

CONTRIBUTION OF THE JOINT RESEARCH CENTRE TO THE CHARACTERISATION OF SHAPE MEMORY ALLOYS AND FULL SCALE VALIDATION TESTS OF RETROFITTING TECHNIQUES FOR MASONRY SHEAR WALLS TYPICAL OF THE ARCHITECTURAL HERITAGE

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SUMMARY

Shape Memory Alloys are characterised by super-elasticity allowing energy dissipation through a phase change without any material damage. The European Laboratory for Structural Assessment performed theoretical and experimental analyses for the material characterisation and laboratory tests of full-scale masonry walls for the validation of innovative techniques for the protection of the Architectural Heritage based on the use of Shape Memory Alloy devices.

1 INTRODUCTION

The activity refers to the contribution of the Joint Research Centre (JRC) of the European Commission (EC) to the project ISTECH (Innovative Stability Techniques for the European Cultural Heritage) funded by EC/DG-XII through the Environment and Climate Programme. JRC contributed to the project through the European Laboratory for Structural Assessment (ELSA) sited at Ispra (VA), Italy. ELSA is a unique facility in Europe for testing, with a big Reaction Wall and the Pseudo-Dynamic method, full/large scale models of structures under seismic loads.

The project investigated the possibility to use the Shape Memory Alloys (SMAs) for the realisation of mechanical and seismic protection systems for cultural heritage structures based on devices having intrinsically energy dissipation capabilities. SMAs materials are characterised by super-elasticity allowing energy dissipation through a phase change from Austenite to Martensite and vice-versa. This stress-strain cycling does not produce any material damage and is always performed in traction, allowing the use of cables for the realisation of the devices.

The most relevant tasks of JRC were oriented towards two specific line of research. The first led to a large experimental campaign for the mechanical characterisation of a wide range of samples of SMAs materials (mainly based on NiTi). The second consisted in performing seismic tests on full-scale models of masonry walls for the validation of a retrofitting technique based on SMAs devices.

2 CHARACTERISATION OF SHAPE MEMORY ALLOYS

In order to identify the different materials, characterisation tests have been conducted and other static and training tests have been carried out to understand more accurately their behaviour. Finally the same experiments have been repeated at high strain rate corresponding to seismic conditions [1].

2.1 Properties of Shape Memory Alloys

Most of SMA's are binary alloys, most frequently composed by an association of Nickel and Titanium. They change their crystalline arrangement as they are cooled down or heated up, as well as in the presence of a stress field. The crystalline geometry is ordered cubic, but after phase transformation from austenite to martensite the crystal, under stress, bends. The result is a large elastic deformation of the sample with reversibility when returning in the austenite phase. This property of no-degrading the crystal structure when the alloy is under stress is the so-called super-elastic behaviour of the material. In addition, the path followed by the material in the theoretical stress-strain curve shows a flat level of stress in the loading phase, whereas another plateau appears at a lower stress level, during the unloading phase. Since the test results under dynamic loading were less promising than the predictions based on quasi-static loads, a specific set-up was derived to enhance the behaviour of SMA for their use in seismic applications. In the following are presented the main tests carried on samples of SMA's of different diameter and composition provided to JRC by FIP Industriale (Padova, Italy).

2.2 Cyclic tests at increasing strain

The characterisation test gives immediately a qualitative response to decide if the material could have the required properties for seismic application.

The test is composed of a series of increasing strain

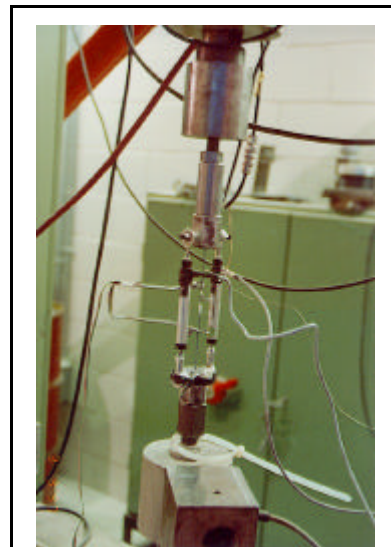


Figure 1: Experimental set-up for the tests

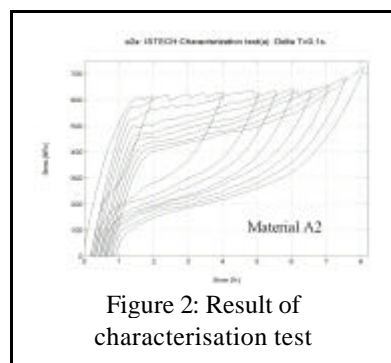


Figure 2: Result of characterisation test

cycles, conducted at a constant strain rate of $2 \cdot 10^{-3} \text{ s}^{-1}$. The strain cycle sequence is 2-4-5 %, then the following increments are constant until 8% of strain, and are of 0.5 % to get more accuracy in the zone where the material ends its super-elastic behaviour. From this type of tests it is possible to define, until which strain it is convenient to use the material. Two criteria have been used to decide which is the maximum super-elastic strain.

The first is at which cycle the residual strain starts to increase (for a constant increment of strain). The second is which cycle corresponds to the end of the stress plateau. Figure 1 shows the experimental set-up for the tests performed on samples of SMAs and in Figure 2 is represented an example of the results of these tests showing a suitable behaviour of the stress-strain of a SMA.

2.3 Strain rate tests at low frequencies

The input applied to the samples is a loading cycle until the maximum super-elastic strain and then unloading at the same strain rate. Two strain rates were chosen and gave origin to two types of test. The low level one for a strain rate of 0001 sec^{-1} and the high level one for a strain rate of 01 sec^{-1} (i.e. 100 time higher). The corresponding frequencies, for the four materials tested, are around 0.8 mHz and 80 mHz. All these tests are applied to new samples (without any prior loading history before). Seven different samples have been tested for both cases of frequency.

From the results of the tests conducted at low strain rate it was possible to deduce the value of the stress plateau, during the loading phase, for virgin materials, affected of an error of about 10% with the sample distribution.

During all the tests the temperature has been measured with a thermocouple in contact with the perimeter of the wire by conductive glue, at the middle of the sample. Due to the motion of the wire, the signal recorded is often noisy and not accurate but welding thermocouple on a sample of SMA presents some difficulties.

As mentioned above the influence of the strain rate was tested on two materials at very low frequency of 0.8 mHz and 80 mHz. Even at these levels of frequency the results showed that the materials are strain rate dependent.

2.4 Stabilisation tests

Stabilisation tests, consisting of twenty cycles, showed the degradation of the material until a nearly stable state. The tests were conducted on at least two samples for each material. A typical result of this kind of test is shown in Figure 3.

2.5 Dynamic tests

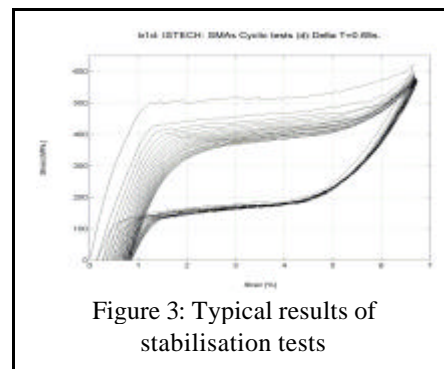
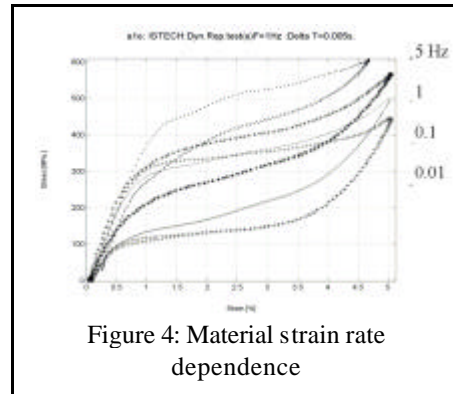


Figure 3: Typical results of stabilisation tests

A large series of tests have been conducted to study the frequency dependence of the material behaviour for frequencies higher than 1 Hz. The main effects observed have been the inclination of both plateau, and a hardening of the material with the frequency as shown in Figure 4. In each case it has been observed a loss of energy dissipation capability. These results showed unfavourable frequency dependence for the purpose of applying SMAs devices for the protection of architectural heritage in seismic areas. Hence an improvement has been studied and validated through laboratory tests. From the different tests carried out on several samples, the shape of the hysteretic cycle during dynamic tests has been improved becoming much more similar to the low frequency curves and the energy dissipation has been considerably increased.



3 EXPERIMENTAL TESTS ON FULL SCALE MASONRY WALLS

The Aim of the task was the validation (based on testing and monitoring of large model of masonry walls) of the effectiveness of the system for the protection of monuments and historical buildings against the effects of earthquakes and other loads leading to instability.

The activity has been focused on the behaviour of masonry shear walls under the effects of in-plane seismic loads [2]. The tests have been performed on three masonry shear walls; the first for assessing the numerical models and the two others to compare the behaviour of the unprotected wall with the protected one.

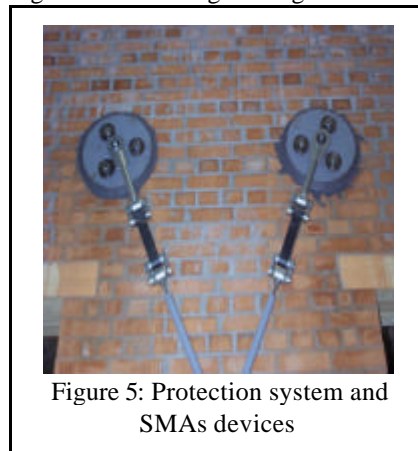
The protection system based on SMAs devices has specific characteristics. In particular the pre-stressing capability and the energy dissipation of SMAs give the following improvements:

The pre-stressing allows reaching a higher value of seismic intensity for which the integrity of the wall is guaranteed.

The constancy of the pre-stressing forces due to super-elastic behaviour of the devices (relevant only for large displacements that occur when damage appears) contributes to the stability of the structure.

The energy dissipation, due to hysteretic behaviour of SMAs devices, reduces the amount of earthquake's energy absorbed by the wall and, hence, the propagation of cracks.

The models tested at ELSA consist of three walls, one of which incorporating the cross-bracing system including the SMAs devices. The walls are made as a classical three brick construction; the model after construction is shown in Figure 6.



3.1 The protection system

Multiple SMA wires are grouped in singles devices in order to have the adequate total section for the development of effective reaction forces. FIP Industriale provided JRC with the devices and has developed the best mechanical solution (Figure 5).

Finite-elements analyses has been conducted to determine correct values of lengths and section areas of the super-elastic wires to avoid deformations exceeding the maximum value of the super-elastic strain. The University of Rome, in close collaboration with JRC, participated to this numerical study. JRC has provided to FIP the basic parameters for the design of the devices.

The cross bracing system has been yet positioned symmetrically on the external surfaces of the Model. This solution allows an easier anchoring of the elements, even after the completion of the model, and the possibility to inspect the devices during the tests. From the architectural point of view, a more attractive solution could be the insertion of the elements into the wall. For the purpose of the tests it is more relevant to have a full control of the devices and the possibility of maintenance and intervention.

The crossbracing system must be strongly fixed to the wall in order to transmit adequately the counterbalancing forces when an earthquake occurs. Problems are in the fragility of the masonry that does not allow a simple fixing of the SMA devices.

F.I.P. has developed special steel anchoring plates, shown in Figure 5, which are connected two by two one per each side of the wall.

This solution provides a good distribution of the crossbracing system on the wall avoiding in this way dangerous stress concentration. The steel bars of the crossbracing system are fixed to a steel beam anchored to the reinforced concrete basement. Load cells and strain gages provide the necessary information on the behaviour of the devices during the tests.

3.2 Tests performed and main results

Preliminary cyclic test has been done for displacements until 12 mm that strongly damaged the model. The damage consisted mainly in opening of cracks in the three lower panels starting from the central one. Those results are fully consistent with the expected ones; in fact a



Figure 6: Full scale Model and SMAs based protection system

horizontal tendon were put up to the openings and calibrated in such a way to avoid cracks generation at the top of the model.

A second bare wall, including the horizontal tendon, was tested for a reference earthquake and for different amplitudes assessed from numerical analyses. The first signal used in the PsD testing had amplitude of 70% on the reference value; the results showed a linear behaviour of the wall and no damage was visible. The second test was run with amplitude of 200% of the reference and showed some crack distribution mainly in the central panel. This test has been repeated once again and some more degradation has been observed also in the two lateral panels. Finally one more test has been performed for 300% of the reference value and the experience was stopped at half of the transient due to big cracks appeared in the three feet of the wall and a strong degradation of the restoring force.

A third wall has been equipped with the cross bracing including the SMAs devices; it is shown in Figure 6. The tests on this wall have been repeated with the same sequence that for the bare one. Until 300% of the reference signal some dissipation of energy has been measured but no crack opening has been seen at a visual inspection. It has been decided to go to 400% of the reference signal and some crack appeared in the central panel of the model but not on the lateral one. Finally a final earthquake was simulated for 500% of the reference value.

Big cracks appeared both on the central and lateral foot. For safety reasons it has been decided to stop the test at half of the transient also if the force-displacement curves showed a good shape and the SMAs devices were working correctly. The results showed in Figure 7 clarified that the SMAs devices contributed to the energy dissipation for about 30% of the total showing a good effectiveness in the improvement of earthquake resistance of the structure.

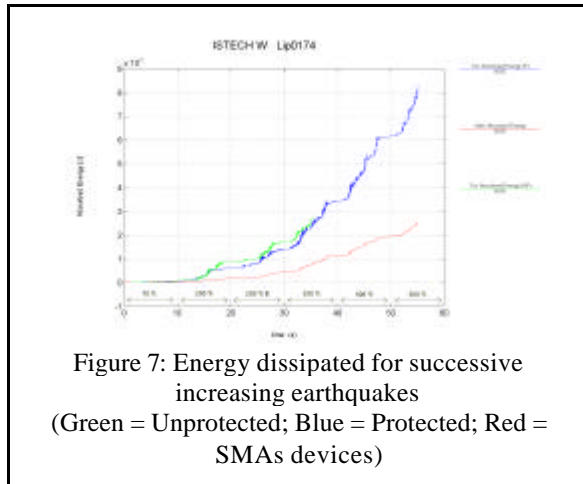


Figure 7: Energy dissipated for successive increasing earthquakes (Green = Unprotected; Blue = Protected; Red = SMAs devices)

4 REFERENCES

- [1] Tirelli, D.; Renda, V.; Bono, F. - *Characterisation and fit to seismic protection of shape memory alloys*. Proceedings of the 4th European Conference on structural dynamics, EURO DYN '99, Prague, Czech Republic, 7-9 June 1999
- [2] Bono, F.; Tirelli, D.; Verzeletti, G.; Molina, J.; Renda, V. - *Shape Memory Alloy crossbracing of brick masonry walls: Cyclic tests of a large-scale model and numerical analyses*. Proceedings of MONUMENT-98 workshop on seismic performance of monuments, Lisbon, Portugal, November 12-14, 1998