group can be characterized a rigid-plastic behavior. When this two behaviors are combined together in a parallel system, the resulting cycles is a "double flag" model (Figure 3).

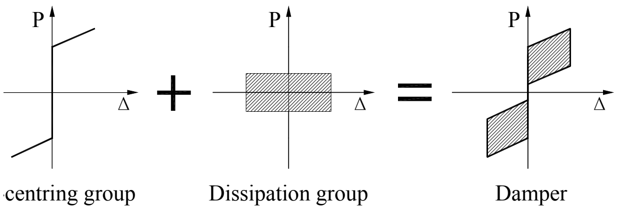

Figure 3 The mechanical model of SMA re-centring damper

3.2 The program analysis for mechanical property of SMA re-centring damper

In order to verify the actual property of SMA re-centring damper, the mechanical behavior of damper under static reversed loading is analyzed by program, and the hysteretic curve is obtained according to Brinson constitutive laws. Assuming a SMA re-centring damper, the Ni-Ti alloy which constant showed in table 1 is applied in it. The geometry parameter of SMA wires is listed as follow. Re-centring group: diameter d=4mm, length L=1010mm, number n=1,pre-strain 1％, Dissipation group: diameter d=4mm, length L=1035mm, number n=4, pre-strain 3.5％.The environmental temperature is 20℃. The result shows that the "double flag" hysteretic curve is obtained (Figure4), which are accords with the theory analysis.

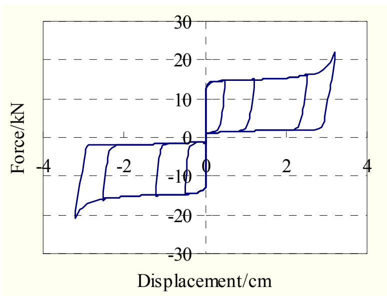

Figure 4 The simulating behavior of SMA re-centring damper

3.3 The restoring model of SMA re-centring damper

According to the constitutive model of SMA (equation 2.7), the restoring model of re-centring group and dissipation group is respectively simplified, then the model of damper is obtained through adding the above two models, and the parameter can be calculated. Because the dissipation group is characterized considerable energy dissipation capacity, it is simplified parallelogram restoring property. The parameters of this model are listed as follow (Figure 5): the maximum displacement $\Delta_{\max}$, the maximum restoring force $F_{d\max}$, the loading stiffness K_{d1} and the unloading stiffness K_{d2} .

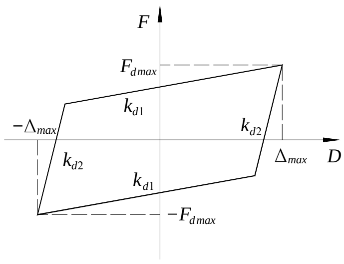

Figure 5 The restoring parameters in dissipation group

$$F_{d\max} = n_d A_d [(k_1 - k_2)(x_b - x_a) + 2k_2 \frac{\Delta_{\max}}{L_d}] \tag{3.1}$$

$$K_{d1} = \frac{2k_2 n_d A_d}{L_d} \tag{3.2}$$

$$K_{d2} = \frac{2k_1 n_d A_d}{L_d} \tag{3.3}$$

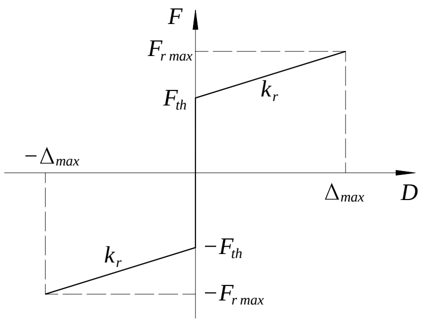

Figure 6 The restoring parameters in re-centring group

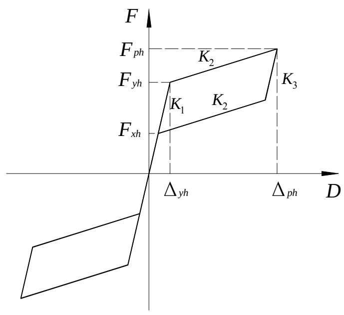

Figure 7 The restoring model of damper

where, n_d is the number of SMA wires in dissipation group, A_d stands for the section area of single SMA wire, L_d is the length of wires before pre-tension, k_1, k_2, x_a and x_b is the parameters in constitutive model of SMA (equation 2.7). Because the re-centring group can be characterized a rigid-elastic behavior, the parameters are(Figure 6): the maximum displacement $\Delta_{\max}$, the maximum restoring force $F_{d\max}$, the threshold force F_{th} , the post-yielding stiffness K_r .

$$F_{r\max} = n_r A_r [(k_1 \quad k_2) x_b + k_2 (\frac{\Delta_{\max}}{L_r} + \varepsilon_{0r})] \tag{3.4}$$

$$F_{th} = n_r A_r[(k_1 \quad k_2)x_a + k_2\varepsilon_{0r}] \tag{3.5}$$

$$K_r = \frac{F_{r\max} \quad F_{th}}{\Delta_{\max}} \tag{3.6}$$

Combining the models of two group, the subsection linear restoring model for SMA re-centring damper is obtained. The parameters of this model is listed as follow (Figure 7): the initial stiffness K_1, the post-yielding stiffness K_2, the unloading stiffness K_3, the yielding force F_{yh}, the critical force F_{ph}, the unloading force F_{xh}, the yielding displacement Δ_{yh}, the critical displacement Δ_{ph}.

$$K_2 = K_r + K_{d1} \tag{3.7}$$

$$K_3 = K_r + K_{d2} \tag{3.8}$$

$$\Delta_{ph} = \Delta_{\max} \tag{3.9}$$

$$F_{yh} = F_{th} + F_{d\max} \quad K_{d1} \quad \Delta_{ph} \tag{3.10}$$

$$F_{ph} = F_{th} + K_r \quad \Delta_{ph} + F_{d\max} \tag{3.11}$$

$$F_{xh} = F_{th} \quad (F_{d\max} \quad K_{d1} \quad \Delta_{ph}) \tag{3.12}$$

$$\Delta_{yh} = F_{yh} / K_1 \tag{3.13}$$

4. The elasto-plastic seismic analysis of SMA re-centring isolation structure

4.1 SMA re-centring isolation system

The new isolation system combining the above damper with laminated rubber bearing (LRB) is proposed to provided the isolation structure with re-centring capacity. The LRB carries vertical load while the RCD damper absorbs and dissipates seismic energy and provides the super-structure with fully re-centring capacity. The laminated rubber bearing is made of natural rubber which can provide with large stretching capability, little creep and insensitive to temperature fluctuation. Because of the restraint of the steel plates in the bearing and the properties of the rubber material (the Poisson's ratio is about 0.5), the required vertical stiffness and bearing capacity are guaranteed accordingly. Under the cyclic horizontal load, however, the areas of hysteretic loops of the LRB are very small. Since the LRB shows stable elastic character throughout the whole deformation and its hysteretic characters are irrelevant to the change of axial force and displacement, the resulted behavior can be idealized as linear-elastic. Since the LRB has reliable linear-elastic character, the resulted cycles of the isolation system are a "double flag" model, shown in Figure 8.

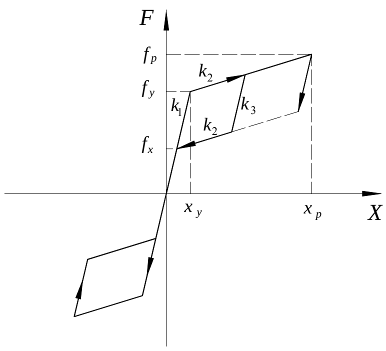

Figure 8 The restoring character of SMA re-centring isolation system

4.2 Example and discussion

In this paper, the program based on the theory of the shear-typed storey model is compiled to conduct the elasto-plastic time-history analysis of this kind of isolation structures. As an example, an isolated four- storey R.C frame was chosen for numerical investigation. The mechanical parameters of the super-structure are listed in table 1. It is assumed that the site classification is Ⅱ, the design ground motion group is the first group, the site design characteristic period of ground motion is 0.35s and the earthquake fortification intensity is 8 degree.

Table1 The Parameters of Super-structure

Storey	Mass/kN	Height/m	Damping Ratio	Elastic Stiffness $/kN \cdot m^{-1}$	Yielding Stiffness $/kN \cdot m^{-1}$	Yielding Displacement /cm
1	4880	4.5	0.5	437000	21800	2.08
2	4576	4.5	0.5	335000	16700	1.64
3	4576	4.5	0.5	335000	16700	1.64
4	3464	4.5	0.5	252000	12000	1.19

Considering the vertical strength and stiffness, 32 Φ500 laminated rubber bearings are located in the structure. The horizontal stiffness of single LRB is 700kN/m, and vertical stiffness is 1.1×10^6 kN/m. Eight SMA re-centring dampers are set up and Ni-Ti alloy is selected. The geometric parameters of SMA wires in the two groups are listed as follow. Re-centring group: diameter d=4mm, length L=4.04m, number n=6, pre-strain is 1%, dissipation group: diameter d=4mm, length L=4.14m, number n=24, pre-strain is3.5%. The environment temperature is 20°C. According to the arrangement of SMA re-centring dampers and LRB, the parameters in restoring model of isolator layer are determined. $k_1 = 63080$ kN/m、$k_2 = 23656$ kN/m、$k_3 = 63080$ kN/m、$f_y = 989$ kN、$x_y = 0.016$m、$x_p = 0.12$m、$f_p = 3672$ kN、$f_x = 0$. the mass of isolation layer is 1824 kN.

In analysis, the NS component of El-centro 1940 ground motion (T=10s) is used., and the input peak ground acceleration is adjusted to 70cm/s^2 in the intensity of frequently occurred earthquake and 400cm/s^2 in the intensity of seldom occurred earth- quake. The result is expressed as figure9 and figure 10.

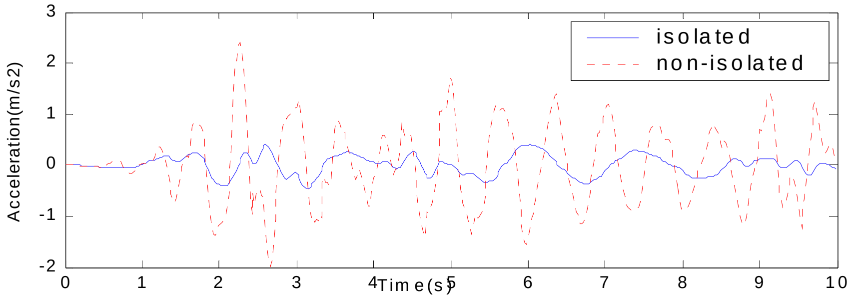

Figure 9 Comparison of fourth floor acceleration (frequently occurred earthquake)

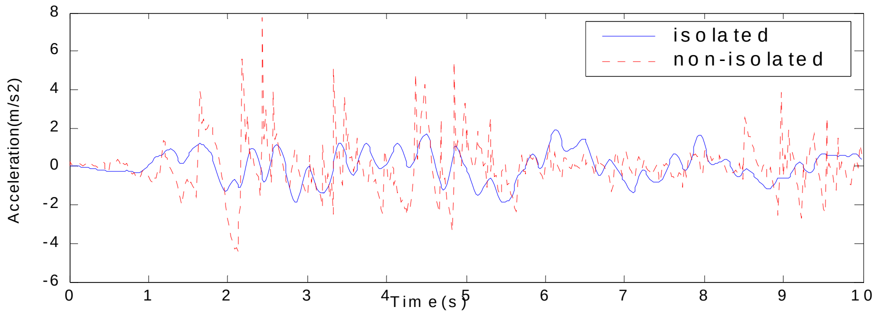

Figure 10 Comparison of fourth floor acceleration (seldom occurred earthquake)

The result of analysis indicate:

1. Under frequently occurred earthquake, the drift of super-structure decreases greatly, some even by 80% in contrast with that of the non-isolation structure (Figure 11). The maximum drift angle of SMA re-centring isolation structure is 1/2419, while 1/640 in non-isolation structure. And the maximum inter- storey force decrease too (Figure 12).The maximum acceleration of each floor in the above isolation structure is remarkably decreased, and top floor decreases by 79% in contrast with that of the non-isolation structure, so the safety of structure is insured. Besides, the fundamental mode of SMA re-centring isolation structure is “integer moving type”, which is the commonness of all kinds of isolation system (Figure 13).

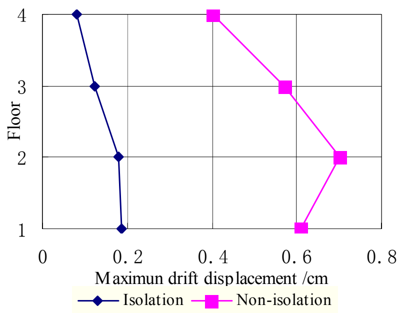

Figure 11 Comparison of maximum drift displacement

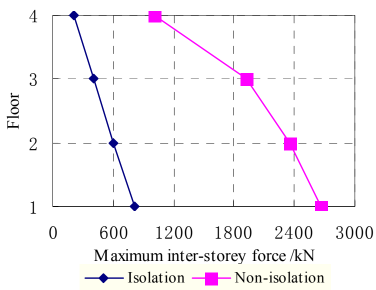

Figure 12 Comparison of maximum inter- story force

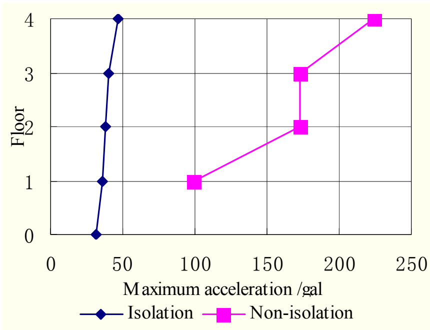

Figure 13 Comparison of maximum acceleration (frequently occurred earthquake)

2. Under seldom occurred earthquake, the maximum acceleration of each floor in the above isolation structure is rather smaller than the input peak ground acceleration ($400 cm/s^2$), and decreases by almost 75% in contrast with that of the non-isolation structure (Figure 14), so the amplification of the ground acceleration in the super-structure is avoided. Furthermore, the maximum drift angle of SMA re-centring isolation structure is 1/651 and smaller than the critical value of elastic drift angle (1/550), which indicate that the super-structure of isolation system remains elastic. While the maximum drift angle of the non-isolation structure is 1/54 (Figure 15), which is approach the critical value of elastic-plastic drift angle (1/50).

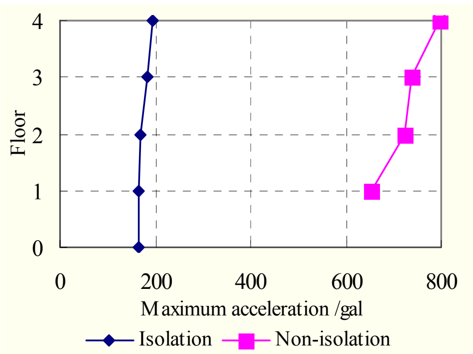

Figure 14 Comparison of maximum acceleration (seldom occurred earthquake)

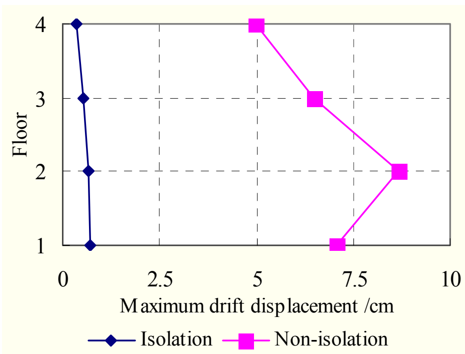

Figure 15 Comparison of maximum drift displacement

3. When the time history curve of displacement is solved, the free vibration analysis for SMA re-centring isolation structure after the ground motion (T=10s) is conducted in program. The process of free vibration continues 10 seconds. It is verified that the structure can return to its original disposition after earthquake.

5. Conclusions

The following conclusion is achieved through the above study:
(1) The transformation pseudo-elasticity property of SMA is simulated exactly with the above mentioned method of value calculation for Brinson constitutive laws.
(2) The SMA re-centring damper presents typical “double flag” hysteretic curve, and the result accords with the theory analysis.
(3) In above isolated structure, the drift displacement in super-structure is drastically reduced, so the whole system primarily moves as almost a rigid body and the super-structure still remains elastic. The peak acceleration of each floor is much less than that of the non- isolated structure during earthquake. In consequence, the seismic response of the isolated structure is reduced greatly. Furthermore, the super-structure can return to its original position after earthquake.

References

Zhou F.L. (1997) The vibration control of civil engineering. Earthquake Press,China.
Wang S. L. (2000) Applications of shape memory alloy in structural vibration control. Xi’an: Shaanxi Science & Technology Press,China.
Mauro D. and Donatello C.(2000) Implementation and testing of passive control device based on shape memory alloy. Earthquake Eng. and Struc. **29:2**,pp.945-968.
L C Brinson，A Bekker，S Hwang. Deformation of shape memory alloys due to thermo-induced transformation. Journal of Intelligent Material Systems and Structures, **7**:97-106.
Peng G, Li L, Tang J.X. Theory method of design shape memory alloy damper. Industrial Construction. 2002,**32:8**,47-49
Jiang S. Z. and Wang S.L.(2003) Research on damp capacity of passive isolation device based on shape memory alloy. [J]. of Xi’an Univ. of Arch. and Tech., **35**:317-320.