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PRESTRESSED BEAM-TO-COLUMN MOMENT CONNECTIONS USING CU-BASED SMA RODS

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ABSTRACT

This study focuses on moment resisting frames with end plate beam-to-column moment connections, where Cu-based SMA rods are used as connectors. First, experimental tests were performed on a beam-column connection and a one story steel frame that includes those connections. Later, a prototype low-rise steel building was designed and an analytical model was constructed to investigate the building seismic performance. The SMA connections were modeled using non-linear rotational springs capable of reproducing the observed experimental behavior of these connections. The model was subjected to several earthquake ground acceleration records. The performance of this prototype was compared to that of a building with conventional MRFs. The results showed an improved response of the building with SMA connections in terms of residual displacements and damage control.

Introduction

The unexpected damage on steel structures observed after the Northridge (1994) and Kobe (1995) earthquakes motivated the development of multiple research projects to investigate and propose solutions to the problems detected. One of the main conclusions from these efforts was the need to confine the damage to specific locations ("structural fuses") where sufficient ductility could be ensured, thereby limiting the damage in the main structural members (Bruneau et al. 2005).

To provide those fuses, different beam-column connections have been proposed and studied analytically and experimentally. Few experimental studies have been conducted to investigate the response of a complete structure. Ivanyi (2000) tested quasi-statically a full-scale frame with semi-rigid connections, where loading was exerted by means of hydraulic jacks using three different load patterns. Ultimate failure occurred with bolt failure in beam-column connections. The test results compared well with the theoretical calculations. Wang et al. (2008) tested, in a shaking table, a 1/3 scale steel frame with self-centering post-tensioned (SCPT) connections. The displacement response of the SCPT frame was very similar to that of the fully welded frame but the acceleration response was reduced.

Shape memory alloys (SMA) constitute a family of new materials that exhibit properties especially suited to fabricate elements that can act as fuses and, additionally, provide self-centering capabilities to the structure. SMAs can sustain large inelastic deformations and recover their original

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shape immediately upon unloading (superelasticity) or after subsequent heat application (shape memory).

This study focuses on moment resisting frames with end plate beam-to-column moment connections, where Cu-based SMA rods are used as connectors. A beam-column connection and a reduced scale one story frame were tested. Then, a three story benchmark structure that included SMA connectors was designed according to the current Chilean seismic code (INN 1996) and steel design provisions (AISC 2005) and an analytical model was constructed to investigate the building seismic performance. The SMA connections were modeled using non-linear rotational springs capable of reproducing the observed experimental behavior of these connections. The model was subjected to several earthquake ground acceleration records. The performance of this prototype was compared to that of a building with conventional MRFs. The results showed an improved response of the building with SMA connections in terms of residual displacements and damage control.

Experimental Studies

Connection tests

An experimental study on the feasibility of using copper-based shape memory alloy rods on a partially restrained (PR) connection was conducted previously and reported elsewhere (Sepulveda et al 2008). A summary is presented here.

The proposed configuration consisted on an end plate connection between a rectangular hollow structural steel beam (100x5x4mm) and a wide flange steel column (150x160x7x9mm) as shown in Fig. 1. Four 240 mm long, 3 mm diameter SMA CuAlBe rods, in austenitic phase, were fixed into anchorages designed to allow for prestressing of the rods, so that they would sustain tension loads only, leaving an effective flexible length of 182 mm. This was done to avoid the buckling of the rods under load reversals that was observed in previous tests (Ocel et al. 2004). The beam end plate was fitted between two steel stubs welded to the flange column above and below the plate, to support the shear forces. The tip of the beam was pin-connected to a shaking table, which was used as an actuator to impose the displacements at the beam tip. The rods were prestressed at the beginning of each test.

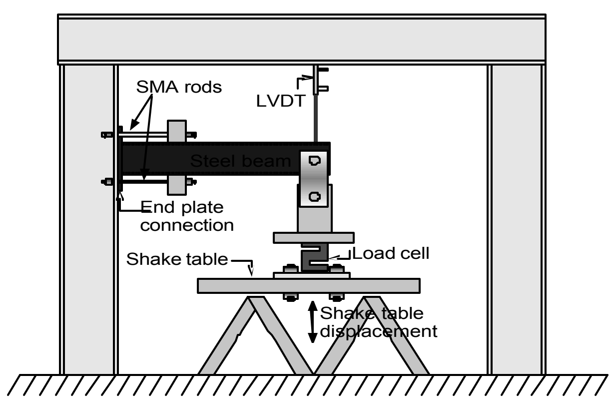


Figure 1. Connection test specimen

The study involved testing the connection by applying controlled cyclic displacement histories at the tip of the beam with two different characteristic frequencies of 0.25 and 1 Hz. Isolated rods similar to those used in the connection were tested previously under cyclic tension to characterize the mechanical and energy dissipation properties of these components.

Fig. 2 shows the forces on the rods versus the rotation considering the top and bottom rods for a test performed at 0.25 Hz. Loops are stable and symmetric. For this assembly, and for a drift of 3%, the equivalent damping ratio was approximately 5.5%. During the different tests, the rods were subjected to a maximum strain of 1.7%. Most of the energy was effectively dissipated by the rods.

Fig. 3 shows a comparison between test results for isolated rods and the rods tested in the connection. Significant differences can be seen between the stress-strain curves obtained from the individual rods tested in tension and from the rods used in the connection. The type of grips or the amount of pre-strain may explain part of the differences.

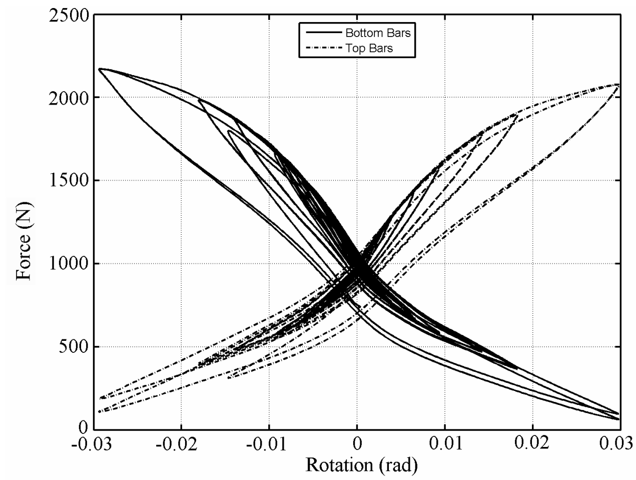


Figure 2. Force-rotation curves

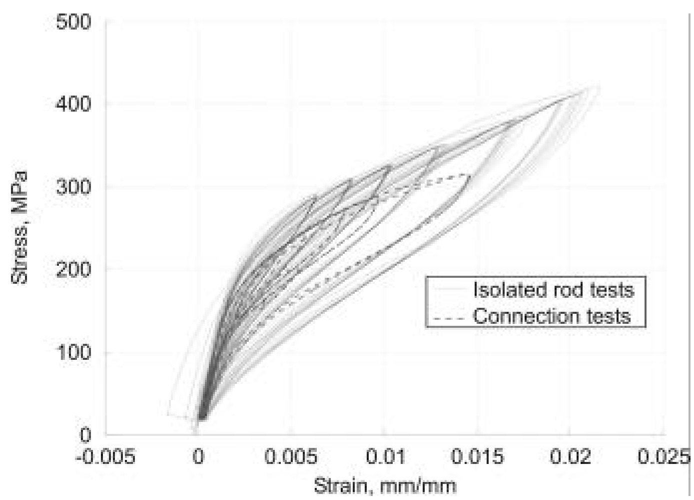


Figure 3. Stress-strain relation from isolated rod and connection test.

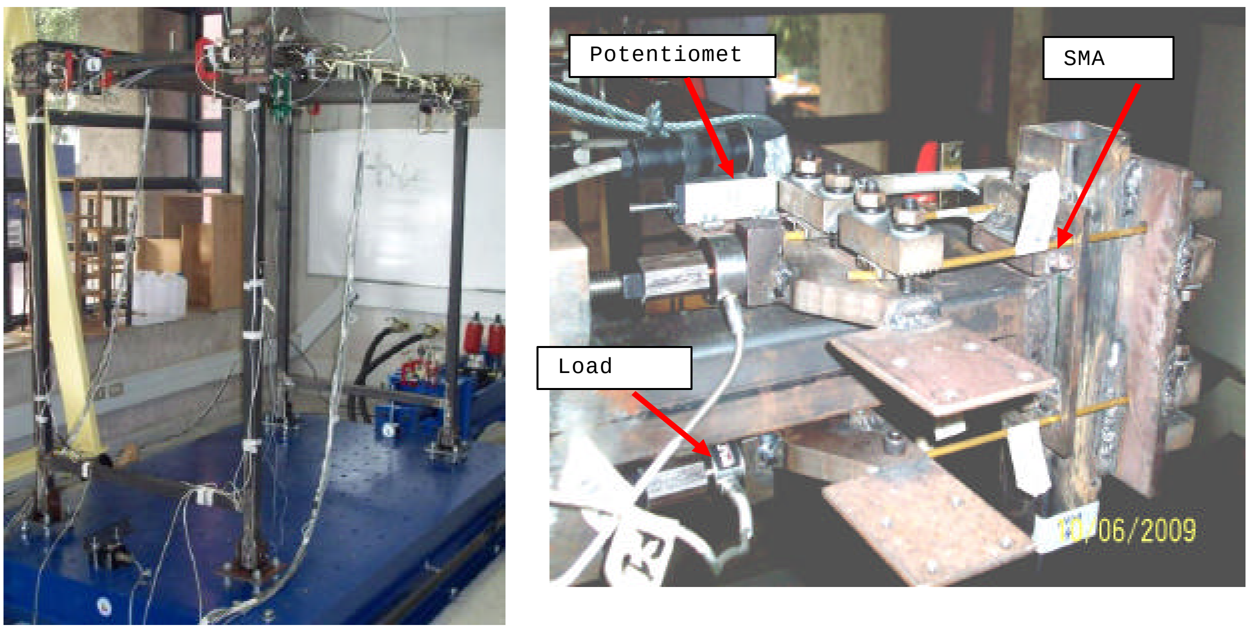
Frame Tests

A reduced scale one story steel model 1.5m height and 1.5 m by 0.8 m rectangular plan was built as shown in Fig. 4a. The columns were pinned at the base. Four 180 mm long, 3.3 mm diameter SMA CuAlBe rods were used at each corner, following the construction details of the isolated connection tests, leaving an effective flexible length of 130 mm. Top and bottom rods were separated

80 mm apart. The rods were prestressed at the beginning of each test with 1.50 kN. The total weight of the structure was 1.8 kN.

The frame was mounted on a 2.1 by 2.0 m, one-degree of freedom shaking table, designed and fabricated locally (Barrientos, 2008). The movement of the table is driven by a 5 ton hydraulic actuator with a displacement range of $\pm$ 0.2 m, maximum acceleration of 9.8 m/s, maximum velocity of 0.6 m/s, and frequency up to 15 Hz.

The instrumentation consisted on accelerometers located at the top and base of the frame, a potentiometer to measure the top displacement, and eight load cells and eight potentiometers to measure the forces and deformations at the top and bottom rods in each connection. Additionally, a 50 mm extensometer was used on one rod, as shown in Fig. 4b, to compare the total deformation with the local deformation of the rod.

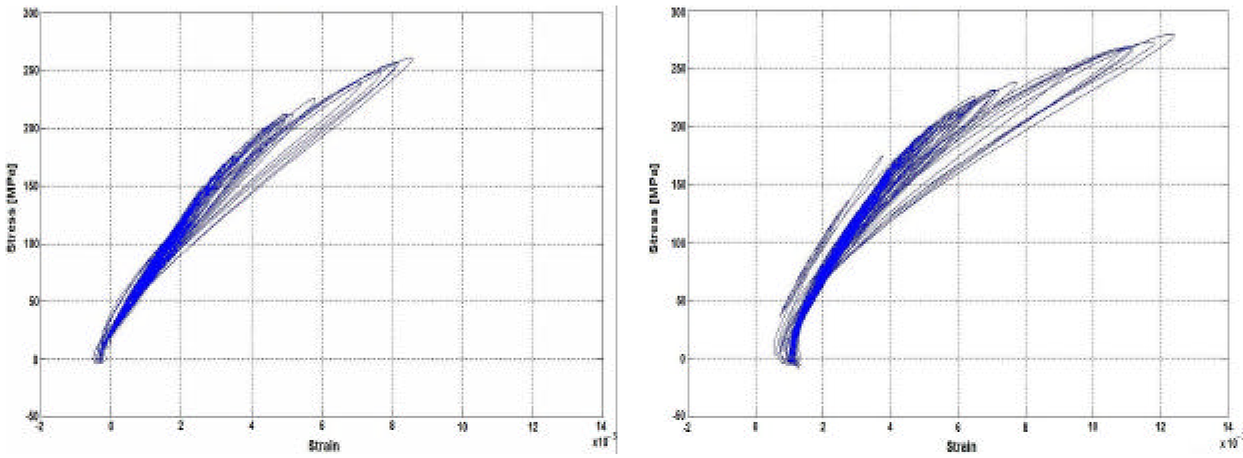


(a) Frame (b) Beam-column details

Figure 4. Test frame characteristics

A period of 0.46 sec and a damping ratio of 1.42% were obtained from pullback tests. The frame was subjected to a sinusoidal signal with a frequency of 1.5 Hz and amplitude of 8 mm, and to the N10E component of the Llolleo record from the March 3, 1985 Chile earthquake, reduced to 25%. These two inputs generated maximum accelerations at the table of 0.07g and 0.12g, respectively, where g is the acceleration of gravity, while the maximum accelerations at the top were 0.4g and 0.48g, respectively. The spectral acceleration corresponding to a SDOF with similar characteristics subjected to 25% of the N10E Llolleo record would be 0.56g, which indicates a moderate reduction.

Fig. 5 shows the stress-strain relationship for the top and bottom rods due to the seismic record. Maximum stresses are 261 and 279 MPa and maximum strains are 0.85 and 1.24%. These values and the dissipated energy are lower than those obtained in the isolated connection. At the end of the tests the rods had no measurable residual deformations.



(a) Top rods (b) Bottom rods

Figure 5. Stress-strain response of rods at one connection from frame test

Analytical Studies

Connection Finite Element Model

A finite element model of the connection tested was developed using ANSYS (ANSYS 2005) to reproduce the experimental results (Fig. 6). Using symmetry considerations, only one half of the connection was modeled. The column was represented by rigid boundary conditions. Three dimensional 20-node brick SOLID186 and 10-node tetrahedral SOLID187 elements were used to represent the SMA rods and the steel components respectively (Garrau, 2008).

The model was made up of eight pieces: two SMA rods 178 mm long, two rigid rods 104 mm long, that represent the grips and pre-loading system, two nuts 41 mm long, the beam, and a block attached to the beam. Contact elements CONTA174 and TARGE170 were defined between components. A bonded contact was defined between the rigid rod and the nuts and between the block and the beam, to impede relative displacements. The contact between the rods and the block was defined as frictionless in order to allow the rods could to slide freely inside the block. The SMA rods were fixed at the column side; the beam end plate had a compression only support to simulate the effect of a stiff column flange; and vertical sliding supports were imposed at the plane of symmetry.

A flag-shaped material stress-strain relationship available in ANSYS was used to simulate the non-linear behavior of the SMA. An elastic modulus of 90 GPa and a yield stress of 250 MPa were used based on results from the isolated rod tests.

PRETS179 element was used to simulate 1 KN prestress in each SMA rod. A vertical load was applied at the tip of the beam that produced the same displacements registered during the experiment.

Figs. 7 and 8 compare experimental and analytical curves for the vertical displacement at the tip of the beam versus the applied force, and the moment at the connection versus the rotation calculated from the strain on the rods, respectively. The differences observed between the experiment and the model are related to: the difference between the behavior of the rods tested individually (used to calibrate the model) and the actual rods used in the connection; the uncertainty in the support conditions of the beam; and the limitations of the material model available in ANSYS.

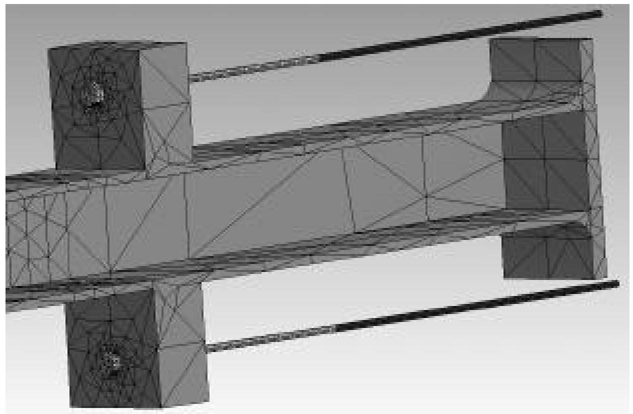


Figure 6. Detail of finite element model of the connection

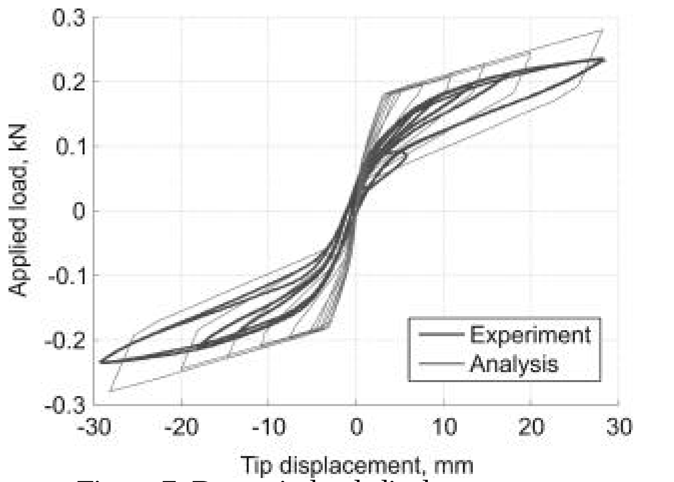


Figure 7. Beam tip load-displacement curves

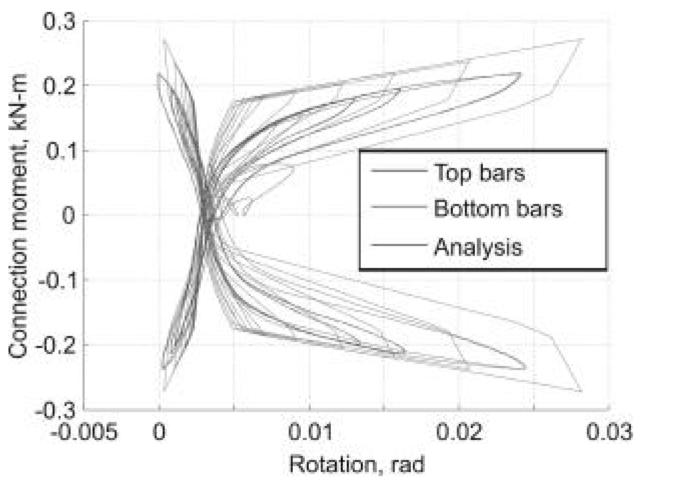


Figure 8. Connection moment-rotation curves

Prototype Design

A 20 by 20 m plan three-story building was designed according to the current Chilean seismic code (INN 1996). Column spacing was 5.0 m and story height, 2.5 m. The columns were pinned at the base. Floor weights are listed in Table 1. Fig. 9 shows the resulting conventional three-story four-bay steel frame and Table 2 the I beam and column dimensions. Yield stresses for beams and columns were 253 MPa. Numerical analysis using the nonlinear analysis program DRAIN-2DX (Prakash et al. 1993) were performed.

Table 1. Floor weight

Floor	Seismic weight (kN)
3	620
2	2410
1	2410
Total	5440

Table 2. Prototype member dimensions

Size	Height (mm)	Web thickness (mm)	Flange width (mm)	Flange thickness (mm)
HN 40x159.5	400	12	400	20
IN 30x55	300	5	200	14

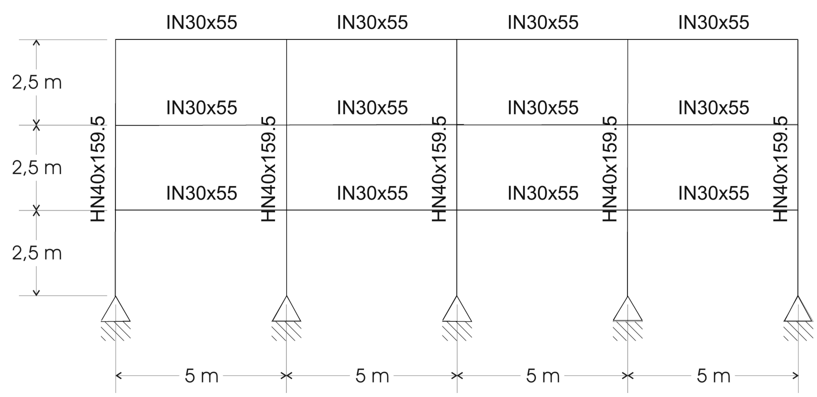


Figure 9. Prototype building elevation

Connection Design

The SMA connections were designed for a frame with the same beam and column sizes as the conventional steel frame. The number and size of SMA connectors were determined considering the design objectives illustrated in Fig 10 and explained below.

For frequent earthquakes, it is expected that the connections will remain below or near the decompression point. For a design level earthquake, the SMA rods should yield, but still have significant deformation capacity. For the maximum considered earthquake, extensive yielding of the SMA rods and structural members should be expected, but no rod fracture that could end up in structural collapse is allowed. To achieve the first objective, the decompression moment was set equal to the moment generated by the dead and live loads. To achieve the second, the connections were designed in such a way that the SMA rods yield for the design load prescribed by the seismic code. Finally, to achieve the third objective, the connection capacity associated to the fracture of the SMA rods was set higher than the beam capacity. This design approach was adapted from the one formulated by Garlock et al. (2007) for prestressed steel MRFs. With this approach, it is possible to control the performance of the structure through the selection of the number and size of connectors.

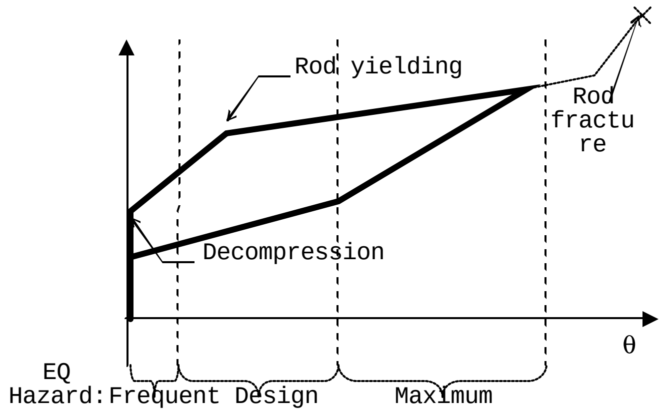


Figure 10. Design objectives for SMA-MRF

Each SMA connection consisted of four 12 mm-diameter rods that were assumed to be placed above the top flange and below the bottom flange of the beams.

Prototype Analysis

Two analytical models were generated using DRAIN-2DX (Prakash et al. 1993), one for the conventional steel MRF and the other for the SMA-MRF. A beam-column element with plasticity concentrated at its ends (Element 2 in DRAIN-2DX) was used to model beams and columns, and an inelastic rotational spring element (Element 4 in DRAIN-2DX) was used to model the SMA connection. The properties of the inelastic rotational springs were determined assuming a Young Modulus equal to 90 GPa, a hardening ratio equal to 0.345, a total area of SMA wires of 4.52 cm^2, and a length of 35 cm. The resulting yield moment of the connection was 41.3 kN·m and the initial connection stiffness 18.3 MN-m/rad.

The natural period of the SMA-MRF was 1.04 s, while the natural period of the rigid frame was 0.675 s. The N10E component of the Llolleo record (Chile 1985, PGA = 0.65g) was used in the simulation. Mass and stiffness proportional Rayleigh damping was considered, with an equivalent viscous damping ratio of 2% for modes 1 and 3.

The overall response of the steel MRF and the SMA-MRF was compared in terms of story displacements, story drifts, residual drifts, and story shears. Figures 11 and 12 compare base shear and top displacement for both frames. In the steel MRF all beams yielded and residual displacements were apparent (0.15 cm at the top). In the SMA-MRF there is neither yielding in the steel elements, nor residual displacements. The maximum strain in the SMA rods was 2.5% and they dissipated most of the seismic energy. Acceleration at the top of both models were similar.

However, when the SMA-MRF was subjected to other type of seismic records (Sylmar and Northridge) some beam yielding occurred and the main effect of the SMA rods was to provide recentering capacity. To consider the variation of the mechanical properties of the alloy, some parametric analyses were performed. It was concluded that the rod section could vary between 1.15 and 0.5 of the original values without changing the beneficial effect of using SMA rods (Astorga, 2009).

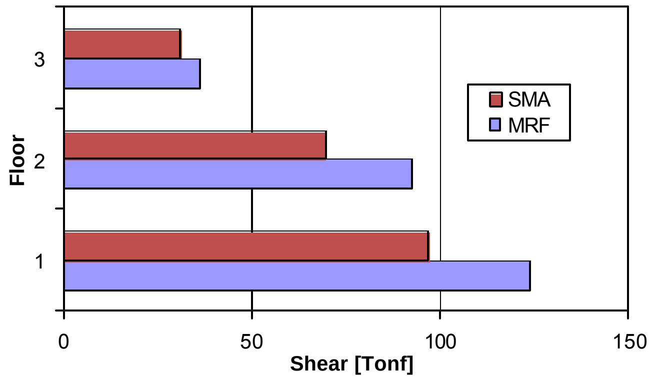
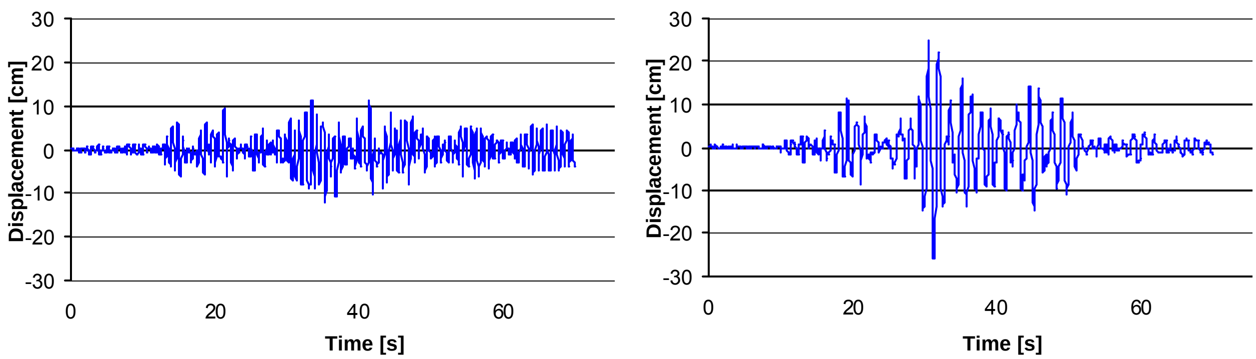


Figure 11. Story shear comparison



(a) Steel MRF (b) SMA-MRF

Figure 12. Top displacement comparison

Conclusions

An innovative connection using prestressed superelastic SMA rods as connectors was presented. Tests conducted on a prototype showed significant energy dissipation and self-centering capabilities of the connection. A finite element model of the test specimen was able to reproduce the experimental behavior within reasonable approximation.

Based on these results, a methodology for the design of SMA connections was developed and applied to the design of a prototype building. Analytical models of the SMA-MRF building and a conventional steel MRF were subjected to earthquake ground acceleration records and their responses were compared. The results showed that the SMA-MRF effectively concentrates the inelastic behavior in the SMA elements, leaving the structural members undamaged, and that residual deformations are reduced with respect to the conventional steel MRF. However, the experimental test of the frame showed less dissipation than the single connection test. Construction details must be improved before proceeding to real applications.

Acknowledgments

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References

AISC 2005. ANSI/AISC 360-05. *Specification for Structural Steel Buildings*, American Institute of Steel Construction Inc., Chicago, Illinois.

ANSYS 2005. *ANSYS Inc. Theory Reference. ANSYS Release 10.0*, ANSYS Inc., Canonsburg, Pennsylvania.

Astorga J. 2009. Estudio sísmico de un edificio de marcos de acero con conexiones viga columna SMA. *Civil Engineering Thesis*, University of Chile

Barrientos J. 2008. Montaje, puesta en marcha y calibración de una mesa vibradora de un grado de libertad. *Civil Engineer Thesis*, University of Chile.

Bruneau, M., Engelhardt, M., Filiatrault, A., Goel, S., Itani, A., Hajjar, J., León, R., Ricles, J., Stojadinovic, B., and Uang, C., 2005. Review of Selected Recent Research on US Seismic Design and Retrofit Strategies for Steel Structures. *Progress in Structural Engineering and Materials*, 7 (3):103–114.

Garlock, M.M., Sause R., Ricles, J.M. 2007. Behavior and Design of Posttensioned Steel Frame Systems, *Journal of Structural Engineering-ASCE*, 133 (3): 389-399.

Garrau S. 2008. Estudio Analítico de una conexión viga co-lumna usando aleación SMA CuAlBe. *Civil Engineer Thesis*, University of Chile.

INN 1996. NCh433Of96. *Earthquake Resistant Design of Buildings*, Instituto Nacional de Normalización, Santiago, Chile.

Ocel, J., DesRoches, R., Leon, R.T., Hess, W.G., Krumme, R., Hayes, J.R. and Sweeney, S. 2004. Steel Beam-Column Connections Using Shape Memory Alloys, *ASCE Journal of Structural Engineering*, 130 (5): 732-740.

Prakash V., Powell G.H., and Campbell S. 1993, "DRAIN-2DX Base Program Description and User Guide," *Report No. UCB/SEMM-93/17&18,* Department of Civil Engineering, University of California, Berkeley, CA.

Sepúlveda, J., Boroschek R., Herrera R., Moroni, M.O., Sarrazin, M. 2008. Steel beam-column connection using copper-based shape memory alloy damper. *Journal of Constructional Steel Research* 64: 429-435.

Wang D., Filiatrault A., 2008, Shake table testing of a self-centering post-tensioned steel frames, *Proc. 14th World Conference on Earthquake Engineering*, Beijing, China, paper 11-0005