Using SMA Hybrid Composites to Energy Absorption on Frame Structures Subjected to Earthquake Loads

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Abstract: Natural dynamical loads are unavoidable and usually have a catastrophic consequence for engineering structures. Earthquakes are a possible situation where loads are abruptly applied on the structure. This kind of behavior leads to be avoided, favoring the application of passive control to avoid dramatic situations. Hysteretic behavior is a candidate to be employed on engineering structures promoting energy dissipation. In this regard, shape memory alloys (SMAs) have been exploited in order to use pseudoelastic behavior promoted by phase transformation that results in hysteresis loops that are related to energy dissipation. SMA Hybrid Composites (SMAHC) constitute interesting alternative for engineering structures using a combination of SMA embedded in a polymer matrix. This paper investigates the use of SMAHC on engineering frame structures subjected to earthquakes loads. It presents a parametric analysis about the influence of the constituent volume fractions. Results indicate the great energy dissipation capability of this device, pointing the optimum SMA volume fraction for design conditions.

Keywords: SMA, composite materials, earthquake, smart structures

INTRODUCTION

Natural loading sources as earthquakes and hurricanes are always related to important issues associated with engineering structures (Saadat *et al*., 2001). The sudden energy release has usually catastrophic consequences with a lot of engineering damages. Since it is impossible to control the loading process, it is important to analyze and design mitigation approaches. In this regard, passive control strategies are interesting in order to present the required instantaneous activation (Ozbulut *et al*., 2011).

Shape Memory Alloys (SMAs) offer an interesting characteristic related to engineering structures subjected to earthquake loadings. Typical hysteretic behavior of SMAs has a strong energy dissipation capacity when compared to other energy dissipation mechanisms as plasticity (Baratta and Corbi, 2002). Moreover, the temperature dependent behavior may be useful in order to obtain an adaptive behavior (Costa and Savi, 2017). In a futuristic perspective, it is possible to imagine situations where it would be possible to have self-recovery together with energy dissipation capacity.

Different devices using SMAs have been developed for earthquake applications (Asgarian *et al*., 2016, Yang *et al*., 2010). Most of the works is related to frame structures (Ozbulut *et al*., 2011). Diagonal braces reinforcements are especially attractive due to the facility to be coupled in existent structures (Yan *et al*., 2013). The use of shape memory alloy hybrid composites (SMAHC), combining SMA elements with polymer matrix, seems to be the more effective way to develop structural elements to be applied to prevent earthquake damages.

This paper deals with the dynamical analysis of a one-story frame structure reinforced with SMAHC elements along the diagonals subjected to earthquake loads. An equivalent nonlinear single degree of freedom oscillator is analyzed considering the restitution force provided by the SMAHC. Numerical simulations are carried out showing the influence of the SMA volume fraction on the structural response.

DYNAMICAL MODEL

The phase transformation induced by thermomechanical loads is the key point of SMAs unique capabilities. Several constitutive models can be applied to properly describe all the phenomena included in this mechanism. Based on the discussion presented by Paiva and Savi (2006), the Brinson model (Brinson, 1993) is chosen in this paper for the SMA thermomechanical description. Considering the SMAHC, SMA elements are considered to be fibers embedded in a polymer matrix. Under this assumption, the fiber constitutive relation is described as follows (Brinson, 1993)

$$\sigma^{(f)} - \sigma_0^{(f)} = (E_f \varepsilon^{(f)} - E_{f0}\varepsilon_0^{(f)}) - \varepsilon_R (E_f \beta_\sigma - E_{f0}\beta_{\sigma_0}) \tag{1}$$

where $E_f = E_f(\beta) = E_A + \beta(E_M - E_A)$ is the SMA equivalent elastic modulus, E_A and E_M are the austenite and martensite elastic modules, respectively, and ε_R is the maximum recoverable strain due to thermal treatment.

$\beta = \beta_T + \beta_\sigma$ is the martensite volume fraction, where β_T is the twinned and β_σ is the detwinned martensite volume fractions. For this analysis, as just mechanical loads are considered, $\beta_T = 0$, hence $\beta = \beta_\sigma$, The lower index "*0*" is used to denote the previous state before the load initiate or the previous state before the load direction be reversed.

The evolution of SMA phase transformation is defined with two equations:

i) if $\sigma_s^{cr} + C_M(T - M_s) < \sigma^{(f)} < \sigma_f^{cr} + C_M(T - M_s)$ and $T > M_s$, the forward transformations (A→M) is modelled by

$$\beta_\sigma = \frac{1-\beta_{\sigma_0}}{2}\cos\left\{\frac{\pi}{\sigma_s^{cr} - \sigma_f^{cr}}\left[\left|\sigma^{(f)}\right| - \sigma_f^{cr} - C_M(T - M_s)\right]\right\} + \frac{1+\beta_{\sigma_0}}{2} \quad (2)$$

ii) if $C_A(T - A_f) < \sigma^{(f)} < C_A(T - A_s)$ and $T > A_s$, the reverse transformations (M→A) is modelled by

$$\beta_\sigma = \frac{\beta_{\sigma_0}}{2}\left\{\cos\left[a_A\left(T - A_S - \frac{\left|\sigma^{(f)}\right|}{C_A}\right)\right] + 1\right\} \quad (3)$$

were $a_M = 2\ln(10)/(M_s - M_f)$, $a_A = 2\ln(10)/(A_f - A_s)$, $b_M = a_M / C_M$, $b_A = a_A / C_A$, $A_M = \pi/(M_s - M_f)$ and $A_A = \pi/(A_f - A_s)$.

By assuming that the polymer has a linear elastic behavior, the matrix constitutive equation is

$$\sigma^{(m)} = E_m \varepsilon^{(m)} \quad (4)$$

The SMAHC is modeled considering two assumptions related to matrix and fibers: they present the same strain by kinematical hypothesis; the applied load provides equilibrium requirements. Therefore,

$$\varepsilon^{(f)} = \varepsilon^{(m)} = \varepsilon^{(c)} \quad (5)$$

$$V_f\sigma^{(f)} + (1 - V_f)\sigma^{(m)} = \sigma^{(c)} \quad (6)$$

where the upper index "*(c)*" is used to denote the equivalent quantity of the hybrid composite

Manipulating these equations, the constitutive relation of the hybrid composite is obtained

$$\sigma^{(c)} - \sigma_0^{(c)} = (E_c\varepsilon^{(c)} - E_{c0}^*\varepsilon_0^{(c)}) - \varepsilon_R(E_c^*\beta_\sigma - E_{c0}^*\beta_{\sigma_0}) \quad (7)$$

where $E_c = V_fE_f + (1 - V_f)E_m$, $E_c^* = V_fE_f$, $E_{c0}^* = V_fE_{f0}$ and $\sigma_0^{(c)} = V_f\sigma_0^{(f)}$.

Once the equivalent constitutive relation of the SMAHC is obtained, the dynamical model of the one-store frame subjected to earthquake ground acceleration must be established. Figure 1 represents three different stages of the modeling strategy: a) the initial geometry is composed by one floor over two columns with two SMAHC braces along the diagonals; b) the earthquake load is equivalent to imposed ground acceleration; c) the system is equivalent to a mass in a non-inertial reference system, where the mass relative displacement is $\bar{u} = u - u_g$, with two linear spring (the columns) and two nonlinear springs (the SMAHC rods). The equation of motion of this dynamical system is

$$m(\ddot{\bar{u}} - \ddot{u}_g) = -2k\bar{u} - 2\sigma^{(c)}A\cos\theta \quad (8)$$

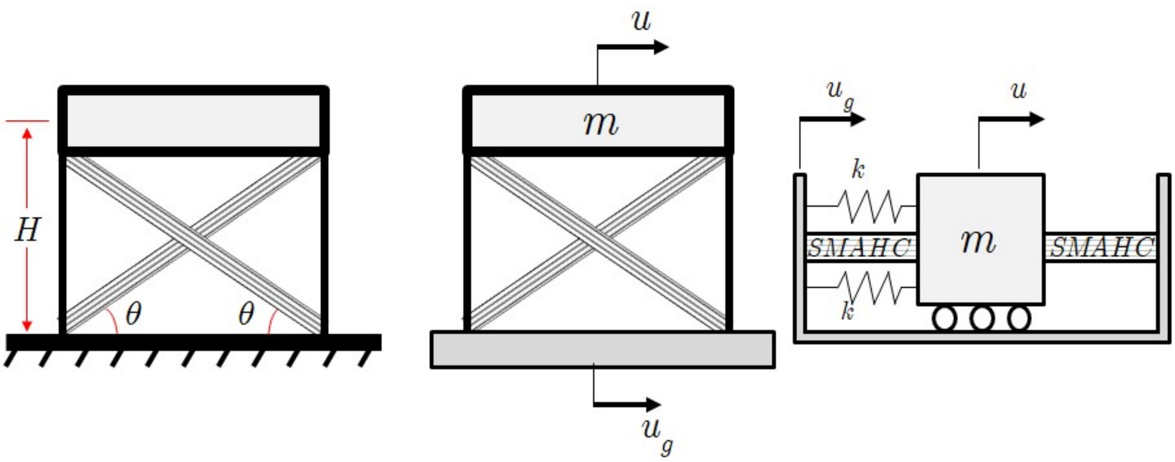

Figure 1 – Dynamical model for the one-story frame under earthquake load.

By kinematics analysis, strain is given by

$$\varepsilon^{(c)} = \Delta L_c / L_c = [(u - u_g)\cos\theta] / (H / \sin\theta) = (\bar{u} / H)\sin\theta\cos\theta \tag{9}$$

The equation of motion is rewritten as follows

$$\ddot{\bar{u}} + \omega^2 \bar{u} - \zeta\beta_\sigma = \ddot{u}_g + U_0 \tag{10}$$

where $U_0 = (E^*_{c0}\varepsilon^{(c)}_0 - E^*_{c0}\beta_{\sigma_0} - \sigma^{(c)}_0) / \mu$, $\zeta = \varepsilon_R E^*_c / \mu$, $\omega^2 = \omega_0{}^2 + \omega_c{}^2$, $\omega_c{}^2 = (E_c / \mu H)\sin\theta\cos\theta$, $\omega_0{}^2 = 2k / m$ and $\mu = m / 2A\cos\theta$.

RESULTS AND DISCUSSION

Numerical simulations are carried out employing the fourth order Runge-Kutta method following the procedure indicated by Savi (2015). SMA properties are the following: $E_A = 37.3\text{GPa}$, $E_M = 21.4\text{GPa}$, $\varepsilon_R = 0.04$, $M_f = 195\text{K}$, $M_s = 210\text{K}$, $A_s = 247\text{K}$, $A_f = 253\text{K}$, $C_M = 4.7\text{MPa} / \text{K}$, $C_A = 4.7\text{MPa} / \text{K}$, $\sigma_s^{cr} = 380\text{MPa}$, $\sigma_f^{cr} = 400\text{MPa}$ (Santos and Cismasiu, 2010) and the frame characteristic are $\omega_0 = 3\text{s}^{-1}$, $\mu = 4 \times 10^8 \text{kg} / \text{m}^2$, $H = 0.3\text{m}$ and $\theta = 30°$.

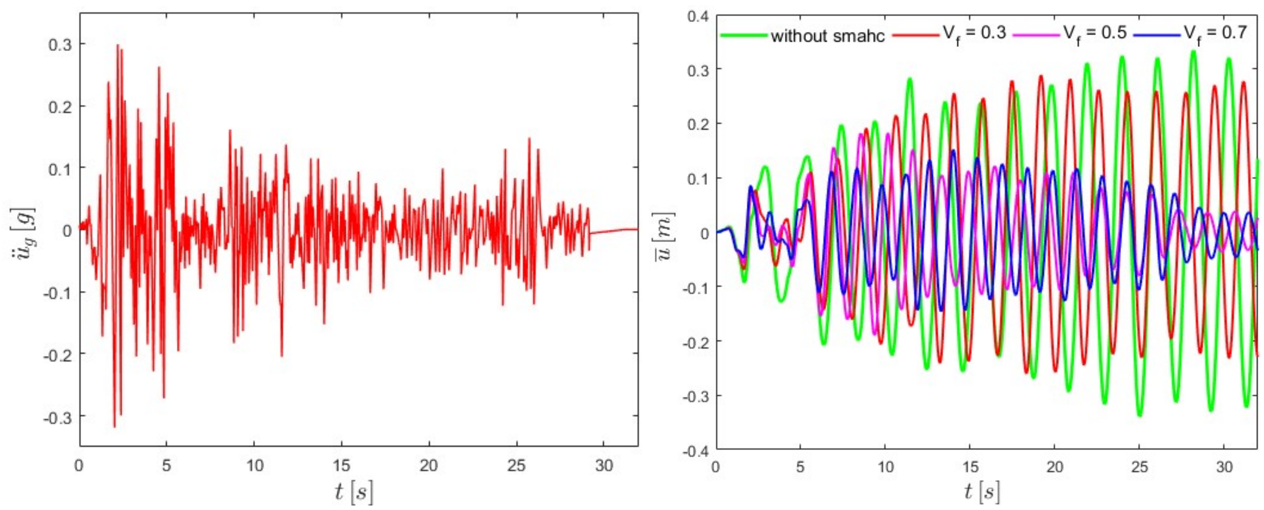

Figure 2 – El Centro earthquake ground acceleration (left) and relative displacement of the one-frame structure with and without brace reinforces (right).

In general, earthquakes absorbers need to present two main capabilities: recentering promoting vibration amplitude decrease. The ground acceleration (Vibrationdata, 2018) and the relative displacement are plotted in Figure 2. Four situations are treated: without SMAHC element; and with different SMA volume fractions (0.3, 0.5, 0.7). Note that the case without SMAHC has the greatest amplitudes. When $V_f = 0.5$, the best recentering is achieved while $V_f = 0.7$ presents the smallest amplitude. As pointed out by Vignoli *et al*. (2017), phase transformations define the system behavior and there is a competition between loads and SMA volume fractions. Therefore, smaller values of V_f can induce a high level of phase transformation in SMAHC with small load levels. On the other hand, if V_f is too small, the amount of energy dissipated is also very limited. These two points explains why the recentering capability is higher for $V_f = 0.5$. Besides that, stiffness has a great influence on system amplitude and due to that, $V_f = 0.7$ has the smallest relative displacement.

CONCLUSIONS

Dynamical behavior of one-frame structure reinforced with SMAHC braces is investigated. The hybrid structure has a rich response with great influence of SMA fiber volume fraction. Numerical simulations show the design capability with SMAHC to decrease vibration amplitude and dissipate energy.

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