Shape Memory Alloys in Structural Vibration Control

Research at UNIC/DEC/FCT/UNL

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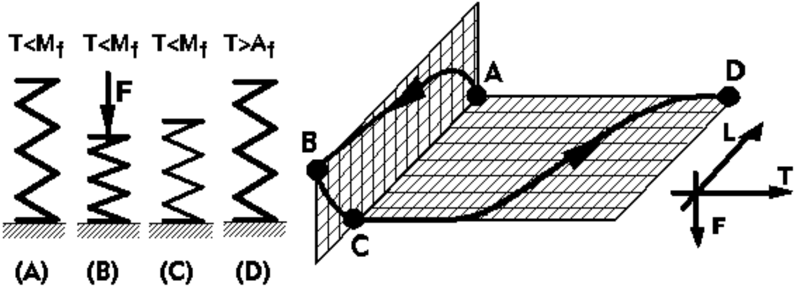
Shape Memory Alloys (SMAs)

Metallic alloys exhibiting two peculiar thermo-mechanical properties:

- shape memory effect – allows the material to recover its original geometry through a heat cycle, after withstanding large deformations;
- superelasticity – enables the material to recover from large nonlinear strains during a mechanical cycle of loading and unloading, while dissipating a considerable amount of energy through hysteresis.

Five primary alloy families are of interest in civil engineering aplications: the nickel-titanium family (**Nitinol**), the iron-magnesium-silicon alloys, two copper-based families, the cooper-zinc-aluminum-nickel and the copper-aluminium-nickel, and some special stainless steel formulations.

Shape memory effect



The sample is deformed (A to B) and unloaded (B to C) at a temperature below M_f. The residual deformation is restored during heating to a temperature above A_f.

(M_f – martensite finish temperature, A_f – austenite finish temperature, $M_f < A_f$)

Shape memory effect - civil engineering applications

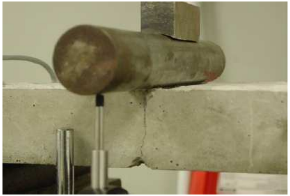
Smart prestressing of the bridge carrying Sherman Road over US-31 [NCHRP-96-IDO29]

Shear cracks on beam stem

Heating of SMA rods

Rehabilitation of a concrete structure using intelligent materials [Soong *et al.*, 2006]

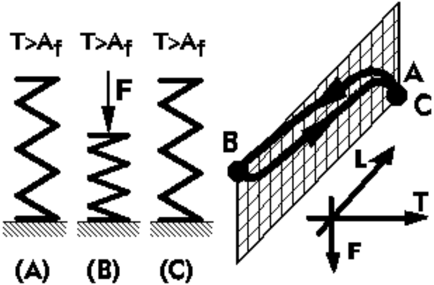
During loading



After heating the crack closes up

Self-repairing performance of concrete elements using superelastic SMA wires, smart prestressing, RC beams with variable stiffness and strength, health monitoring and rehabilitation of concrete structures, self actuating fuse for auto-adaptive composite structures.

Superelasticity

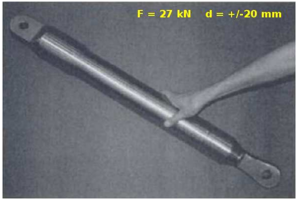


The sample is strongly deformed at relatively low stresses (A to B) at a temperature above A_f. During subsequent unloading a complete shape recovery occurs (B to C).

Superelasticity - civil engineering applications

Seismic protection of cultural heritage structures


Basilica of St. Francis of Assisi [Croci, 2001]

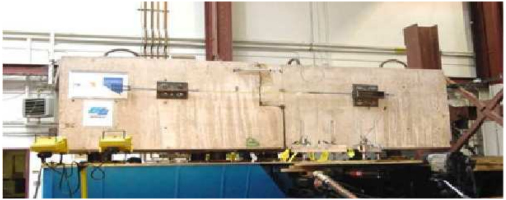
St. Feliciano Cathedral [Castellano *et al.*, 2000]


S.Giorgio Church Bell-Tower [Indirli *et al.*, 2001]

Research project:

- ISTECH - *Shape Memory Alloy Devices for Seismic Protection of Cultural Heritage Structures*

Superelastic restrainers and connectors



[Johnson *et al.*, 2008]

[Padgett *et al.*, 2009]

[Ocel *et al.*, 2004]

Research projects:

- NEES Payload Project - *Large-scale experimental evaluation of shape memory alloy bridge cable restrainers*
- MANSIDE - *Memory Alloys for New Seismic Isolation and Energy Dissipation Devices*
- SUPERB - *Seismic Unseating Prevention. Elements for Retrofitting of Bridges*

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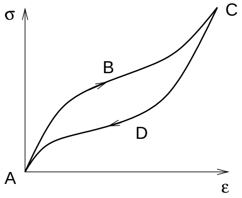
Superelasticity



Transformations in the crystaline structure:

- forward transformation (A $\rightarrow$ M) – curve ABC
- inverse transformation (M $\rightarrow$ A) – curve CDA

hysteretic cycle $\Downarrow$ energy dissipation $\Downarrow$

null residual deformations $\Downarrow$ repositioning capability $\Downarrow$

Vibration control devices based on superelastic SMAs

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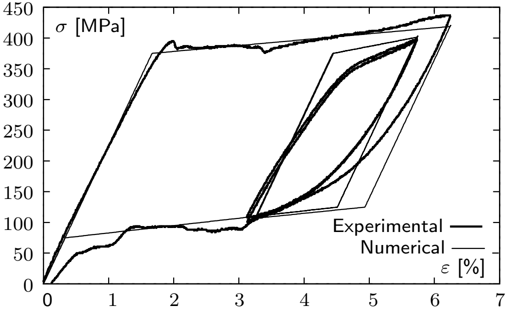
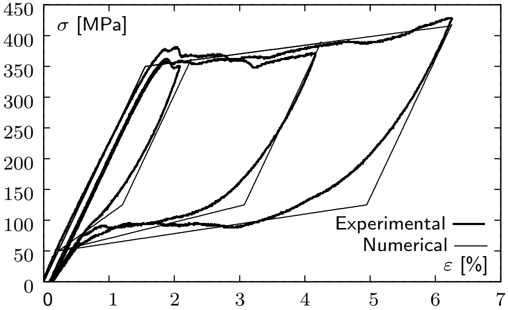
The constitutive model is characterised by the austenitic elastic modulus, the strain associated with the transformation process and the starting and final stresses during the forward and inverse transformations.



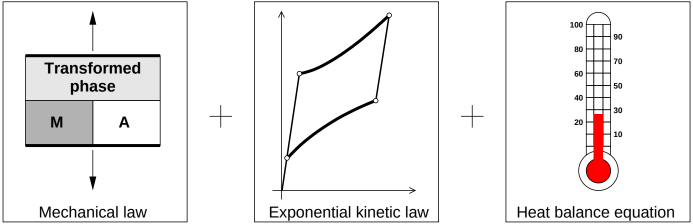
Complete cycle followed by a small inner cycle



Three complete cycles of decreasing amplitude

SMA - temperature and strain rate dependent thermo-mechanical models

As the strain rate increases, the SMA wires can no longer expel the internal heat generated during the loading phase and absorb heat from its environment during the unloading phase and therefore the constitutive model must relate stress, strain, austenite fraction and the temperature in the material.



The model couples the constitutive relations, a kinetic law that describes the volume fraction of austenite and a balance equation that considers the thermal effects on the material $\Rightarrow$ reliable constitutive model even for high strain rates.

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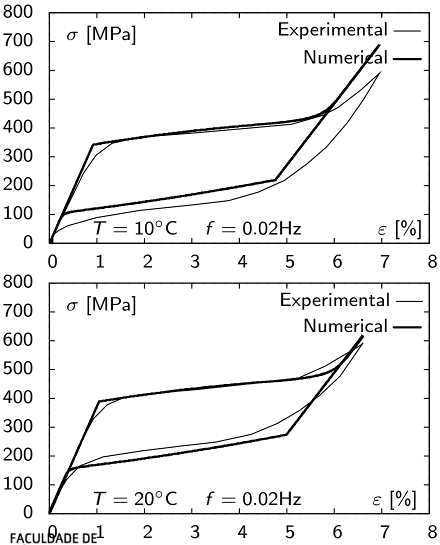
SMA - temperature and strain rate dependent thermo-mechanical models



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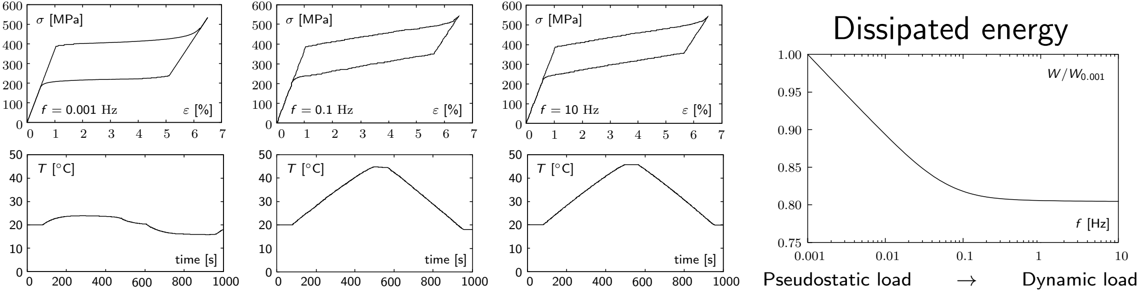
Strain rate analysis using thermo-mechanical model



Room Temperature = 20°C

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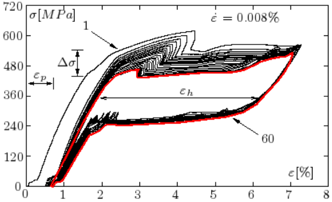
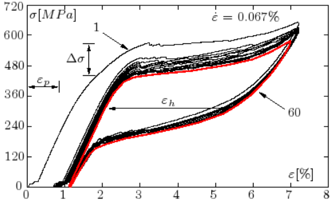
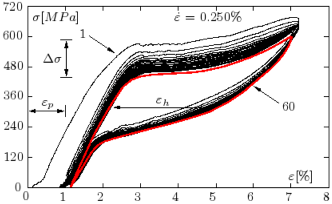


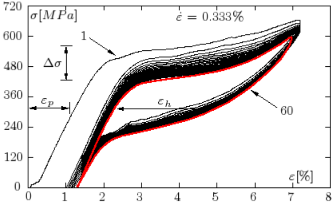
(a) Cyclic loading at $\dot{\varepsilon} = 0.008\%/s$



(b) Cyclic loading at $\dot{\varepsilon} = 0.067\%/s$



(c) Cyclic loading at $\dot{\varepsilon} = 0.250\%/s$

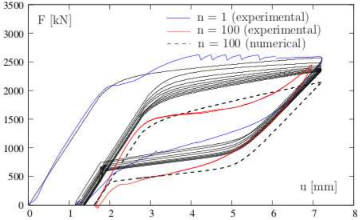


(d) Cyclic loading at $\dot{\varepsilon} = 0.333\%/s$

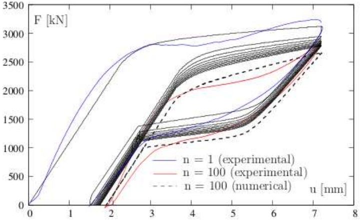
Evolution of:

- Cummulative creep deformation;
- Critical stress to induce martensite;
- Strain associated to the transformation.

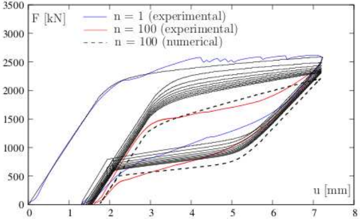
Cycling effects - experimental validation of the numerical model



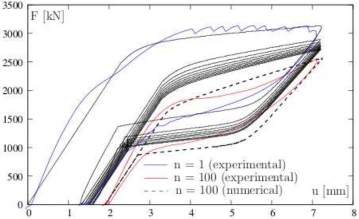
(a) $T_0 = 20°\text{C}$ and $\dot{\varepsilon} = 0.15\%/s$.



(b) $T_0 = 40°\text{C}$ and $\dot{\varepsilon} = 0.15\%/s$.

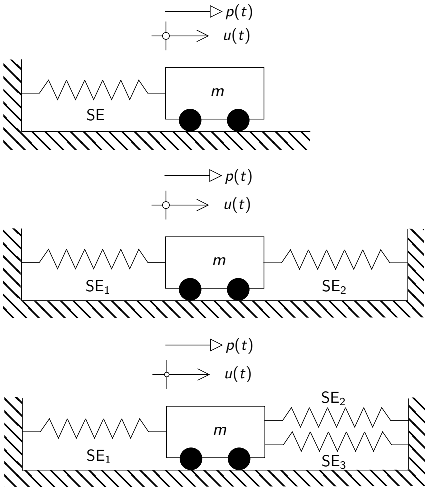


(c) $T_0 = 20°\text{C}$ and $\dot{\varepsilon} = 0.30\%/s$.



(d) $T_0 = 40°\text{C}$ and $\dot{\varepsilon} = 0.30\%/s$.

Superelastic SMA based oscillators



- simple SMA wire
- two pre-tensioned wires working in phase oposition
- two pre-tensioned wires with re-centring element

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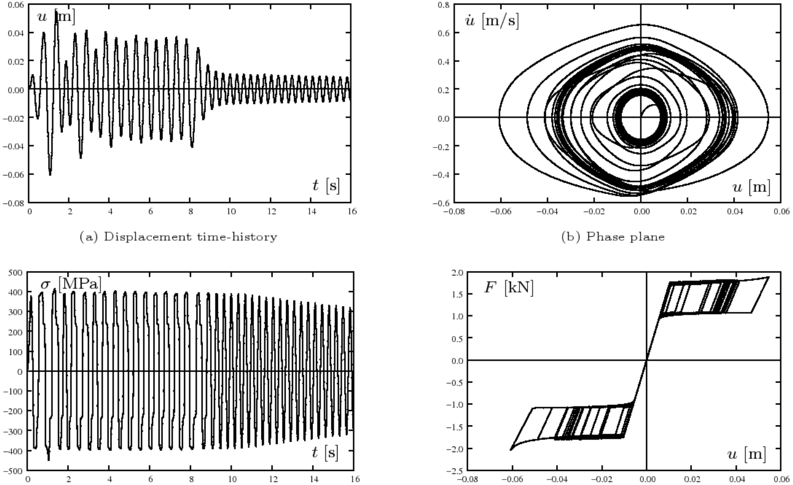
Simple SMA wire ($T = 20°$C, $f = 2$ Hz)



(a) Displacement time-history

(b) Phase plane

(c) Stress time-history

(d) Force-displacement

Exhibits:

- self-recentring
- low energy dissipation ($\zeta_{eq} \simeq 8\%$)

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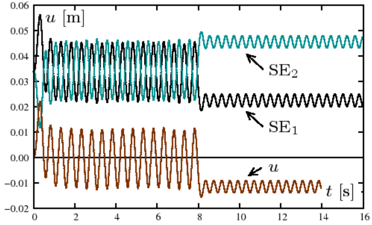
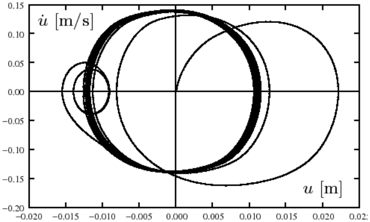
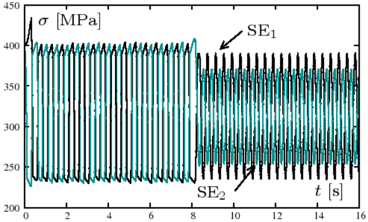


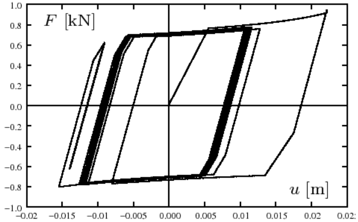
(a) Displacement time-history



(b) Phase plane



(c) Stress time-history

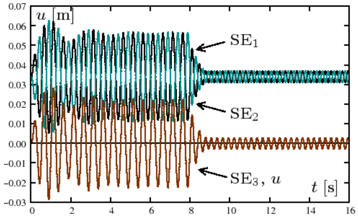


(d) Force-displacement

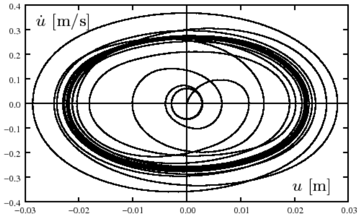
Exhibits:

- good energy dissipation ($\zeta_{eq} \simeq 15\%$)
- no self-recentring

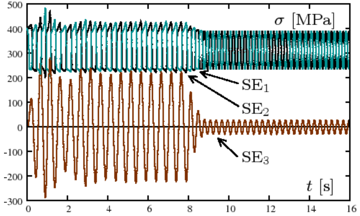
Two pre-tensioned wires with re-centring element ($T = 20°$C, $f = 2$ Hz)



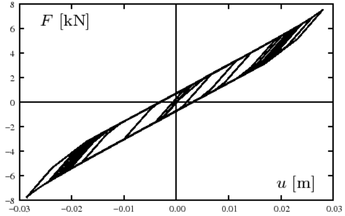
(a) Displacement time-history



(b) Phase plane



(c) Stress time-history



(d) Force-displacement

Exhibits:

- good energy dissipation ($\zeta_{eq} \simeq 15\%$)
- self-recentring

↓

appealing properties for seismic control devices

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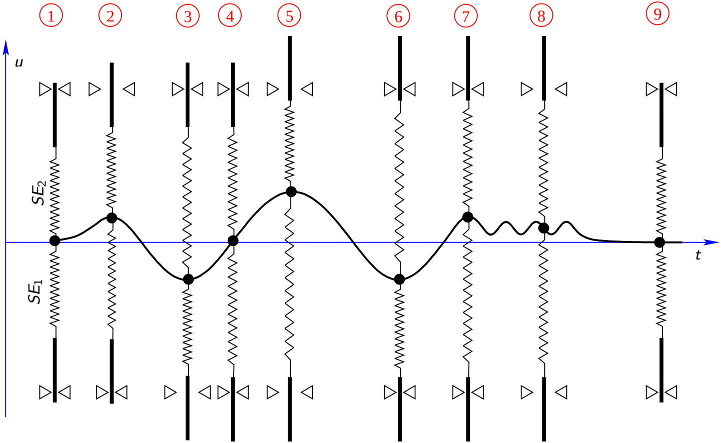
Drawbacks of SMA based passive control devices

- Re-centring capabiliy implies a third elastic element;
- Relaxation can not be avoided, as the use of permanent pre-strained SE wires is a must in order to obtain competitive damping ratio;
- Cumulative creep can be avoided by keeping the strains inside a so called pseudo-elastic window, which ensures appropriate material behaviour, but this is a very challenging task when dealing with arbitrary seismic excitations.

Proposed semi-active device



General behaviour of the proposed semi-active control system

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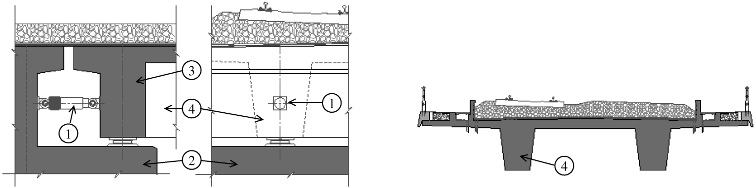
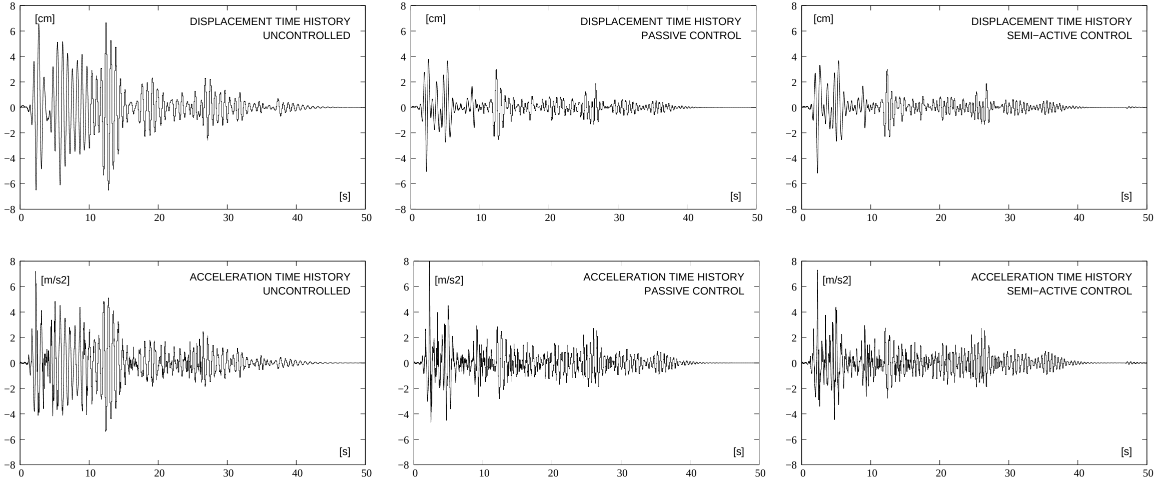


Legend: 1. SMA device, 2. Abutment, 3. Transverse girder, 4. Main girder

For the longitudinal analysis, the viaduct is assimilated to a 1DOF dynamic system: 4650 ton mass, 355×10^3 kN/m stiffness and 5% structural damping.

Two passive control devices are placed at the two ends of the viaduct, one for each main girder. The devices consist of two sets of 1.0 m SMA wires, each set with a total area of 1963 mm^2 (bars or a set of smaller wires laid parallel in strands, to form a cable).

Response of the structure to “El Centro” earthquake



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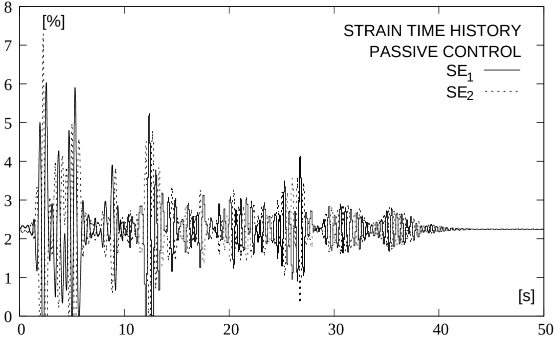

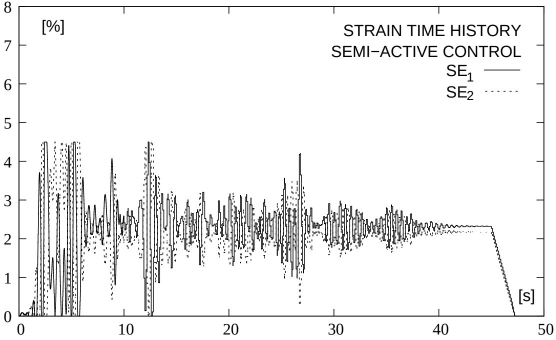

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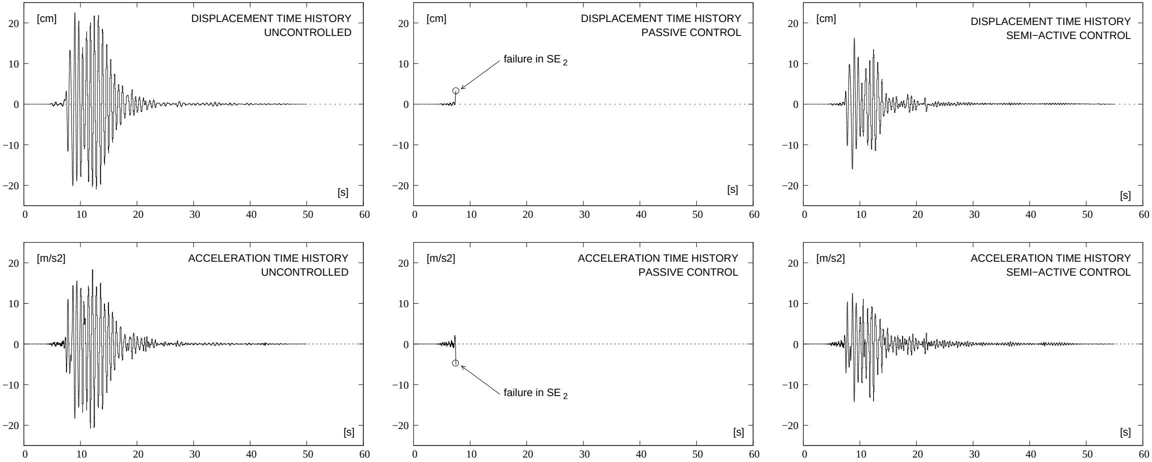
Response of the structure to "Kobe" earthquake



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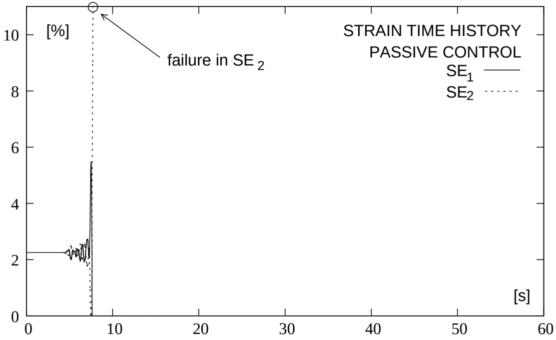

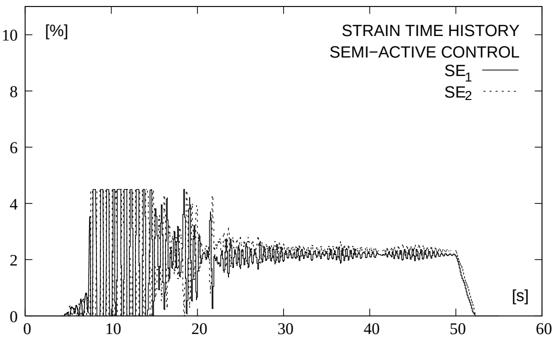

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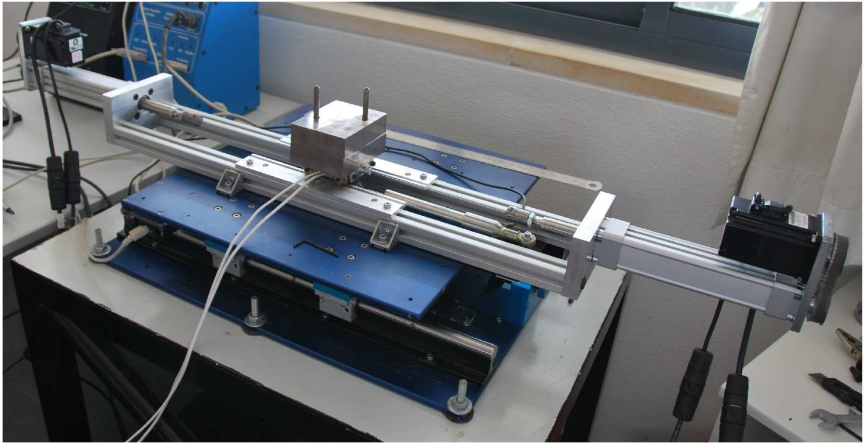
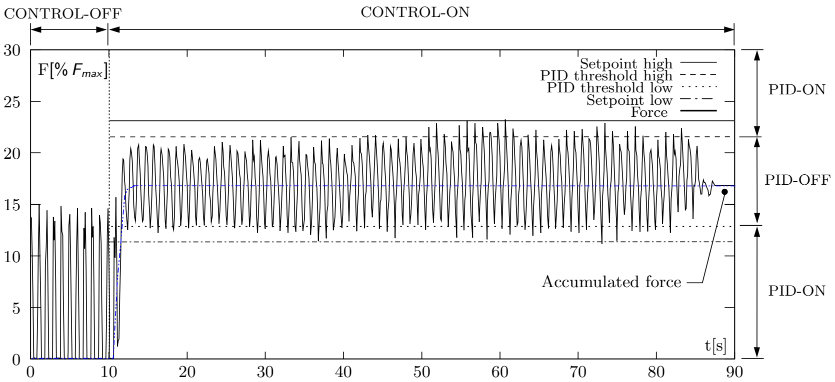
Experimental prototype



Experimental prototype under harmonic load



Force time-history in a SMA wire

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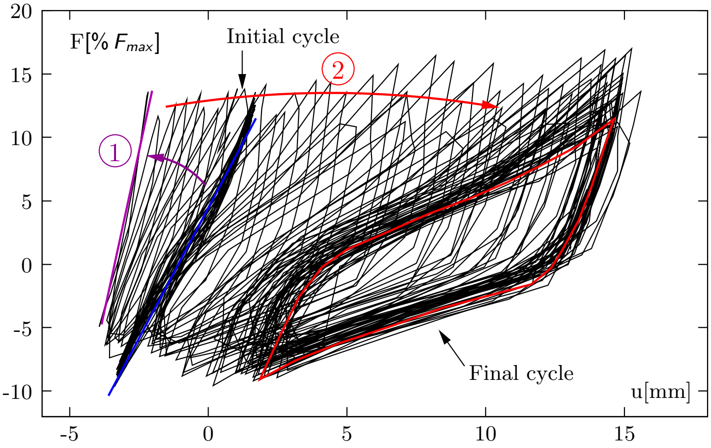

Force-displacement diagram

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Conclusions regarding the proposed semi-active device

- The strain accumulation in the wires is a result of the motion of the structure itself, with no need of external energy input in the system;
- With no need of initial pre-strain calibration, the device responds well to virtually any level of dynamic excitation;
- It presents important damping capabilities, is able to confine the strains in the SE wires inside recoverable limits to minimise the rheological effects related to cumulative creep, and finally, at the end of the action, is able to recover the SE wires strain free condition exhibiting efficient re-centring capabilities and avoiding relaxation problems;
- Is able to confine force values throughout the entire duration of the seismic action, meaning that the force the semi-active device transmits to the structure can be conveniently bounded.

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