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SHAKING TABLE TEST OF A REDUCED-SCALE STRUCTURE WITH COPPER-BASED SMA ENERGY DISSIPATION DEVICES

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ABSTRACT

A series of pullback and shaking table tests were performed for evaluating the seismic performance of (1) a scale model of a three-story steel rigid frame structure and (2) the same model equipped with shape memory alloy (SMA) dampers. The dampers consisted of wires made of a copper, aluminum and beryllium alloy, located as bracings at each level. The Sylmar, Kobe, Taft, El Centro and Llolleo scaled earthquake records, as well as white noise motion were used as input for the shaking table tests. Acceleration at different levels, deformation and force at the dampers were registered. The inclusion of Cu-Al-Be dampers increased the damping ratio from 0.59% in the bare structure to 5.95% in the braced one. At the same time the structure stiffness increased making the first natural frequency to change from 2.5 Hz to 3.7 Hz. The net effect of these two factors was a reduction of peak acceleration and peak displacements to near 60% of the bare case.

Introduction

The Shape Memory Alloys (SMA) are metallic alloys that can undertake large strains, and recover their initial configuration after unloading (named superelastic effect) or by heating (named shape memory effect), without permanent deformation. Energy is dissipated during the loading-unloading process, fact that makes them suitable for its use as seismic dissipation devices.

Although Nitinol, a binary alloy of nickel and titanium, have received most of the commercial attention, especially because of biomedical applications, copper-based alloys may be more attractive for seismic applications because they are less expensive and easier to

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machine. In fact, due to the hardness of Nitinol, machining large bars is difficult and special tools are required.

Thorough reviews concerning potential uses of Ni-Ti in earthquake engineering can be found in DesRoches and Smith (2004a) and Wilson and Wesolowsky (2005). Both include state of the art information about modeling, design and testing of devices as well as theoretical and laboratory studies on their use in buildings and bridges. Janke et al., (2005) discuss Ni-Ti and Fe-Mn-Si SMA potential applications on civil engineering. With respect to copper-based SMA alloys most of the literature covers aspects of material sciences, material models and mechanical behaviour of tertiary alloys such as Cu-Zn-Al, Cu-Al-Ni and Cu-Al-Be. Studies on mechanical properties and energy dissipation capacity of copper-based alloys can be found in Witting and Cozzarelli (1992) and Gillet et al. (1994). More recently, Casciati and Faravelli (2004) and Torra et al. (2005) studied Cu-Al-Be alloy towards its exploitation in passive control devices.

Cyclic behaviour depends on the type of alloy, the thermo-mechanical processing which influences the grain size; the temperature at which the material is used in relation to the phase transformation temperatures, dimension of the test sample, loading history and loading rate. For instance, DesRoches et al. (2004b) found that Ni-Ti wires show higher strength and damping compared with bars and that increased loading rates lead to decreases in equivalent damping.

In this study, a series of experiments were conducted on a scale model of a three-storey moment resistant steel frame building. Damping devices based on austenite Cu-Al-Be wires were installed in the longitudinal direction as braces. Pull-back and shaking table tests were performed on the bare frame structure and on the braced one. The main objective was the evaluation of the effectiveness of Cu-Al-Be dampers during severe seismic loads.

Characteristics of SMA Braces

Cu-Al-Be shape memory alloy wires ($\phi = 0.5$ mm) were selected as energy dissipation devices. Material was produced by Trefimetaux, France. Previously, in order to characterize their actual behavior, sinusoidal displacements were applied to pre-tensioned austenite wire samples that were submitted to different thermal treatment and, therefore, had different grain sizes. Wires were heated at 717ºC during different periods of time, followed by water quenching and aging process at 88ºC for 20 h and at 96ºC for 4 h. For comparison, an untreated wire was also tested.

Tests were performed at 1 Hz with displacement amplitude of 3.2 mm on wire samples that were 130 mm long. Strains were measured with a 2.5 cm length extensometer. Table 1 shows some results from the tests as secant stiffness, energy loss per cycle E_D, internal friction, and maximum strain attained. The secant stiffness is the difference between the maximum and minimum load divided by the difference between the maximum and minimum deformation. The energy loss is the area enclosed by the hysteresis loop. The internal friction is expressed as

$$\xi = \frac{E_D}{2\pi * A} \qquad (1)$$

where A is the area under the loading branch of the curve. Heating softens the wires and the energy loss increases. Clearly, the untreated material is much more rigid than the treated one, and in the latter case, less cycles were needed to stabilize the stress-strain loops. Based on these results the wires installed in the structure were heated at 717ºC for 225 sec, followed by water quenching and aging as explained earlier.

Table 1. Characteristics of Cu-Al-Be wires

Time of heating at 717ºC (sec)	Secant stiffness (kN/m)	Energy loss E_D (N mm)	Internal friction (%)	Maximum strain (%)
0	35.42	29.9	2.1	3.82
90	24.88	38.7	5.2	6.08
135	25.36	37.1	4.9	6.50
180	27.95	36.9	5.3	8.36
225	21.48	41.0	4.5	8.40

Model Description

Dimensions of the model are 120 cm high, 70 cm long and 42 cm wide; the steel columns (3 x 0.4 cm) are bolted to the beams which are welded to the floor slab. The model was intended to work in the longitudinal direction, so four steel wires (ϕ =0.5 mm) were installed at each story in the transverse direction to avoid torsion. Each floor weights 180 N which gives a total weight of 540 N, [Cerda, 2005].

Four SMA dampers were installed at each level. Each brace consists of a steel channel shape 15 x 15 x 1.5 mm, 45 cm long, and a Cu-Al-Be wire (ϕ = 0.5 mm) that is 40 cm long. The steel angle has at one extreme a longitudinal 3/8’’ bolt (ϕ = 9.19 mm) that serves to tension the damper by means of a nut. The wire is fixed to the steel angle and to the floor slab through a transverse 1/16’’ bolt (ϕ = 1.53 mm).

Instrumentation and Experimental Results

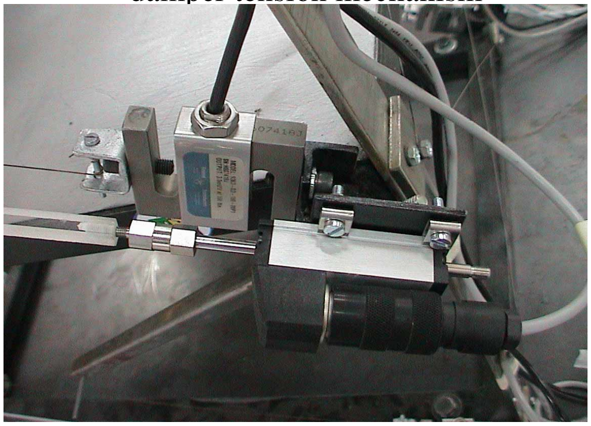
Twelve accelerometers that measure longitudinal and transverse accelerations were installed in the bare structure. Additionally, in the damped structure, eight load-cells and eight potentiometers were installed to measure forces and axial deformations in each damper located at the first and second floor. Figure 1 shows the model, the damper tension mechanism and instrumentation details.

Three pull-back tests were first performed to the bare structure to obtain the modal parameters in the longitudinal direction. Shaking table tests were then performed using 5 minutes of white noise motion and amplitude-scaled records from Sylmar 1994 (0.36g peak acceleration), Kobe 1995 (0.23g peak acceleration), Taft 1952 (0.36g peak acceleration), El Centro 1940 (0.21g peak acceleration) and Llolleo 1985 (0.24g peak acceleration) earthquakes. The test series ended with three pull back tests followed by 25 minutes of low amplitude white noise motion. The long duration white noise motion was intended for fatigue evaluation. A similar sequence was used for the damped model. All tests were performed at room temperature

(≈ 20ºC).

The shake table is a MOOG system, Model 6DOF2000E, with a load capacity of 10 kN and approximately 25 cm of displacement capacity in three directions. Longitudinal as well as simultaneous longitudinal and vertical components were applied.

damper tension mechanism



model and dampers

load cell and potenciometer

Figure 1. Steel frame scaled model and instrumentation

The CuAlBe wires were pre-stressed with a tensile force of 30 N. This was performed at the beginning of the tests; stressing first the wires on the east side and then those on the west side. This sequence produced non uniform pre-strain, being them some what larger at the west side. For each test the initial and final tensions were registered and some relaxation was noticed, but due to the test procedures no action could be taken to restore the original 30 N.

Table 2 shows the frequencies and equivalent damping ratios obtained for the bare model from the pull-back tests performed before and after shaking table tests. Analyses to obtain natural frequencies and damping ratios were conducted using the Ibrahim Time Domain Method [Ibrahim and Mikulcik, 1977]. Differences in frequencies are very small for both set of test. Damping, although rather low, shows a larger percentage variation in the first and second mode that may be related to relaxation of some of the connections.

Table 3 shows the first fundamental frequency and equivalent damping ratio for the damped structure obtained from the pull-back tests, prior and post shaking table tests. In this case there is a range of frequencies indicating non-linear behavior of the wires. The logarithm decrement method was used to determine an average damping.

Table 2. Frequencies and damping ratio in bare model (pull-back tests)

Mode	Prior to shake table test		Post shake table test	
	Frequency [Hz]	Damping [%]	Frequency [Hz]	Damping [%]
First	2.49	0.59	2.50	0.40
Second	7.25	0.35	7.20	0.54
Third	10.95	0.44	10.90	0.45

Table 3. First mode frequency and damping ratio in braced model

Prior to shake table test		Post shake table test	
Frequency [Hz]	Damping [%]	Frequency [Hz]	Damping [%]
3.35-3.71	5.63	3.45-3.73	4.44

Experimental data from shaking table tests shows the effectiveness of the SMA dampers in vibration reduction. Figure 2 compares peak accelerations and peak relative displacements in each floor for the bare and braced structure for all applied records. Calculation of the relative displacements included (1) filtering the absolute acceleration records at each floor to eliminate noise, (2) obtaining relative acceleration at each floor by subtracting the shake table absolute acceleration record, (3) integrating the relative acceleration records twice, and (4) comparing the drifts with the horizontal components of the braces' strains, that were measured directly with potentiometers installed at the first and second floors. Llolleo and Kobe records caused the largest relative displacements and accelerations. Significant reductions were apparent for all cases. The coincidence of peak accelerations and absolute displacements at level 0 (shake table level) for the bare and braced structures, respectively, confirms the similitude between the motions applied to each cases.

Figure 3 shows the hysteresis cycles for all dampers located at the first and second floor during the scaled Sylmar record. Some wires in the first floor underwent deformation amplitudes up to 15 mm, which corresponds to approximately 3.75% strain. Stiffness of the wires at the east side differed from those of the west side. Due to the procedure followed to pre-stress the wires, it is believed that differences in the pre-strain from one side to the other may explain some variation in stiffness. In fact, Dolce *et al.* [2000] tested Nitinol wires and bars for several different conditions and established, among other conclusions, that the secant stiffness varies depending on the pre-strain.

Figure 4 shows the wires maximum and minimum load and the maximum horizontal component deformation attained at the first and second floor for different earthquake records and the initial pull-back test. The first two bars correspond to wires located at the east side of the structure (es and en) while the last two correspond to the wires located at the west side of the structure (ws and wn). The largest loads and deformations were registered at the first floor for

Sylmar and Llolleo earthquakes. The 30 N initial load was insufficient to avoid complete loss of preload at the first floor during Llolleo earthquake.

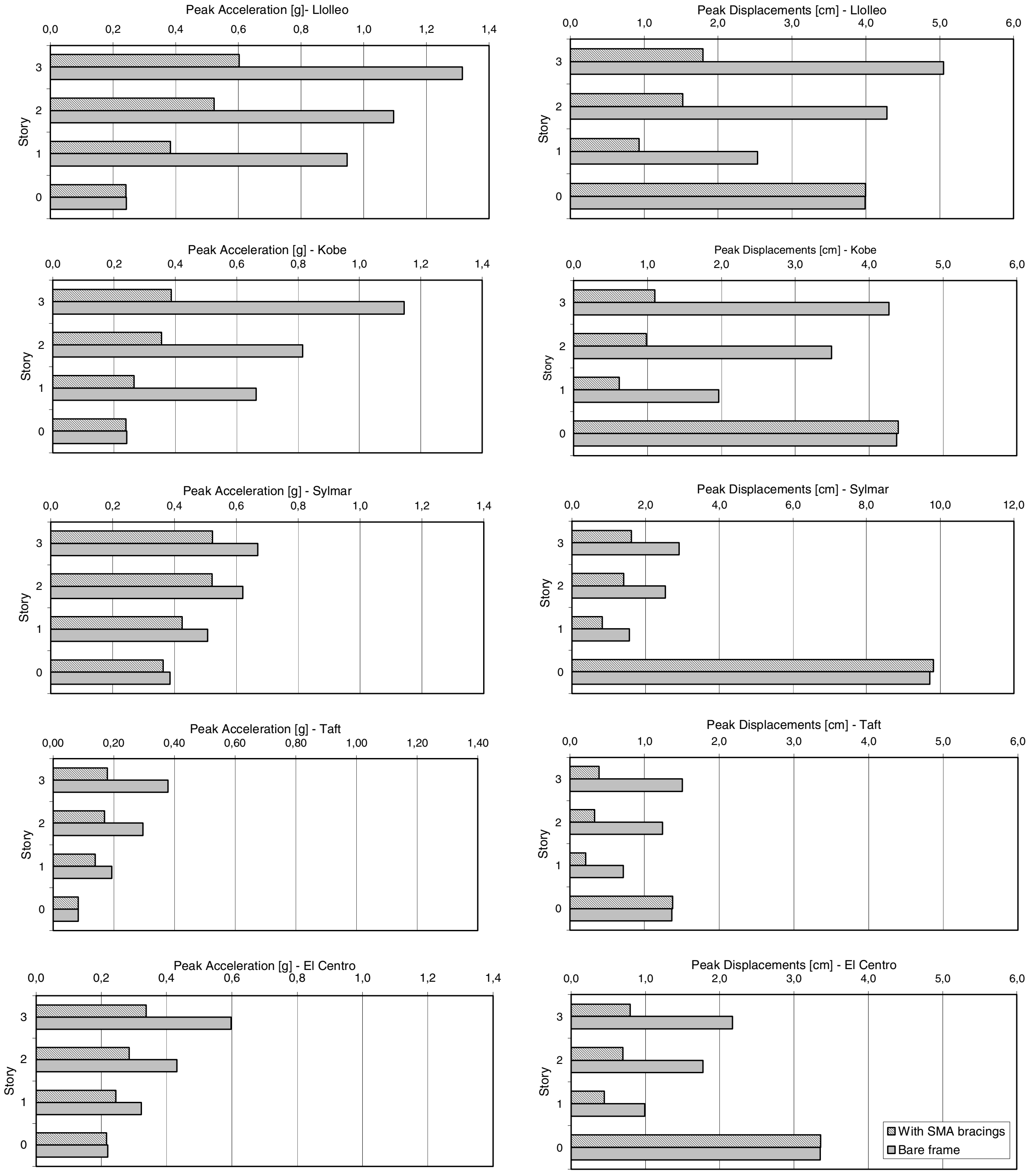
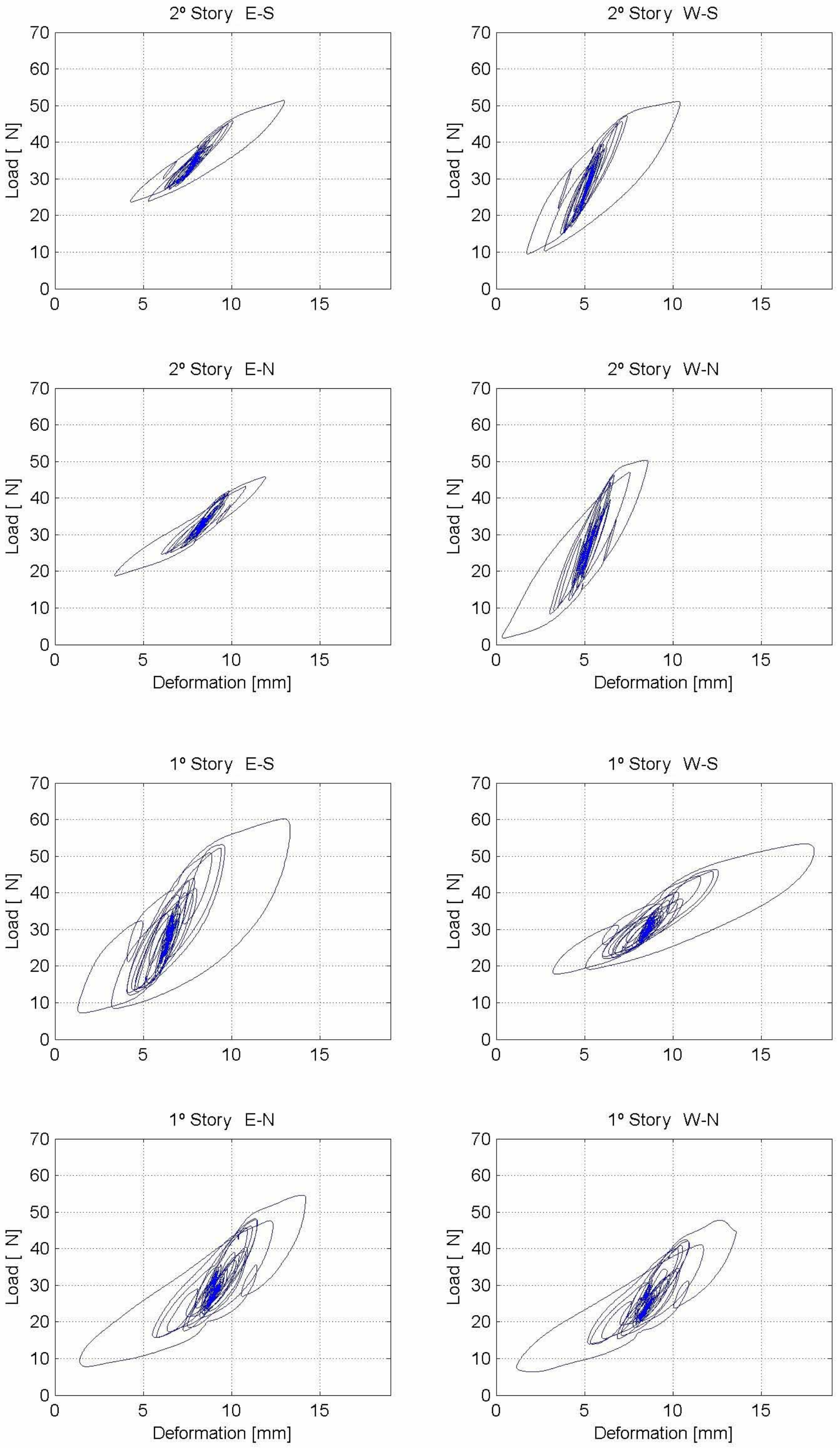


Figure 2. Peak acceleration and displacement comparisons.


2º Story E-S

2º Story W-S

2º Story E-N

2º Story W-N

1º Story E-S

1º Story W-S

1º Story E-N

1º Story W-N

Figure 3. Damper stress-strain relationships for Sylmar earthquake

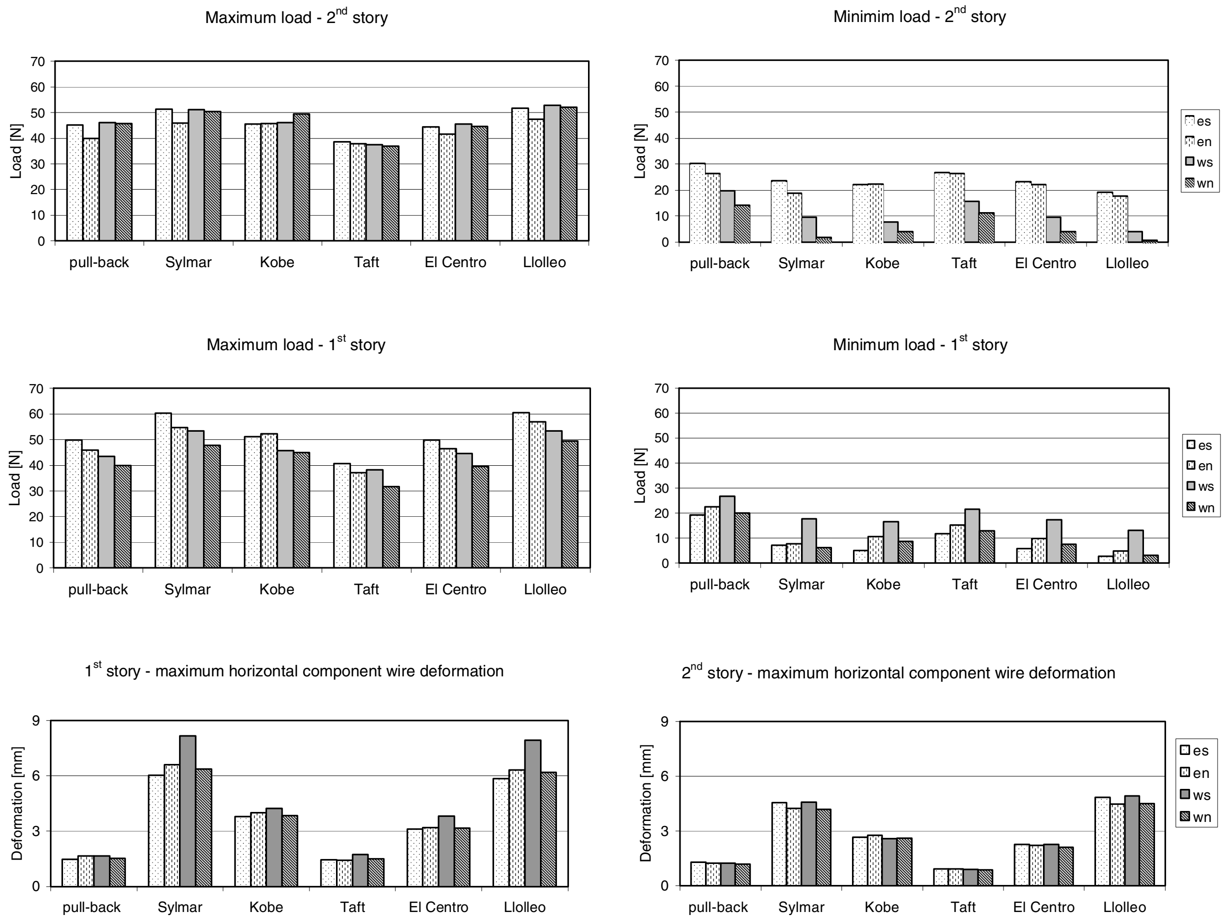


Figure 4. Wire loads and deformations at first and second story.

Figure 5 shows the wires secant stiffness as function of the pre-tensile load. Stiffness increases for lower pre-stress loads. Differences between wires are apparent indicating some problems with the thermal treatment applied. After the application of 25 minutes of white noise all wires showed fatigue problems, as it could be expected, and a dramatic reduction of stiffness. Some of them broke when tension loads were applied again.

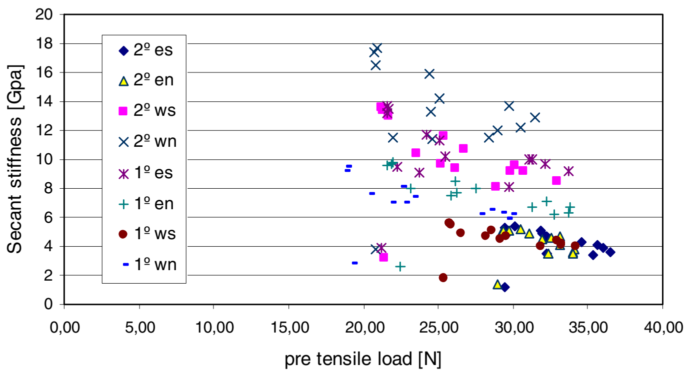


Figure 5. Wires secant stiffness as function of tensile loads

Conclusions

The experimental behaviour of a scale model of a three-storied structure which includes copper-based dissipation devices has been presented. The model corresponds to a rigid-framed steel structure with CuAlBe dissipation devices located as bracing at each story. The weight of the model was 540 N and the volume of the braces was 0.942 cm^3. Three pull-back tests were first performed to the bare structure to obtain the three modal shapes in the longitudinal direction. Shaking table tests were then performed using 5 minutes white noise motion. Afterwards scaled records from Sylmar, Kobe, Taft, El Centro and Llolleo earthquakes were applied. Finally, the model was subjected to three pull-back tests and 25 minutes of white noise motion. A similar sequence was applied to the damped model. All tests were performed at room temperature. The model was instrumented with accelerometers at each story level and LVDT and load cells at the bracing system.

Based on the test results, the following conclusions can be drawn:

(1) Inclusion of the braces produced a stiffness increase of 44, 47 and 50% in the first, second and third mode, respectively.
(2) Equivalent damping in the structure increased from 0.59% to 5.95% in the first mode. This damping is higher than the one obtained by Aiken et al (1993) for a similar model with Nitinol bracings.
(3) The balance of these two factors was a reduction of the peak accelerations and drifts to near 60% compared to the one obtained without dissipation devices.
(4) During the seismic tests a deformation of up to 3.75% was obtained in the SMA wires without rupture.
(5) The thermal treatment of the copper-based SMA material proved to be critical for obtaining the desired superelastic properties.
(6) No appreciable difference was detected when vertical components were included. Movements in the transverse direction were negligible.

In order to scale up these results to actual building structures more research is needed. Large diameter bars of Cu-Al-Be alloy have shown lower damping than Cu-Al-Be wires. Alternatively, cables form by wires could be used in real structures.

Acknowledgments

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