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SHAPE-MEMORY ALLOYS FOR SEISMIC ISOLATION OF BRIDGES

GAËL BONDONET AND ANDRÉ FILIATRAULT

Department of Civil Engineering, École Polytechnique, University of Montreal Campus,
P.O. Box 6079, Downtown Station, Montreal, Canada, H3C 3A7

ABSTRACT

Shape Memory Alloys (SMAs) are metals which are characterized by the superelastic (or pseudoelastic) behavior due to the transformation of martensitic phase in austenitic phase. The existence of these phases depends on of the molecular arrangements in these alloys. The reversible transition from mertensite to austenite exhibits characteristics which are desirable for the seismic base isolation technology: 1) high stiffness for small strain levels, 2) reduced stiffness for intermediate levels of strains due to the austenite formation, 3) high stiffness at large strains caused by the elastic loading of the austenite, 4) hysteretic effect and, finally, 5) no residual strain. This paper proposes a uniaxial constitutive model of superelasticity which is incorporated in a base isolator element. A two degree-of -freedom base isolated bridge model, including the stiffness of a pier and a superelastic isolator inserted on the top of the pier under a rigid deck, has been developed. This model is subjected to an ensemble of earthquake ground motions representative of seismic regions of Western Canada. Numerical simulations investigate the effectiveness of SMAs properties for seismic base isolation.

KEYWORDS

Superelasticity; Shape Memory Alloy; Base Isolation; Bridges

INTRODUCTION

Over the last two decades, various studies made on elastomeric, lead-rubber, and frictional base isolation devices have led to the implementation of the base-isolation technology for protecting bridges and buildings from seismic excitations. Since this technology is relatively new, not all other damping materials have been investigated. This paper evaluates numerically the effectiveness of a special class of metals, called Shape Memory Alloys, for the base isolation of bridges.

SUPERELASTICITY OF SHAPE MEMORY ALLOYS

Shape memory alloys (SMAs) (Patoor *et al.*, 1990; Funakubo, 1984) are a class of materials able to develop the so called superelastic behavior (also called pseudoelastic behavior). SMAs are made of two or three different metals. Nitinol, for example, incorporates 49% of Nickel and 51% of Titane. Copper and zinc can also be alloyed to produce superelastic properties. Depending on the manufacturing process and the temperature range of alloying, several molecular rearrangements are possible. Chemical phases are changing if the temperature of alloying is increased. Low alloying temperatures involve a fully martensitic microstructure, whereas high alloying temperatures involve a fully austenitic microstructure. If a cyclic loading is applied to an alloy containing a fully martensitic microstructure, the viscoplastic behavior illustrated in Fig. 1 is obtained. If a cyclic loading is applied to an alloy containing a fully austenitic microstructure, a linear-elastic behavior is obtained as shown in Fig. 2. Finally, for intermediate alloying temperatures, both martensitic and austenitic phases can co-exist. Loading of an alloy containing both phases results in the transformation from one phase to the other. Furthermore, unloading of the same alloy implies a re-transformation from the latter phase back into the original phase. This transformation process results from elastic loading of the stable austenitic parent phase up to a threshold stress. Larger stresses induce a transformation from austenite to martensite. This transformation process occurs at a significantly reduced tangent modulus in a manner analogous to plastic yielding. As deformations take place, the volume of martensite within the microstructure increases and the path of the stress-strain curve follows a stress plateau. As the microstructure becomes fully martensitic, further straining causes the martensite to be loaded elastically. A re-transformation from martensite to austenite takes place during unloading. This re-transformation, however, occurs at a lower stress level than the original transformation. This remarkable process, called superelastic behavior, produces a hysteretic effect with near zero residual strain as shown in Fig.3.

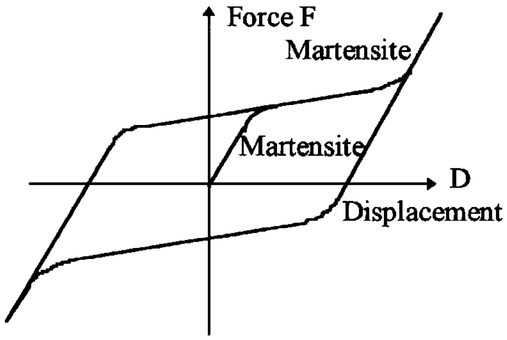

Fig.1. Behavior for low alloying temperatures

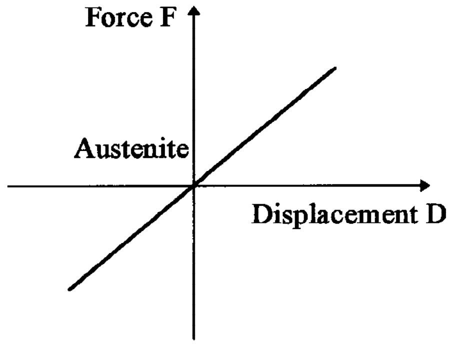

Fig.2. Behavior for high alloying temperatures

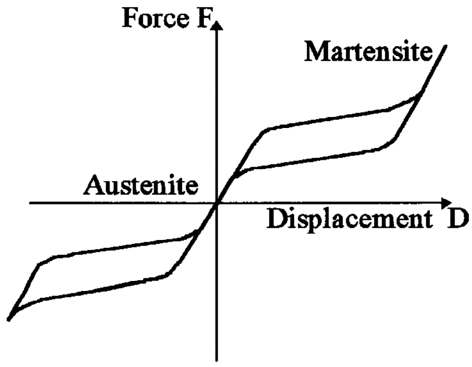

Fig.3. Superelastic behavior for intermediate alloying temperatures

The superelastic behavior has several advantages for seismic base isolation purposes. It exhibits high stiffness and strength for small strains. It become more flexible for larger strains. It presents practically no residual strain and, finally, it is able to dissipate a large amount of energy. The superelastic behavior, however, is sensitive to the fatigue phenomenon. After a large number of loading cycles, SMAs tend to deteriorate into a classical plastic behavior with residual strains.

CONSTITUTIVE MODEL OF SUPERELASTICITY

The superelastic model developed in this investigation is based on the approach proposed by Graesser and Cozzarelli (1991). This constitutive rule has the same origin as the well known viscoplastic rule suggested by Constantinou *et al.* (1990). This rule originates from the Bonc hysteretic model (1967) subsequently extended by Wen (1976). As suggested by Graesser and Cozzarelli, the uniaxial behavior of a superelastic material can be described by the following stress (σ)- strain (ε) relationship:

$$\frac{d\sigma}{dt} = E.\left[\frac{d\varepsilon}{dt} - \left|\frac{d\varepsilon}{dt}\right|.\left(\frac{\sigma-\beta}{\sigma_y}\right)^n\right] \quad (1)$$

$$\frac{d\beta}{dt} = \alpha.E.\left[\left|\frac{d\varepsilon}{dt}\right|.\left(\frac{\sigma-\beta}{\sigma_y}\right)^n + f_t.\left(\frac{d\varepsilon}{dt}\right)^c.erf(a.\varepsilon).signplus\left(-\varepsilon.\frac{d\varepsilon}{dt}\right)\right] \quad (2)$$

$$erf(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}dt \ \ and \ \ signplus(x) = \begin{cases} 1 \ if \ x \geq 0 \\ 0 \ if \ x < 0 \end{cases} \quad (3)$$

where E is Young's modulus, α is the stiffness ratio after and before yielding, a, f_t and c are material constants which can be obtained experimentally and σ_y is the yield strength. If f_t is set to zero, the rule degenerates into a classical viscoplastic behavior, similar to the Constantinou rule except for the β variable which models the strain hardening.

The proposed rule for superelastic behavior is written in terms of force per unit mass F/M and in terms of displacement S, but it could be written as well in a strain-stress relationship:

$$Y.\frac{dZ}{dt} = \frac{ds}{dt}.\left\{(1-\chi) + \chi.Ur.signplus\left(-s.\frac{ds}{dt}\right).\exp\left(-n2.\left|\frac{s}{Y} - Z\right|.signplus\left(\left|\frac{s}{Y}\right| - |Z|\right)\right)\right\} \quad (4)$$

$$\chi = sign\left(\frac{ds}{dt}.\left[Z - Z_y\right]\right).\left(Z - Z_y\right)^{n1} \quad (5)$$

$$Y.\frac{d\beta}{dt} = \frac{ds}{dt}.Ub.\left(\left|\frac{s}{Y}\right| - p1\right)^{n3}.signplus\left(\left|\frac{s}{Y}\right| - p1\right) \quad (6)$$

$$Z_y = Ur.Z_{y0}.sign(s).signplus\left(-s.\frac{ds}{dt}\right) \qquad \& \qquad 0,5 < Z_{y0} < 2 \quad (7)$$

$$\frac{F}{M} = \frac{K_y}{M}.\{Y.(Z+\beta) + Ua.s1\}.\frac{1}{1+Ua} \quad (8)$$

To generate superelastic behavior, Ur must be set equal to 1. Some parameters must be specified as they depend only on the material properties : the initial stiffness (Ky in $m/s^2/m$), the yield displacement (Y in m), the stiffness ratio after and before yielding (Ua), the sharpness of transition from the elastic to the plastic state (n1). Z is an hysteretic dimensionless variable defined as a normalized force with respect to the yield force Fy=Ky.Y. The force Z_{y0} is a shift of Z for the back transition between the threshold force for loading and the one for unloading. A strain-hardening parameter for higher strains (Ub), with a shape factor (n3) and a displacement limit (p1), has been integrated in the equation but must be verified experimentally for practical applications. A power function has been set in the equation but it could be replaced by any other function to fit the strain hardening region. Finally, a sharpness of back transition from plastic to elastic states (n2) is incorporated.

The great advantage of this model compared with the Graesser rule is the ability to change the shift Z_{yo} between loading and unloading . The other advantage is a better fit between experimental results and theoretical predictions for the softening portion of the stress-strain curve during unloading.

To generate the viscoplastic rule of Graesser, the following conditions must be set: Ur=Ub=0. To generate the viscoplastic rule of Constantinou, the following conditions must be set: Ur=Ub=Ua=0.

NUMERICAL MODEL OF BASE ISOLATION ON PIER

A simplified numerical model has been developed in order to study the superelastic behavior of a base isolator including SMAs as shown in Fig. 4. The numerical model takes into account the uniaxial horizontal motion of a single isolator. It is assumed that this isolator exhibits the superelastic properties described in the previous section. The base isolator is located on the top of a pier and under the deck of the bridge. Piers are modeled by a linear spring Kp in parallel with a linear dashpot Cp. The interactions between the pier and the superstructure or between the soil and the structure are not taken into account by this model.

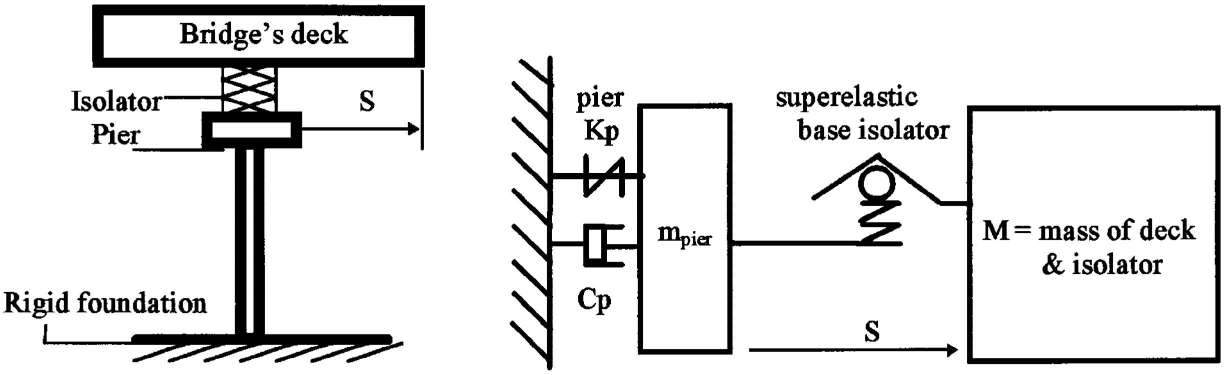

Fig.4. Simplified model of base isolation on pier of bridge

SELECTION OF EARTHQUAKE GROUND MOTIONS

Strong historical ground motion records representative of seismic regions of Western Canada were considered for the parametric study (Filiatrault et al., 1994). A Strong Motion Data Catalog (SMCAT 1989) was used to locate an ensemble of free-field earthquake records with Peak Horizontal Accelerations (PHA) and Peak Horizontal Velocities (PHV) falling simultaneously within the range prescribed by the National Building Code of Canada (1995) for the city of Vancouver located on the west coast of Canada. The PHA and PHV limits used for the search are given in Table 1.

Table 1. Acceleration and velocity limits for selection of historical earthquake ground motions

PHA limits (g)	PHV limits (m/s)	PHA/PHV limits
$0,16 \leq PHA \leq 0,23$	$0,16 \leq PHV \leq 0,23$	$0,70 \leq PHA/PHV \leq 1,44$

Six different accelerograms were selected from 5 different earthquakes as shown in Table 2. All records were calibrated to a PHA of 0,21g corresponding to the design value specified by NBCC (1995) for the city of Vancouver. This value was established from probability seismic hazard analyses based on a probability of exceedence of 10 % in 50 years.

Table 2. Selected accelerograms

Name, station and component	PHA (g)	PHV (m/s)	PHA/PHV (g.s/m)	PHA (g) calibrated
Coalinga aftershock, 1983, Oil Fields Fire Station, 270	0,22	0,16	1,38	0,21
Whittier 1987, Union Oil Yard, 90	0,22	0,16	1,38	0,21
Morgan Hill 1984, San Ysidro School 270	0,22	0,19	1,16	0,21
Puget Sound 1949, Highway Testing Lab, NO4W	0,16	0,21	0,76	0,21
San Fernando 1971, Hollywood Storage, SOOW	0,17	0,17	1	0,21
San Fernando 1971, Hollywood Storage, N90E	0,21	0,21	1	0,21

STRUCTURAL PROPERTIES

The structural properties of an existing highway bridge in Canada were considered for the numerical investigation. The bridge incorporates a reinforced concrete deck supported by steel girders. The bridge is composed of four simply supported girders for a total span of 102 m. Three groups of four reinforced concrete piers act as the vertical and lateral loads resisting system. Results from a linear modal analysis yielded a period of 0,14 s for the fundamental vertical mode of the deck and a period of 0,11 s for the fundamental horizontal mode of the piers. The mass of the pier over the mass of the deck (αp) is equal to 0,245. A fraction of critical damping (ξp) equals to 2% critical was assigned to the model.

NUMERICAL RESULTS

Figure 5 compares , for the 1949 Puget Sound accelerogram, the absolute horizontal acceleration time-history of the deck rigidly connected to the pier with a similar time-history when a superelastic isolator is inserted between the deck and the pier. For this analysis, the superelastic parameters were set as follows: Ur=1 Y=5mm Zy0=1,4 Ua=5% n1=2 n2=1 Ub=0 and Tsp=0,5sec for the effective isolated period of vibration in $Ky/M=(2.\pi/Tsp)^2$ where M is the mass of the deck.. The superior performance of the isolated structure is evident. The peak acceleration at the deck level of the isolated bridge is only 10% of the peak acceleration of the elastic structure with the deck rigidly connected to the pier. Figure 6 gives further details of the behavior of the isolated bridge in terms of the relative displacement time-history between the top of the pier and the deck and the hysteretic behavior of the superelastic isolator. Although a peak relative displacement slightly over 50 mm is observed, the residual displacement between the two components is virtually nil at the end of the earthquake. The re-centering and energy absorption capabilities of the superelastic isolator is clear from the hysteresis loops obtained.

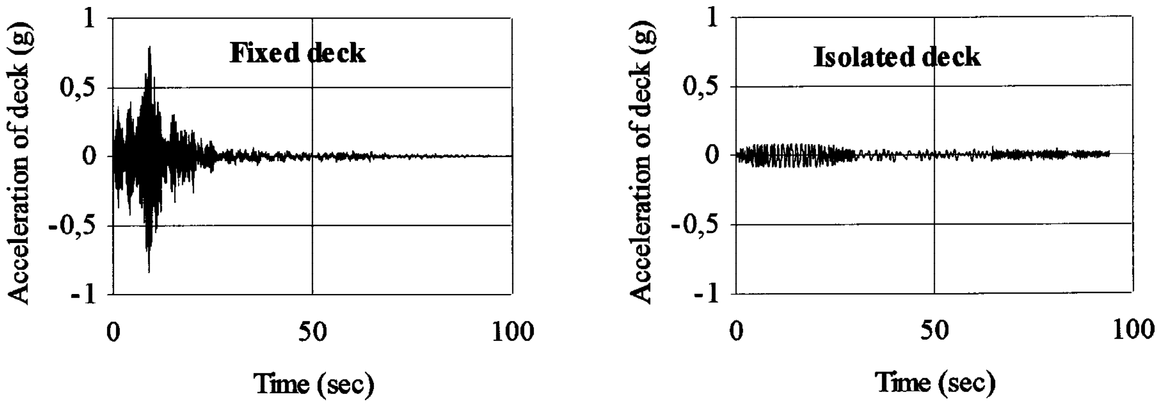

Fig.5. Acceleration time-history for fixed and isolated deck, Puget Sound accelerogram.

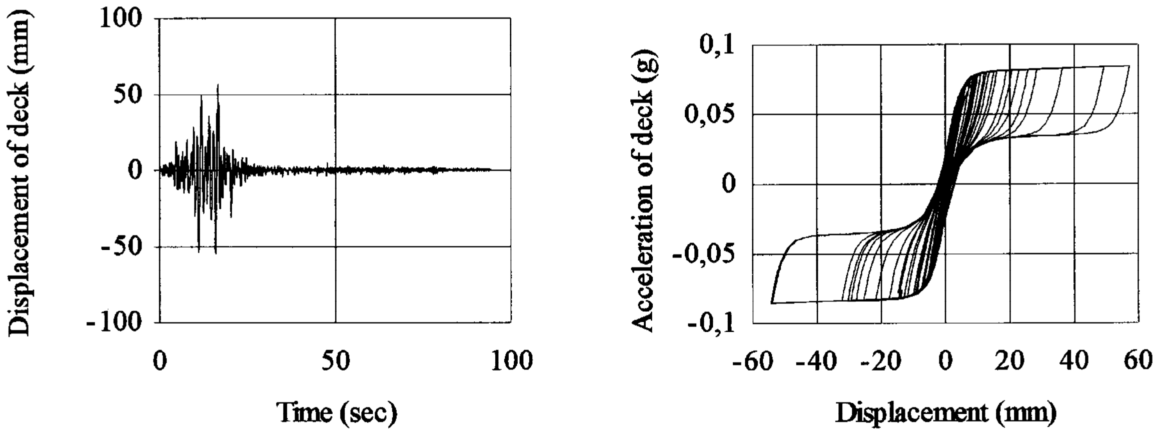

Fig.6. Relative displacement time-history and hysteresis loops of superelastic base isolator, Puget Sound accelerogram.

Table 3 presents the results of a parametric study carried out for a wide range of parameters for the base isolator. Four parameters were varied within the known physical limits of superelastic behavior: 1) the yield force per unit mass (Fy), 2) the effective isolated period (Tsp), 3) the stiffness ratio after and before yielding (Ua) and 4) the force shift for the back transformation during unloading (Zy0). Results are presented for the maximum and mean values, taken across the earthquake ensemble, of the following parameters: 1) the residual horizontal displacement between the top of the pier and the bridge deck (sr), 2) the maximum horizontal displacement between top of the pier and the bridge deck (sm) and 3) the maximum absolute horizontal acceleration of the deck (aubm). The results indicate various trends as discussed below.

When the yield force (Fy) increases, the residual displacement reduces. This reduction is particularly significant for an isolated period (Tsp) of 0.05 s. The maximum horizontal displacement (sm) decreases with an increase of the yield force (Fy). Finally, the maximum acceleration (aubm) increases significantly (almost a factor of 2 for Tsp = 0.5 s) when the yield force increases.

Table 3. Results of parametric study for earthquake ensemble.

First row: average value of earthquake ensemble; Second row: maximum value for earthquake ensemble
Fy: yield force by unit of masse (Fy=Ky.Y)
sr: residual horizontal displacement between top of pier and bridge deck
sm: maximum horizontal displacement between top of pier and bridge deck
aubm: maximum absolute horizontal acceleration of the deck

Fy(m/s^2)	Tsp(s)	Ua	Zy0	sr(mm)	sm(mm)	aubm (g)
1	0.05	0.05	1.2	0.04	1.31	0.23
				0.13	2.31	0.28
1	0.05	0.01	1.2	0.62	4.66	0.17
				1.15	7.80	0.23
1	0.05	0	1.2	8.02	9.05	0.10
				20.25	20.38	0.10
1	0.5	0.01	1.2	8.65	28.99	0.11
				17.87	43.36	0.11
1	0.5	0	1.2	19.77	32.85	0.10
				50.22	58.66	0.10
1	0.5	0.05	1.5	1.24	23.71	0.11
				2.29	34.43	0.12
1	0.5	0.01	1.5	8.65	28.99	0.11
				17.87	43.36	0.11
1	0.5	0	1.5	19.77	32.85	0.10
				50.22	58.66	0.10
1	0.05	0.01	1.5	0.62	4.66	0.17
				1.15	7.80	0.23
1	0.05	0	1.5	8.02	9.05	0.10
				20.25	20.38	0.10
0.5	0.05	0.01	1.2	4.17	37.40	0.07
				8.96	63.39	0.18
0.5	0.05	0	1.2	11.24	13.64	0.09
				22.04	32.68	0.10
0.5	0.5	0.01	1.2	6.03	42.98	0.06
				11.30	63.39	0.06
0.5	0.5	0	1.2	25.65	46.84	0.05
				55.77	67.63	0.05
0.5	0.05	0.01	1.5	0.58	5.62	0.18
				1.15	8.03	0.23

An increase of the effective isolated period (Tsp) produces an increase in, both, the maximum displacement (sm) and the residual displacement (sr). The maximum acceleration (aubm), however, is reduced substantially when the effective isolated period (Tsp) increases.

An increase of the plastic plateau stiffness (Ua) results in a decrease in displacements (sm and sr) and an increase in acceleration (aubm). Finally, the shift parameter (Zy0) has a negligible effect on, both, the displacement and acceleration.

CONCLUSION

The results of a numerical study, using an improved uniaxial superelastic rule, indicates that Shape Memory Alloys (SMAs) represent a possible damping material for seismic base isolation of bridge structures. The main advantage of SMAs over traditional base isolation devices, such as elastomeric, lead-rubber or friction bearings, is the combination of a re-centering and high energy dissipation capabilities. The only known disadvantage of SMAs, beside their cost perhaps, is their sensitivity to fatigue loading. Extensive experimental studies are now required to fully assess the qualities and drawbacks of this material for the seismic base isolation technology.

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REFERENCES

Bonc, R. (1967). Forced vibration of mechanical systems with hysteresis, Proceedings of the Fourth Conference on Nonlinear Oscillation, Prague, Czechoslovakia.

Constantinou M., A. Mokha and A. Reinhorn (1990). Teflon bearings in base isolation II: modeling. *Journal of Structural Engineering*, ASCE, Vol .116, No. 2, 455 -474.

Filiatrault, A., D'Aronco, D. and Tinawi, R. (1994). Seismic shear demand of ductile cantilever walls: a Canadian code perspective. Canadian Journal of Civil Engineering, Vol. 21, No. 3, 363-376.

Funakubo, H. (1984). Shame memory alloys. Gordon and Breach Science Publications.

Gresser, E.J. and Cozzarelli, F.A. (1991). Shape memory alloys as new materials for aseismic isolation. Journal of Engineering Mechanics, ASCE, Vol. 117, No. 11.

NBCC. (1995). National Building Code of Canada, Associate Committee on the National Building Code, National Research Council of Canada, Ottawa, Ontario.

Patoor, E. and Beveiller, M. (1990). Les alliages a memoire de formes. In: Technologies de Pointes Hermes, (in French).

SMCAT. (1989). An earthquake strong motion data catalog for personal computers. National Geophysical Data Center, Boulder, Colorado.

Wen, Y.K. (1976). Method of random vibration of hysteretic systems. *Journal of the Eng. Mechanics Division*, ASCE, Vol. 102, No. 2, 249-263