# Damping properties of steel frame equipped with traditional and shape-memory alloy braces

Davide Fugazza*

*European School for Advanced Studies in Reduction of Seismic Risk (ROSE School), University of Pavia, Via Ferrata 1, 27100 Pavia, Italy*

**Abstract**

In this work the attention is focused on the seismic performance of a three-story steel frame equipped with either steel or shape-memory alloy (SMA) braces. A number of non-linear time-history analyses are carried out and the dynamic performance of the structure is judged through computation of the interstory drift as well as the residual drift. The efficacy of the new materials in reducing earthquake-induced vibrations is numerically evaluated by studying the role of superelastic hysteresis.

*Keywords:* Shape-memory alloys; Smart materials; Earthquake engineering; Dynamic analysis; Steel structures; Bracing systems

## 1. Introduction

Shape-memory alloys (SMAs) are a class of alloys showing mechanical properties not present in materials usually employed in civil engineering. At the macroscopic level SMAs feature the superelastic effect (SE) and the shape-memory effect (SME) and, due to these unique characteristics, materials made of SMAs lend themselves to innovative applications in many scientific fields. Recent investigations have also shown the possibility of using such new materials in vibration control devices. In particular, experimental and numerical tests have highlighted the ability of SMAs to improve the seismic performance of buildings [1–3] and bridges [4,5].

Although the existing literature provides a large number of numerical investigations regarding the SMA technology, very little has been done in terms of structural applications in earthquake engineering and, in particular, on the role of the superelastic hysteresis of large cross-section elements in the energy dissipation mechanism.

In order to cover this lack of information, this paper focuses on the use of SMA elements in innovative bracing systems and numerically evaluates the effect of the damping properties of SMAs. In particular, computer simulations are conducted comparing the seismic response of a three-story steel structure having two different bracing configurations: steel buckling-restrained and SMA braces. Steel braces are modeled according to existing design provisions while SMA braces are modeled based on experimental results from uniaxial tests of SMA bars [6,7].

## 2. Shape-memory alloys

SMAs are a particular type of material with the ability to recover large deformations and then return to their original shape upon application of heat or removal of load. The unique properties of SMAs are related to reversible martensitic phase transformations, that is, solid-to-solid diffusionless processes between a crystallography more ordered phase, austenite, and a crystallographically less ordered phase, martensite. Typically, austenite is stable at lower stresses and higher temperatures, while martensite is stable at higher stresses and lower temperatures. These transformations can be either thermal-induced or stress-induced [8].

Accordingly, variations of both temperature and stress level can be imposed on the SMA material in order to trigger the phase transformation and thus controlling the mechanical response of the material itself. In this respect, a remarkable process to give rise to

* Tel.: +1 39 0382 985 475; Fax: +1 39 0382 528 422; E-mail: davide.fugazza@tiscali.it


*Computational Fluid and Solid Mechanics 2005*
K.J. Bathe (Editor)

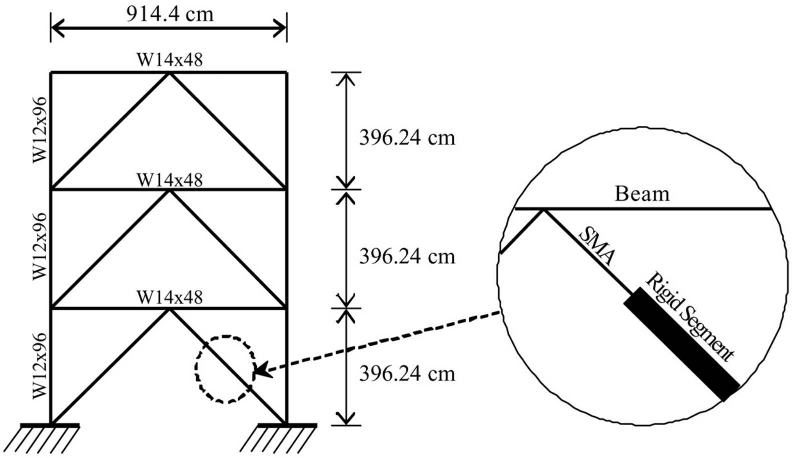


Fig. 1. Model characteristics and particular of the SMA braces.

an energy-absorption with no residual strains (superelasticity) or the ability to recover the imposed deformation by heating (shape-memory effect) can be obtained.

## 3. Earthquake records and model characteristics

The ground motions considered in the analyses are those used by Sabelli [9] and they represent a suite of twenty records with a 10% probability of exceedance in 50 years. They are also scaled based on the average spectral acceleration of all twenty at the fundamental period of the frame.

One of the steel structures considered by Sabelli [9] is studied. In particular, the attention is focused on a three-story frame designed to have buckling-restrained braces (Fig. 1).

The SMA braces, instead, are modeled based on the experimental tests carried out by DesRoches et al. [6], who studied the cyclical properties of 12.7 mm diameter superelastic SMA bars. In particular, the material properties selected for the numerical simulations are based on the dynamic tests in order to correctly consider the reduced energy dissipation capability of such materials at high frequencies. For this particular study and for purposes of comparison, it is assumed that the considered SMA elements are a number of large diameter bars able to sustain, as steel braces, both tension and compression forces.

## 4. Numerical analyses

Non-linear dynamic analyses are carried out using the software OpenSEES [10]. Beams and columns are modeled using nonlinearBeamColumn elements with fiber sections and, apart from the roof level where there are hinges between the columns and the beams, fixed connections are assumed among elements. Braces are pinned at both ends and P-$\Delta$ effects are taken into consideration. Also, a 5% Rayleigh damping is specified, according to the usual values adopted for steel construction [9].

The uniaxial material model Steel01 is used to model columns, beams and braces and mechanical properties of structural steel are assumed to be the same as the ones considered by Sabelli [9]. Instead, the implemented uniaxial constitutive model for superelastic SMAs is a modification [11] of the model proposed by Auricchio and Sacco [12]. Its formulation, developed in small deformation regime, relies on the assumption that the relationship between stresses and strains is represented by a series of straight lines whose form is determined by the extent of the transformation experienced. Also, and in agreement with previous studies, no strength degradation during cycling is considered [7] and austenite and martensite branches have the same modulus of elasticity [13].

The SMA braces are modeled to provide the same axial stiffness and yielding strength (denoted as K and Fy in Fig. 4) as steel braces [9]. In such a way, the structure endowed with SMA braces will have the same natural period of the one endowed with steel braces and both steel and SMA elements will yield at the same force level. Rigid elements are connected to SMA members so all the deformation occurs in the SMAs (see Fig. 1).

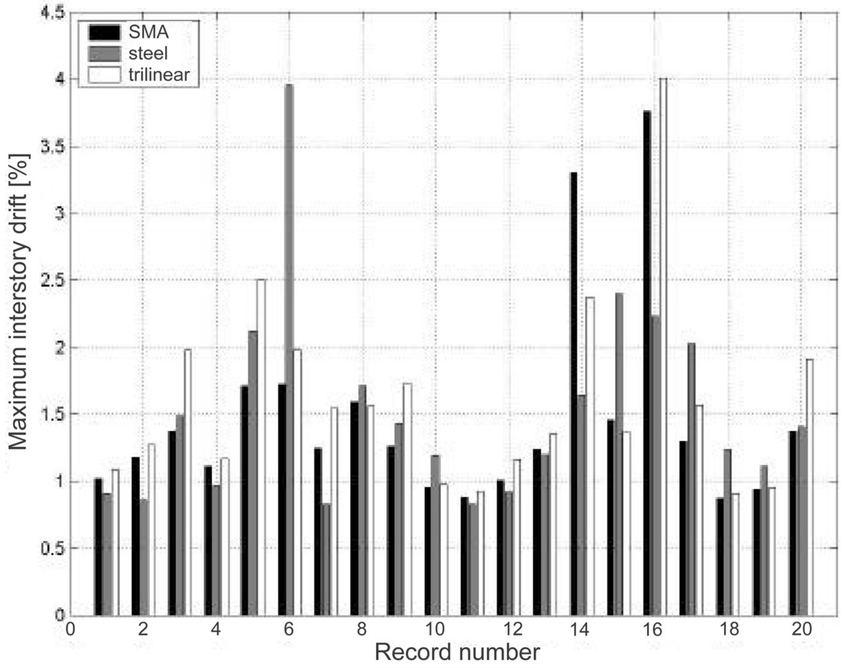


Fig. 2. Maximum interstory drift exhibited by the structure equipped with steel and SMA braces.

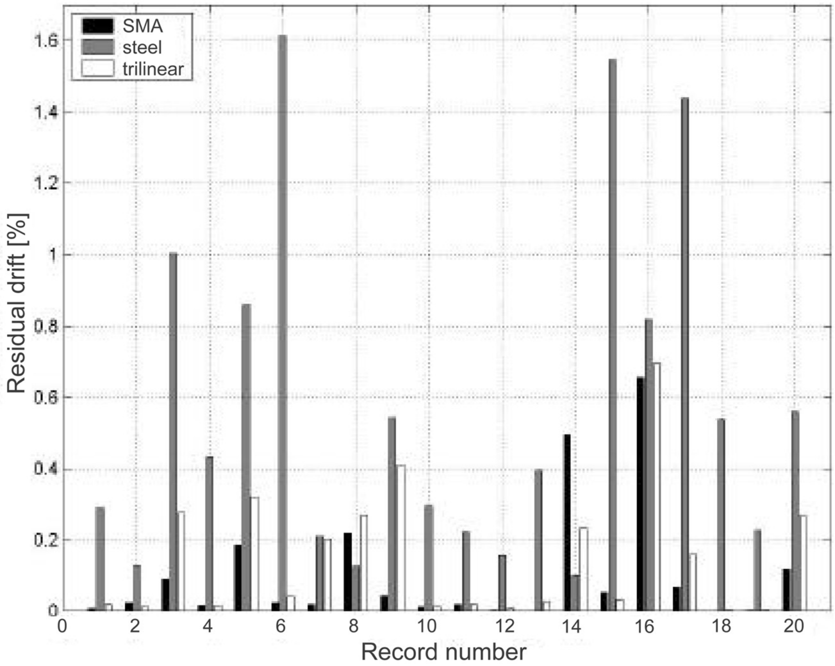


Fig. 3. Residual drift of the top floor exhibited by the structure equipped with steel and SMA braces.

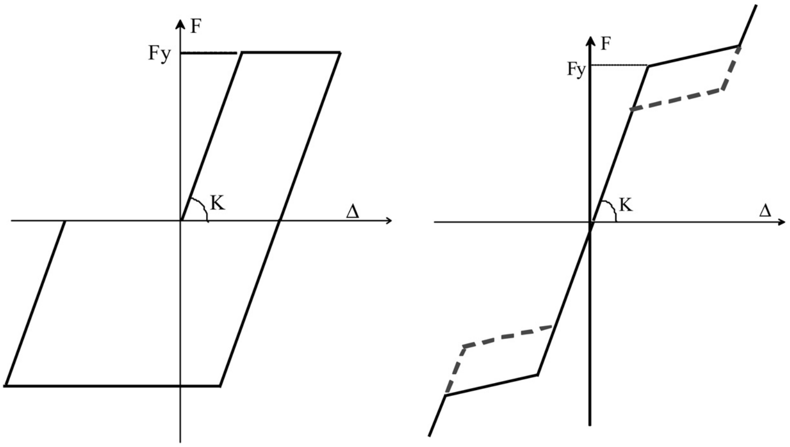


Fig. 4. Constitutive modeling of steel (left) and SMA (right). Note the trilinear behavior (continuous line) and the superelastic hysteresis.

## 5. Results and discussion

The plot of the maximum interstory drift (Fig. 2) shows that although the steel braces provide much wider hysteresis loops (Fig. 3), the SE of SMAs makes them desirable for vibration response reduction. In fact, in most of the cases we observe that SMAs behave better than steel. The superelastic hysteresis provides little contribution in the response meaning that it is the trilinear branch which does play the most important role in the dynamics of such materials. Also, when they experience the martensitic phase, SMAs harden, providing then good displacement control in case of unexpected strong seismic events. Finally, the ability of superelastic SMA elements to bring the structure back to their undeformed shape after the ground motion is over, strongly reduces the permanent deformation in steel (Fig. 4), even in the case of yielding occurring in columns.

## 6. Conclusions

This paper focused on the use of SMA elements as innovative bracing system for steel structures and on the numerical evaluation of the effect of the superelastic hysteresis in the energy dissipation mechanism. The results obtained showed that although steel braces may account for wider hysteresis loops, the recentering ability of SMAs to regain their undeformed shape upon unloading decreases structural vibrations then reducing the damage on the structure.

## Acknowledgments

The author would like to thank Professor DesRoches and Mr. McCormick (Georgia Institute of Technology) as well as Professor Auricchio (University of Pavia) for their help and guidance. Moreover, Davide Fugazza acknowledges the Italian National Seismic Survey for providing the PhD scholarship.

## References

[1] Bruno S, Valente C. Comparative response analysis of conventional and innovative seismic protection strategies. Earthquake Eng Struct Dynamics 2002;31:1067–1092.
[2] Dolce M, Cardone D, Marnetto R. Implementation and testing of passive control devices based on shape-memory alloys. Earthquake Eng Struct Dynamics 2000;29:945–968.
[3] Han YL, Li QS, Li AQ, Leung AYT, Ling PH. Structural vibration control by shape-memory alloy damper. Earthquake Eng Struct Dynamics 2003;32:483–494.
[4] DesRoches R, Delemont M. Seismic retrofit of simply supported bridges using shape memory alloys. Eng Struct 2002;24:325–332.
[5] Wilde K, Gardoni P, Fujino Y. Base isolation system with shape memory alloy device for elevated highway bridges. Eng Struct 2000;22:222–229.
[6] DesRoches R, McCormick J, Delemont M. Cyclic properties of superelastic shape-memory alloys wires and bars. ASCE J Struct Eng 2004;130:38–46.
[7] McCormick J, DesRoches R. Seismic response reduction using smart bracing elements. XL 2003 Conference, Response of Structures to Extreme Loading. Toronto, Canada, 2003.

[8] Duerig TW, Melton KN, Wayman CM. Engineering aspects of shape memory alloys. London: Butterworth-Heinemann, 1990.
[9] Sabelli R. Research on improving the design and analysis of earthquake-resistant steel-braced frames. The 2000 NEHRP Professional Fellowship Report, 2001.
[10] OpenSEES – Open System for Earthquake Engineering Simulations, http://opensees.berkeley.edu, 2004.
[11] Fugazza D. Shape-memory alloy devices for earthquake engineering: mechanical properties, constitutive modelling and numerical simulations. Master's thesis, European School for Advanced Studies in Reduction of Seismic Risk, 2003
[12] Auricchio F, Sacco E. A one-dimensional model for superelastic shape-memory alloys with different properties between martensite and austenite. Int J Non-Linear Mech 1997;32:1101–1114.
[13] Andrawes B, McCormick J, DesRoches R. Effect of cycling modeling parameters on the behavior of shape memory alloys for seismic applications. SPIE International Symposium, Smart Structures and Materials, San Diego, USA, 2004.