I - B340

SHAPE MEMORY ALLOYS FOR STRUCTURAL CONTROL OF BASE ISOLATED BRIDGES

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1. INTRODUCTION

Base isolation provides a very effective passive method of protecting bridges from the hazard of earthquakes. The proposed smart isolation system combines the laminated rubber bearing with the device made of shape memory alloy (SMA). The constitutive law for superelastic material is extended to describe a hardening of the stress-strain relation of SMA at large strain levels. The smart base isolation utilizes the different responses of the SMA at different levels of strain to control the displacements of the rubber bearing at various excitation levels. At the same time the hysteresis of the alloy is used to increase the energy dissipation capacity. The performance of the smart base isolation is compared with the responses of laminated rubber bearing with lead core to quantify the benefits of applying SMA for isolation of elevated highway bridge.

2. EXTENDED SUPERELASTIC MODEL OF SHAPE MEMORY ALLOYS

Since in this paper, SMA is intended to be used in a wide strain range, the Graesser-Cozzarelli[1] model is extended to represent the hardening of the SMA after the transition to martensite state is completed. As the load increases, the pure martensite follows elastic response with modulus E_m. The modified model is of the form:

$$\dot{\sigma} = E \cdot \left[\dot{\varepsilon} - |\dot{\varepsilon}| \cdot \left(\frac{\sigma - \beta}{Y} \right)^n \right] \cdot u_I(\varepsilon) + E_m \cdot \dot{\varepsilon} \cdot u_{II}(\varepsilon) + \left(3a_1 \cdot \dot{\varepsilon}\varepsilon^2 + 2 \cdot a_2 \cdot sign(\varepsilon) \cdot \dot{\varepsilon}\varepsilon + a_3 \cdot \dot{\varepsilon} \right) \cdot u_{III}(\varepsilon) \tag{1a}$$

$$\beta = E \cdot \alpha \cdot \left\{ \varepsilon^{in} + f_t \cdot |\varepsilon|^c \cdot erf(a \cdot \varepsilon) \cdot \left[u(-\dot{\varepsilon} \cdot \varepsilon) \right] \right\}. \tag{1b}$$

The first term in the above equation represents a standard superelastic behavior. The term $E_m \cdot \dot{\varepsilon} \cdot u_{II}(\varepsilon)$ in equation (1a) describes the elastic behavior of martensite. This term is activated when the strain is higher then ε_m. Strain, ε_m, defines the point when the transformation of SMA from austenite to martensite is completed. The smooth transition from the curve of slope E_y to the slope E_m is obtained by adding the last term in equation (1a) which is evaluated only during loading and for strain $\varepsilon_1 < |\varepsilon| < \varepsilon_m$. The limits are selected from the experimental data for the given shape memory alloy. The constants a_1, a_2 and a_3 are controlling the curvature of the transition. The functions $u_I(\varepsilon)$, $u_{II}(\varepsilon)$ and $u_{III}(\varepsilon)$ activate the appropriate terms of (1a) according to the strain level. Figure 1 explains the introduced constants.

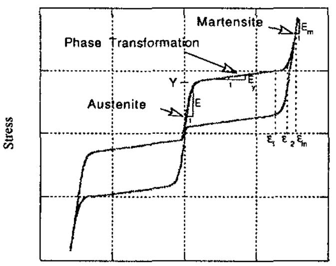

Figure 1. SMA stress-strain hysteretic model

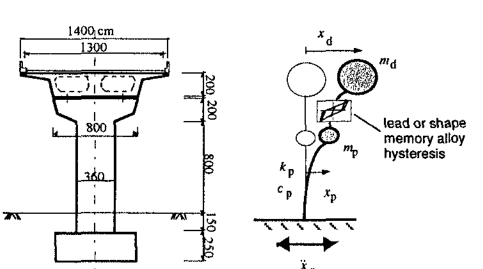

Figure 2. Structural model of elevated highway bridge with isolation system

3. RESPONSE OF ELEVATED HIGHWAY BRIDGE WITH SMA DAMPING DEVICES

The considered elevated highway bridge, shown in Figure 2, is a three-span-continuous concrete box girder of 14 m width. The reinforced concrete piers have height of 11.5 m and the distance between them is 40 m. The isolation between the pier and the superstructure is achieved by two laminated rubber bearings with lead core or bearings with SMA. The cross sectional area and the height of rubber layers in a single bearing are 0.8881 m and 0.154 m, respectively. The equations of motion of two degree of freedom model bridge are:

$$\begin{aligned} m_d \ddot{x}_d(t) - N \cdot F(x_d, \dot{x}_d, x_p, \dot{x}_p, t) &= -m_d \ddot{x}_g(t) \\ m_p \ddot{x}_p(t) + c_p \dot{x}_p(t) + k_p x_p(t) - N \cdot F_{NZ/SMA}(x_d, \dot{x}_d, x_p, \dot{x}_p, t) &= -m_p \ddot{x}_g(t) \end{aligned} \tag{3}$$

where x_d, x_p and m_d, m_p are displacements and masses of the deck and pier, respectively, and $\ddot{x}_g$ is the ground acceleration. The coefficient of damping and stiffness of the pier are denoted by c_b and k_b.

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$F_{NZ/SMA}(x_d, \dot{x}_d, x_p, \dot{x}_p, t)$ is the hysteretic force generated by the isolation system and N the number of bearings supporting the deck. The parameters of the two degree of freedom model were estimated by the method given in reference[2] and are given as follows

$$m_d = 8 \cdot 10^5 kg \qquad k_p = 3.2256 \cdot 10^8 N/m$$
$$m_p = 1.4 \cdot 10^5 kg \qquad \xi_p = 5\% \tag{4}$$

The proposed base isolation system[3] has the potential ability of dissipating energy and controlling the maximum displacements of the deck at different levels of external excitation. The main focus in the following analysis is placed on the relative displacement between deck and pier. The advantages and disadvantages of smart base isolation are presented by comparing with the performance of the structure isolated by rubber bearings with lead core. For easy understanding and interpretation, the earthquake excitation is assumed to be a simple harmonic function. The preliminary simulations are conducted for a sinusoidal ground motion with frequency $\omega_g = 6.28$ rad/s ($T_g = 2\pi/\omega_g = 1$) and for three acceleration amplitudes: 0.2g, 0.4g and 0.6g. Figure 3 compares the force-displacement relations of the laminated rubber bearing (LRB) with lead core and LRB+SMA system for the different loading levels. Relative displacement between deck and pier of the system with SMA device under 0.2g excitation amplitude is very small compared to the lead rubber bearing system, since the alloy almost remains in its elastic range, going only into the very beginning of the formation of stress-induced martensite (SIM) phase. For the excitation amplitude 0.4g and 0.6g the steady-state relative displacement in case of LBR+Lead system is, in both cases, around two times the steady-state relative displacement for LRB+SMA. Computation of the energy of the vibrating structure showed that the damage energy entering the pier and the deck is drastically reduced by adding SMA element.. However, the acceleration response of the deck and the shear force at the base of the pier are increased.

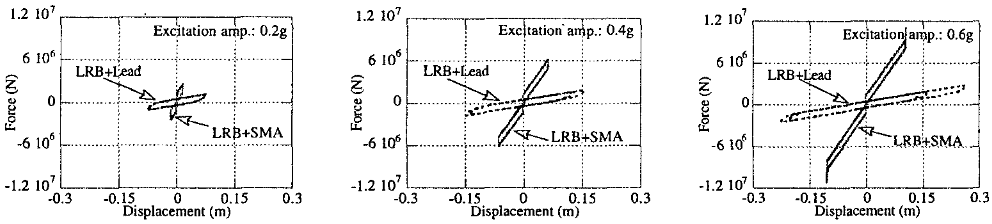

Figure 3. Hysteretic force-displacement relations of LRB+lead core and LRB+SMA under harmonic excitation of different intensity

4. CONCLUSIONS

The most suitable device for isolation of the bridge deck from seismic input should have variable properties with respect to the intensity of external excitation. For loading caused by stopping of cars, wind action or small earthquake, the bearing should behave as rigid connector, so that the minor external force are not damaging the expansion joints or other auxiliary elements of the bridge. Since, at this level of excitation, the pier shear force is small, the isolation of the superstructure form pier vibration is not essential. For medium intensity loading the isolation system should be fully utilized, providing adequately high damping. At very large ground motions the isolation device should be able to restrain the motion of the superstructure within the design range. Excessive motion of the deck can lead to pounding of the adjacent superstructures which can significantly increase the pier shear force. Large relative displacements between the superstructure and substructure may cause falling down of the deck. At this excitation level the primary objective is prevention from the total destruction of the bridge and some potential damage to piers due to increased shear force from stiffer isolation must be accepted. A simple bar of SMA can provide a damper with the desired variable characteristics based solely on the material properties of alloys (SMAs have high stiffness for small strain levels - elastic modulus of austenite, reduced stiffness for intermediate levels of strain - transformation from austenite to martensite, and high stiffness at high strain - elastic modulus of pure martensite) Furthermore, the proposed device has the inherent centering ability due to pseudoelastic behavior of SMA and high ductility.

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