EARTHQUAKES EFFECTS: REDUCTION OF PLASTIC DEFORMATION IN STRUCTURES BY SMA

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At moderate and high earthquake intensities (Richter scale between 5.5 and 7.0), the steel structures of buildings may suffer plastic deformation and eventually, after the event, some permanent deterioration and deformation can be observed. Also, in lightly damped structures, the oscillation amplitudes during the event may overcome the structural limits producing strong damages and even the collapse of the building. SMAs are proposed to build dampers for light structures such as family houses (one or two stories with areas close to 200 – 300 m$^2$). SMA dampers are specially fitted for light structures because they present an adequate damping capacity, re-centering capabilities and low cost. In this work we analyze the effects of ‘El Centro’ earthquake on a family house steel structure using the ANSYS finite element software. The results indicate that permanent damage in the structure is present after the event. We have designed and modelled the response of SMA dampers and introduced their response into the ANSYS software using the USERMAT routines. With this model we are able to design and simulate the effects of a damping system in this structure. The introduction of appropriate SMA dampers with well defined and prepared alloys permit to reduce the maximum oscillation amplitudes to a half avoiding the damage on the steel structure and, therefore, increasing the lifetime of the entire structure without any periodic maintenance. The introduced SMA dampers absorb the structural damage avoiding the need of costly repairs in the steel beam structure; therefore, this solution may be considered a preventive cure for earthquake actions in buildings.

1 Introduction

When relatively intense earthquakes act on family houses, the structural steel beams and brick walls must dissipate the energy introduced by the event accelerations. During the earthquake the structure must endure big oscillations that may repeatedly overcome the elastic limit of the materials. When this happens the building accumulates structural damage that may eventually induce the collapse of the structure. Thus, even if the structure resists the earthquake it usually requires costly structural checks and repairs or even partial rebuilding.

Recently, Shape Memory Alloys (SMA) [1,2] have been suggested for damping applications in civil structures [3-10]. The singular properties of the SMA such as the shape memory effect, the pseudoelasticity, and the hysteresis cycle are caused by a martensitic thermoelastic phase transformation between two metastable phases. SMA can be used as sensors and/or actuators.
In the current application we take advantage of their hysteresis cycle to convert mechanical energy (oscillations) into heat. Our damper design reinforces the structural design providing recentering functions besides the energy dissipation. In the passive application domain, without external power, the practical SMA can be classified into two groups, the Cu-based and the NiTi alloys. There are always some possible tunable actions (or use of semi-active control methods) for SMA, but the main interest for use on the Civil Engineering time scales focuses on their use as passive devices without continuous technical supervision.

To avoid the damage in the steel frames it is necessary to reduce the oscillation amplitudes induced by the earthquakes below the plastic limit of the steel beams. To accomplish this goal there are several solutions such as increasing the stiffness of the structure, building costly damping systems or isolating the structure from the terrain. All these systems are expensive and because of it they are rarely applied to small buildings as family houses. Our SMA dampers achieve this goal by two means. On one hand the stiffness of the building is increased by the dampers response. On the other, the phase transformation on the wires increases the damping capacity of the structure. The structural damage is absorbed by the SMA dampers that are capable of dissipating the energy without being destroyed by the large strains due to the martensitic transformation. If the earthquake intensity is high enough the dampers may be damaged while absorbing more energy, but they keep the steel frames integrity. Then, replacing the SMA material the structure is again functional. This system is not a self-healing solution for the structure, but a preventive cure for earthquake effects in light Civil Engineering structures.

In this paper, we review the basic working principles for the SMA and outline the design of the dampers. The simulation model used to design and check the dampers with ANSYS is also briefly presented. Then, we analyze the response of family house with a steel structure under the effects of “El Centro” earthquake. The response with purely elastic steel and plastic steel is presented showing that the designed structure without dampers is permanently damaged by the earthquake. Finally, we introduce the SMA dampers and simulated the system response. The results indicate that the steel structure with the SMA dampers is capable of resisting the event without damage. The SMA properties required to ensure the correct damping functionality are discussed at the end of the paper.

2 SMA dampers

In this section we introduce the basic behavior of SMA in order to justify the proposed damper design. Then we introduce the model we have developed to predict the damper response while performing structural simulations of the house structure using ANSYS software.

2.1 Basic SMA behaviour

The origin of the peculiar properties of SMA is a first-order solid-solid phase transformation between two metastable phases with hysteresis cycle. In single crystals, this thermoelastic martensitic transformation produces a shape change (shear type) that induces a length change up to 10% in the main crystallographic direction. In polycrystalline samples the maximum strains are close to 6%. Martensitic transformations may be induced by stress ($\sigma$) and temperature ($T$).
In the phase coexistence between parent and martensite, the macroscopic coupling between the stress and temperature is related by the Clausius-Clapeyron coefficient (CCC) (defined by the slope $\alpha = \Delta\sigma / \Delta T$) \cite{2,11}. Classically, in temperature induced transformations without external stresses, the hysteresis cycle may be described by four temperatures. Starting from austenite (high temperature phase), $M_s$ (martensite start) establishes the initial appearance of martensite, and $M_f$ (martensite finish) the complete conversion to martensite. The backwards process starts with $A_s$ (austenite start) ending the retransformation process with $A_f$ (austenite finish) with the complete recovery of the parent phase.

Figure 1 depicts the hysteresis cycle for different working temperatures. As the temperature increases, the critical stress ($\sigma_{cs}$) necessary to initiate the phase transformation also increases ($\sigma_{cs,T1} < \sigma_{cs,T2} < \sigma_{cs,T3}$) according to thermodynamic formalism (i.e., Clausius-Clapeyron equation \cite{12}). The cycle is not modified by this shift, but it is necessary to consider that the working temperatures near the spontaneous transformation temperature (martensite start or $M_s$) may prevent the return to parent phase in the unloading process due to the hysteresis width ($\Delta\sigma_h$) (see, point a in fig. 1). Temperatures which are too high ($> T_3$) may produce a stress which overcomes the plastic deformation level ($\sigma_{pd}$) for a given strain, producing a permanent deformation in the alloy or, eventually, its fracture. The macroscopic pseudoelasticity or the slope ($\Delta\sigma / \Delta\varepsilon$) in the transformation zone, the hysteresis in coordinates of stress ($\sigma$), strain ($\varepsilon$) and temperature (T), and the Clausius-Clapeyron equation are the more relevant thermomechanic macroscopic properties in damping applications. These properties depend on the material characteristics, the sample preparation, and the evolution of the sample while cycling. The prediction and control of those are basic for the dampers reliability. The annex at the end of this paper summarizes the material requirements to ensure a proper damping functionality.

![Figure 1: Schematic behavior of the hysteresis cycles in $\sigma$, $\varepsilon$, T representation](image)

### 2.2 SMA damper implementation

A SMA damper is simply a wire of alloy with the necessary mechanical set-up to fix it to the structure (i.e., the bracers holding the wires, the anchorage points to the structure and a steel cable to attach the device to those). The alloy, thanks to its hysteresis cycle, is able to convert the mechanical energy into heat reducing the oscillations on the structure. Figure 2 shows a damper prototype composed by 12 CuAlBe wires with diameter 3.4 mm. Each wire is able to undergo tensions of 2.5 kN with a maximum strain above 6%.
Therefore this damper is capable of working with tensions of 30 kN and strains below 4.5% (to maintain a security margin). The design of a damper consists in choosing the number of wires and their length to optimize the structure response. Other set-ups for the dampers may be used (i.e., thicker or thinner wires), but according to our experimental results wires with diameters around 3-5 mm produce the best results as they minimize the number of wires composing the damper without inducing important parasitic effects in the treated samples. Obviously, this mechanical design does not allow the dampers to work in compression. Therefore these dampers always work in pairs on a counteracted geometry.

![Image of SMA damper composed by 12 CuAlBe wires with diameter 3.4 mm](image)

2.3 Model implementation for dynamic structural simulations

Detailed experimental observations indicate that the martensitic phase transformation structure in Cu-based single crystal samples follows a serial pattern of small transformation domains with simple mechanical behavior as depicted in Figure 3 left. A detailed model built following this serial structure is able to accurately predict the long time evolution and dynamic effects of SMA [2,13]. However, the computational load is too large to use it in complex structural simulations which include several dampers. Considering that an earthquake is a fast event compared to the material evolution time constants we have developed a simplified model only considering the mechanical behavior of the material in a reduced time period. The complex model is used to calculate the initial state and the worst and mean case for the material response in a given time and, therefore, the simplified model only needs to predict the stress-strain behavior of the damper.

![Diagram of basic element mechanical model and parallel structure of basic transformation elements](image)

Structural simulation routines usually consider displacement as the input of a system and then they calculate the forces acting in the structure. Due to this requirement a serial architecture for our model is not adequate as it then requires a computationally costly inversion.
To further reduce the computation time required for simulating the SMA behavior in structural analysis we have devised a model based on a parallel array of simple elements as indicated in Figure 3 right. Each element in the structure follows the simple force-elongation function in Figure 3 left. Obviously, each element function has different defining parameters such as hysteresis width and stiffness. Adjusting these parameters for all the elements in the model a good representation of the experimental SMA behavior is obtained. In the present work, the used model is composed of only 9 parallel elements. Figure 4 shows the model predictions and the experimental data for CuAlBe (a) and NiTi (b). Temperature changes are calculated using the CCC. The model accuracy for global, partial, and internal cycles is good and has a reduced computation time.

3 Effects of earthquakes on light steel structures

3.1 A family house

Light buildings, such as single or double-floor family houses, under the effects of an earthquake (i.e. "El Centro" [14]), suffer oscillation amplitudes close to 10 cm and reaction forces under 800 kN. These buildings are usually unprotected against earthquakes due to the cost of current damping systems and their maintenance. To illustrate the damping capabilities of SMA, we have designed a building according to structural Spanish standards. Figure 5 shows the house structural scheme (left) and an external view of the house (right) with a ground area of 11.5 x 16.6 m². It is a two story building with approximately 200 m² on the ground floor and 100 m² on the first floor. The structure has two main sections separated by a ground garden. The front section has a single floor with a second garden on the roof establishing an excellent view from the main living area (first floor). The structure of the building has been designed with steel beams to increase its resistance to earthquakes. The possible emplacement for the dampers in the portico diagonals is indicated in the structural scheme.
Figure 5: Steel beam structure and external view of the analyzed family house

The house steel structure is built by repeating a triple portico structure. We analyze the response of this structure to identify the effects of the event on the structure. The central portico of the elevated garden with the highest load has been selected for study (Figure 6 left). The portico height is 3 m and the arch widths are 2.35 m (lateral) and 6.80 m (central). The pillars are built by HEB200 beams (central) and HEB140 (external). The horizontal girders are HEB240 for the central arch and IPN160 at the sides. In simulation, we use A570 grade 50 steel with Young modulus 206 GPa, density 7850 kg/m$^3$, yield stress of 344 MPa and damping coefficients $\alpha=0.01$ and $\beta=0.001$ according to ANSYS steel model. The total portico load is 46.5 Tm. The pairs of dampers are installed in the diagonals of the lateral arches. Steel cables (with higher stiffness than the dampers) are used to link the dampers with the structure. To further illustrate the dampers capabilities the entire two-storey section is also simulated with and without SMA dampers. The steel structure with the reinforced concrete slabs and the initial damper placement are depicted in Figure 6 right.

Figure 6: Left: Basic triple portico structure used to build the steel frame of the house with the inserted SMA dampers. Right: Two-storey section of the house analyzed in the present work. The SMA dampers can be observed in the diagonals of the structure

3.2 Structure response with elastic steel model

Using a purely elastic model for the steel beams we have simulated the effects of ‘El Centro’ earthquake on both steel structures. We perform a dynamic analysis using ANSYS transient and introducing each point of the earthquake acceleration pattern [18].
The registered accelerations for ‘El Centro’ are depicted in Figure 7 (a) showing maximum acceleration above 3 m/s². The horizontal displacements of both structures with elastic steel response are depicted in Figure 7 (b) and (c). The triple portico oscillations present maximum displacements of nearly 8 cm and repeated displacements higher than 5 cm.

The effects are similar in the double-storey section with nearly 7 cm maximum displacements and repeated oscillation above 5 cm (9 and 6 cm for the relative displacements of first floor).

Performing a static analysis on the beams (fixing one end and bending the beam) we calculate that the beams in the triple portico and in the ground floor overcome their elastic limit for displacements above 5 cm and 6 cm for the beams in the first floor. Due to the extra loads and the rigidity of the joints between the beams the permitted displacement in the structure must be below these values. Considering these maximum displacements we can determine that the structures are largely damaged after the event as the beams repeatedly overcome their elastic regime.

3.3 Structure response with plastic steel model

To evaluate the effects of the steel yielding in the structure we perform the same simulation but considering a plastic model for the steel beams. The results for both structures are depicted in Figure 8. Comparing the simulation with elastic beam and with plastic beams it is clear that the steel structure is largely damaged as the response is completely different. The maximum displacement for the triple portico is around 5.5 cm and at the end of the event the structure presents a permanent deformation indicating extensive structural damage. The two-storey section simulation results also indicate the existence of large deformations in the steel beams as the maximum displacements are reduced. This indicates that the steel deformation is dissipating mechanical energy and therefore that the structure is being damaged.
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Figure 8: Horizontal displacements for the triple portico (left) and for the first and second floor of the two-storey section (right) considering the steel beams yielding at a stress of 344 MPa.

Figure 9 presents the deformed shape magnifying the relative to displacement to appreciate the critical points in the structure that appear at the unions between the beams and in the ground anchorages.

The circles indicate the points where the plastic deformation of the steel is higher. As these points appear in the central beams of the structure the building collapse due to the earthquake is problem that must be solved.

Figure 9: Schematic deformed shape of the portico magnifying the relative displacements to appreciate the sections with highest deformation that are indicated by the circle.

3.4 Structure response with SMA dampers

As shown in the previous sections the house structure is damaged by the action of the earthquake. To avoid the collapse of the building we need to either avoid or repair this damage during the event. The use of self-healing materials or techniques in the steel beams is usually not possible unless the house is rebuilt. Therefore, we have applied a slightly different approach to the problem. Instead of healing the system we apply a preventive cure strategy. This system allows the implantation of the solution in already built structures and ensures that the house resists the earthquakes preserving the integrity of the structure by introducing external elements that absorb the structural damage that can be easily checked after the event and easily replaced if they suffered heavy damage.

To reduce the structure oscillations we add SMA dampers in the diagonals of the small arches as indicated in Figure 6. Using the results from the elastic response of the two structures we can design the dampers by adjusting the number of SMA wires and their length [15]. Once the dampers are optimized the responses of the building structures under the effects of ‘El Centro’ earthquake are simulated. Figure 10 presents the horizontal displacements for the triple portico and the ground and first floor of the building. In this situation the maximum displacement for the triple portico and the ground floor is around 3 cm with repeated oscillations below 2 cm (4 cm and 2 cm respectively for the first floor) ensuring that the steel beams work clearly below their plastic limit and ensuring the health of this structure.
During the seism, the structure oscillations modify length of its diagonals forcing a strain in the SMA wires. The corresponding increase in the wires stress induces the martensitic phase transformation dissipating mechanical energy into heat. To avoid rapid damage in the dampers we design them to work with strains below 5%. Figure 11 left shows the mechanical response of the dampers in the triple portico structure (in stress-strain coordinates) where we can clearly observe that the dampers work below 4%. Figure 11 right plots the energy received by the structure and the energy dissipated by the dampers.

Even working the dampers below the critical strain, structural damage is slowly accumulated in the SMA material while cycling, due to the small fractures appearing during the transformation and the accumulation of frozen martensite. These phenomena increase the length of the wires reducing their effectivity. Hence, each seism reduces the lifetime of the materials composing the dampers.

4 Conclusions

A damping solution for family houses using passive SMA dampers has been presented. The detailed experimental analysis and modeling of the SMA has permitted the design and modeling of the SMA dampers to validate the long term response. A model has been specifically developed to study the dampers responses in complex civil structures. Using this model inserted in the ANSYS finite element software we have analyzed the response of a two-storey family house. The analysis indicates that ‘El Centro’ earthquake damage the house structure. However when the SMA dampers are introduced the oscillations in the house are reduced by a half and the structural damage is avoided.
The SMA dampers absorb the energy and slowly accumulate damage that being necessary to replace them after some events. The SMA damping system (steel structure plus SMA dampers) may be considered a preventive cure for earthquake effects in light Civil Engineering buildings.

4 Annex: required properties of the SMA materials for dampers

Earthquake damping in Civil Engineering structures requires systems able to remain inactive for several years without deterioration and capable of resisting the fast actions produced by an earthquake after the long inactivity. These constraints indicate that the SMA long term behavior must be guaranteed. Earthquake duration is estimated to be below 2 min. Considering a typical principal frequency for the structures close to 1 Hz, we can estimate that the alloys should be able to resist 200 cycles at full deformation.

The dampers work with a reduced increase of their length (usually below 5 cm). This is required to avoid damage in the structure. It is, therefore, necessary to avoid the accumulation of permanent deformation on the SMA as it reduces the effectivity of the dampers by reducing the total energy dissipation and preventing the damping of small oscillation amplitudes.

SMAs obtained as is do not present the required behavior for this application. It is necessary to treat them with a thermo-mechanical process to reduce the progressive accumulation of deformation. This treatment consists in a short betatization of the material at high temperature followed by a long homogenization at low temperature and a mechanical aging. The resulting alloys are able to cycle at 5% with a maximum accumulated deformation below 1%. Obviously, if the material works above this strain level the permanent deformation increase as plastic deformation appears.

The material behavior is related to a phase transformation. As indicated previously the three thermodynamic potentials that determine the alloy response are related by the Clausius-Calpeyron equation. As the dampers convert mechanical energy in thermal energy the temperature of the SMA wires grows during the earthquake due to self-heating. The temperature increase due to self-heating and external conditions should be estimated and considered when designing the dampers as it reduces the maximum stress and strain the material can undergo.

The parasitic effects associated to static and dynamic changes of the atomic order induced by stress and/or temperature in parent, martensite or in coexistence zone should be carefully estimated. In particular, their effects on the eventual change in SMA response after the several years (or decades) previous to the earthquake need to be quantified to guarantee the damper behavior.

All these considerations can be summarized and applied in the design by defining a pseudo-elastic window that determines the region where the material can work safely. Table 1 lists the different effects that must be experimentally evaluated in each material and determines the pseudoelastic window for CuA1Be and NiTi that ensures a correct damping function.
More details about the experimental characterization and considerations for SMA in damping applications can be found in [2,15].

Table 1: Expected changes in CuAlBe ($\sigma_p < 300$ MPa) and in NiTi alloy ($\sigma_p < 700$ MPa). The CCC approaches, respectively, 2.2 and 6.3 MPa/K. The manufacturer establishes that the yield strength of NiTi is close to 700 MPa. (*) indicative values

<table>
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<tr>
<th>Parameters</th>
<th>$\Delta T$ in K (CuAlBe)</th>
<th>$\Delta T$ in K (NiTi)</th>
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