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Large-Scale Tests at the European Laboratory of Structural Assessments of Innovation Devices and Techniques for Seismic Protection of Structures

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ABSTRACT

The European Laboratory for Structural Assessment of the European Commission is engaged in testing large-scale models of structures protected by new anti-seismic techniques and devices. During the last years the activity focused essentially on anti-seismic techniques including base isolation and passive energy dissipation devices. The most recent work was done on one concrete frame protected with rubber damping devices and one masonry wall protected with cross-bracing including dissipation devices made with Shape Memory Alloys.

1 INTRODUCTION

The European Commission is strongly engaged in research and development actions oriented to support the protection of the populations of the Union against the effects of strong earthquakes. To this end, the Institute for Systems, Informatics and Safety is in charge, through the Safety in Structural Mechanics Unit, of the European Laboratory for Structural Assessment (ELSA), which is a unique facility in Europe for the execution of pseudo-dynamic seismic tests on large-scale models of structures. ELSA contributes, through its theoretical and experimental work, to the validation of the European norms and standards (Eurocodes) for construction in seismic zones and the development of innovative technologies and techniques for the mitigation of the seismic effects on both civil and cultural heritage structures. The contribution of ELSA is given both through its own institutional work and performing competitive actions in collaboration with international networks and making validation assessments and tests for specific relevant projects for third parties. Tests at ELSA are performed on large-scale models of civil buildings and bridges, and also of parts of monuments; these lasts are built in the laboratory with materials and criteria similar, as far as possible, to the ancient constructions.

2 PROTECTION OF CIVIL STRUCTURES

The seismic risk reduction in Europe through the protection of civil engineering structures is one of the major items of JRC and the reason leading to the construction of ELSA. Earthquake protection of important buildings, bridges, potentially hazardous industrial plants and vital equipment is of key importance both on safety and economical grounds.

A project, named "REEDS", was funded by the EC through the Brite-EuRam programme. It has been set up to focus the efforts of manufacturers, developers and end-users of anti-seismic devices towards identifying methods to augment the options currently available and therefore greatly increase the possibility that economic seismic protection can be provided to any particular structure, plant or equipment.

2.1 Description of the Mock-up

A two-storey mock-up of the reinforced concrete office building was designed for pseudo-dynamic (PsD) testing to be performed at JRC. To make the mock-up compatible with the experimental equipment and with the available space in the laboratory, it was necessary to agree about its dimensions and about the characteristics of the attachment of the electro-hydraulic actuators. The mock-up (10m long, 4m wide and 5.2m high) represents a portion of the building scaled by 2/3 in dimension and consists of two bays of 5m in the direction of testing and of one bay across its width (see Figure 1). Eight energy dissipation devices were placed in each bay along the longitudinal facades and were supported by steel K-bracings (see Figure 2). The RC frame was constructed at the ELSA laboratory following the design specifications provided by BOUYGUES.

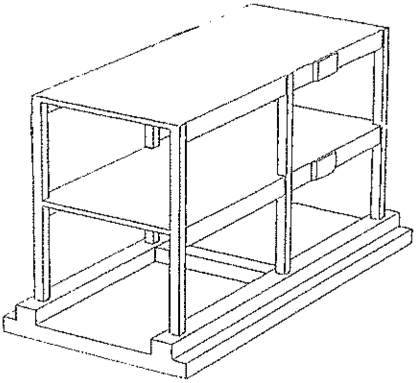

Figure 1: Isometric view of the mock-up

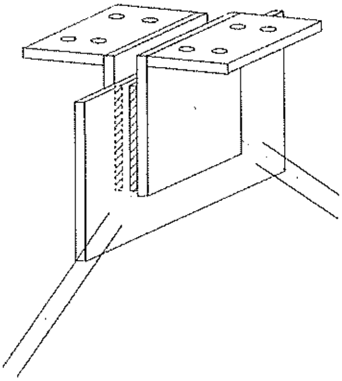

Figure 2: Details of the attachment of the VE devices to the mock-up structure

The civil building has been moved into the laboratory and fixed to the strong floor. The steel wedges for the application of the force from the actuators were mounted against the floor slabs by means of post-tensioning rods. The bracing was installed in the bare frame and a specific interface has been designed and mounted to connect the TARRC visco-elastic device. The connections of the steel bracing with the reinforced concrete frame have been made by means of anchor bolts to simulate a real retrofitting situation. The masses to be placed on the floor slabs have been installed. JRC in co-operation with Bouygues carried out material characterization of the concrete and reinforced steel used in the construction of the mock-up.

A particular attention has been devoted to the instrumentation of the mock-up, to measure the relative rotation between beam and column at the joints, and to measure the deformation of the antiseismic devices. The JRC has designed and instrumented the steel bracing in order to measure the shear force developed by the TARRC devices. This measurement was necessary to compensate the strain rate effect induced by the PsD method.

2.2 *Characterization and seismic tests*

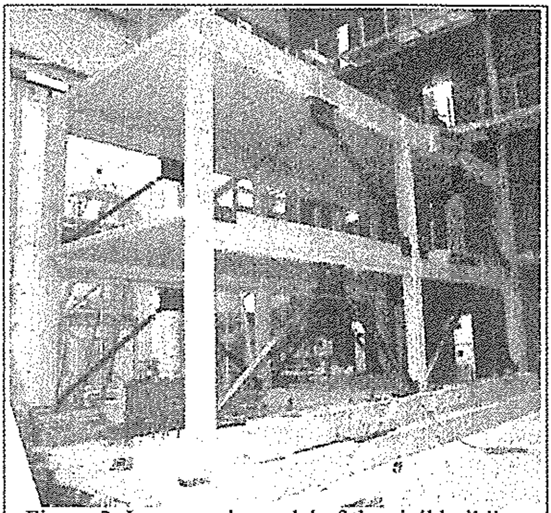

Figure 3: Large-scale model of the civil building with anti-seismic protection for earthquake simulation tests at ELSA

The identification of seismically vulnerable structures and equipment leaded to the adoption of a reinforced concrete frame civil structure. The choices practiced until now to meet seismic criteria for this type of structure are mainly based on strengthening of the design. The introduction of Viscoelastic Energy-Dissipative (VED) devices brings a "soft" alternative to the well known strengthening method or more recent seismic isolation technology. Seismic regulations are relatively recent and consequently many buildings have no or very little protection. The fact that the life of most buildings is around 100 years has lead to the realization that seismic retrofitting is potentially a big market, and VED devices may well be the most economic solution in many cases.

The tests performed at the ELSA laboratory have been lasted to verify and quantify the effectiveness of such a system. To this end a large-scale two-floor and two-bay building was built outdoor of the laboratory and brought indoors in front of the reaction wall to be tested with the Pseudo-Dynamic (PsD) method (Figure 3).

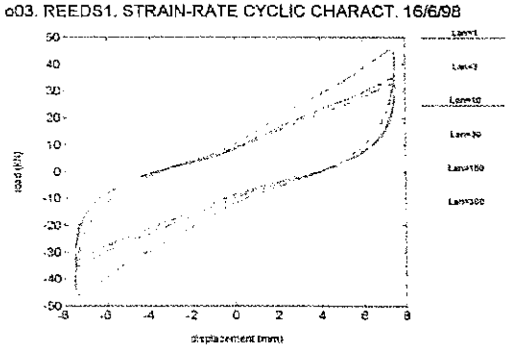

Figure 4: Results of the characterization tests on the devices

The model of building has been equipped with damping devices made with natural rubber and the tests were performed with and without the damping devices for the same earthquake signal used as input. Being the rubber behavior of the devices sensitive to strain-rate, the execution of the PsD tests needs a specific characterization of the devices in order to take into account the strain rate effects as a numerical correction to be applied to the forces measured on the devices themselves [1]. This procedure is made possible tanks to the flexibility of the PsD intrinsic characteristics. It is in fact a hybrid numerical-experimental method coupling the equation of the motion (used to evaluate the displacements induced by the earthquake) with the restoring forces of the structure measured on line on the model during the ongoing of the testing. This procedure bypass the problem of the theoretical assessment of the restoring forces and allows the precise calibration of the PsD method also for materials moderately sensitive to strain rate by introducing correction factors to account the real expected forces produced by the strain-rate dependent devices.

The results of the characterization tests for various strain-rates are shown in Figure 4, while in Figure 5 is shown the effectiveness of the correction by comparing a high velocity test with a PsD tests including the correction factor.

The tests performed at JRC-Ispra showed a relevant reduction of displacements (see Figure 6) and highlighted the effectiveness of the devices for earthquake engineering applications.

The VED devices need to experience a minimum amount of displacement during an earthquake to operate efficiently. Therefore their total stiffness per floor must be of the order of the floor stiffness of the building. Consequently, the use of these devices could be difficult for very stiff concrete structures, especially those containing shear walls. Nevertheless, with frame structures, which are quite common in seismic areas of Europe, the technical study has proved that reinforced concrete frame buildings designed initially for non-seismic areas may be up-graded, by incorporating viscoelastic dampers to respond elastically to earthquakes specified in European Seismic Code - EuroCode 8.

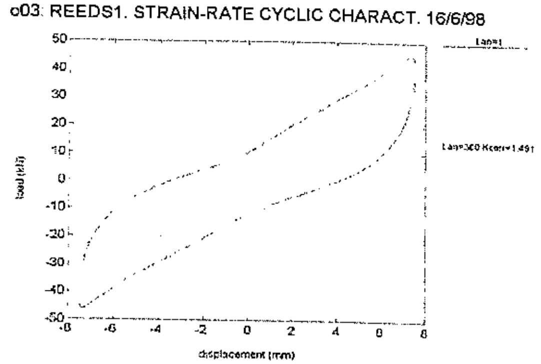

Figure 5: Comparison of a high strain-rate test with a corrected PsD test on the dissipative device.

The devices can indeed provide an alternative protection strategy for such buildings. The dampers raise the stiffness between floors, the increase itself contributing to the reduction in the response. However, the inherent damping of the devices reduces the response much further. The PsD tests carried out at ELSA on the large-scale civil building have shown that when the structure is installed with the devices it responds elastically to earthquakes twice the magnitude of that for the bare structure.

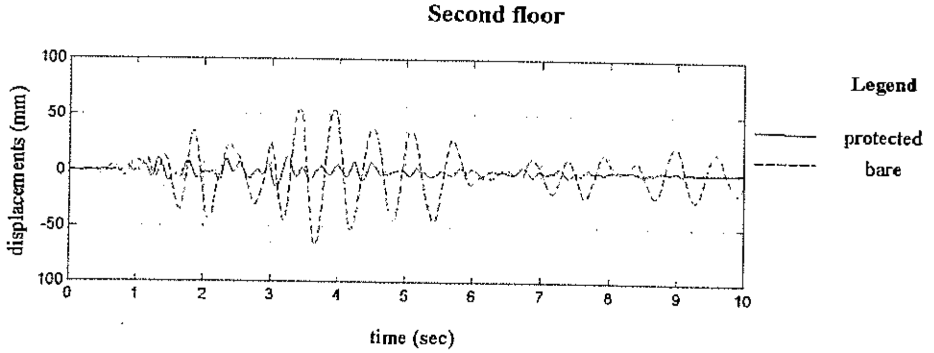

Figure 6: Comparison of the displacement at the second floor for the same earthquake

3 PRESERVATION OF CULTURAL HERITAGE STRUCTURES

The main objective is to contribute to the definition of intervention methodologies and design guidelines for the structural diagnostics and retrofitting/repair techniques for structures of the Cultural Heritage. To reach the objective, an effort is done to extend the recent advances in optical technologies and earthquake engineering to the structures of the Cultural Heritage. This attempt to make compliance between the engineering and the architectural approach for the retrofitting/repair techniques is a first step to set-up a unified theory for the restoration of Cultural Heritage structures. The purpose of the activity is the development of innovative techniques for the improvement of the overall stability, in particular seismic protection, applicable to the rehabilitation of cultural heritage. The research and validation tests for strengthening and retrofitting the structures of cultural heritage is performed at ELSA both through numerical and experimental vulnerability assessments and PsD testing of large-scale models representatives of masonry buildings and cultural heritage structures [2].

ELSA is actually engaged in activities performed in the field of innovative retrofitting techniques. The work is carried out in close collaboration with partners from different countries of the European Union and is funded by the General Directorate XII through the Environment and Climate Programme. The project, named ISTECH (Innovative Stability Techniques for the European Cultural Heritage), investigates the possibility to use the Shape Memory Alloys (SMAs) for the realisation of intrinsically energy dissipation devices to be applied for the retrofitting of cultural heritage structures.

The protection system based on SMAs device couples strengthening due to compression on the masonry wall with energy dissipation that can occur for strong earthquakes. The strengthening with constant force will be use for the seismic upgrading of the structure, while the energy dissipation will provide stability improvement to avoid the loss of the structure. A demonstrative application is foreseen to retrofit the bell tower of Trignano (RE) in Italy damaged by a recent earthquake. JRC is involved mainly in the characterisation tests of SMAs samples for engineering applications foresees in the project and in testing of large scale models of masonry walls comparing cases without and with the application of the protection system.

The design and the preparation of the experiments are supported with numerical analyses. The analyses are of relevant interest also for the interpretation of the results of the tests and for the validation of the numerical models. This is of basic importance for the vulnerability assessment of historical buildings and monuments, the classification in terms of seismic risk and the preliminary design of interventions for the retrofitting and upgrading of the structures.

3.1 *Characterization of Shape Memory Alloys*

SMAs materials are characterized by super-elasticity allowing energy dissipation through a phase change from Austenite to Martensite and vice-versa (Figure 7). This stress-strain cycling doesn't produce any material damage and is performed always in traction allowing the use of cables for the realization of the devices. The stress-strain cycle produces dissipation as it is shown in Figure 8.

ELSA contributed to the project through some relevant theoretical and experimental tasks mainly oriented to material characterization for this specific engineering purpose and full-scale tests of masonry walls. The experimental campaign has been done on models both unprotected and protected with the innovative system in order to quantify the benefit due to the techniques.

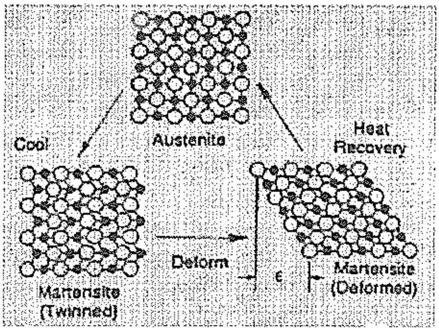

Figure 7: SMAs change of phase

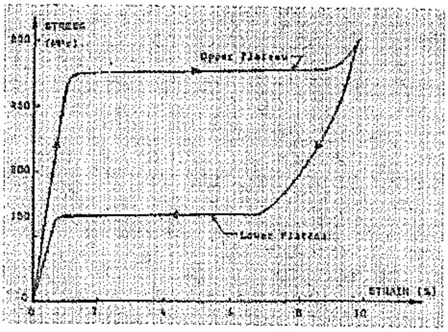

Figure 8: Super-elastic dissipation cycle

As regards the characterization tests, they have been performed for various types of SMAs and on samples consisting in cables of various diameters ranging from 1.0 to 3.5 millimeters. The machine for the realization of the tests is shown in Figure 9.

Both static (low strain rate) and dynamic tests have been performed. The range of frequency investigated was from 1-Hz to 5-Hz. Some typical result of characterization tests is shown in Figure 10.

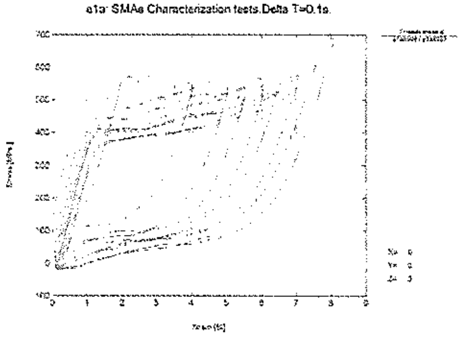

Figure 10: Result of the characterization test for a sample of NiTi SMA (Φ=1.03 mm)

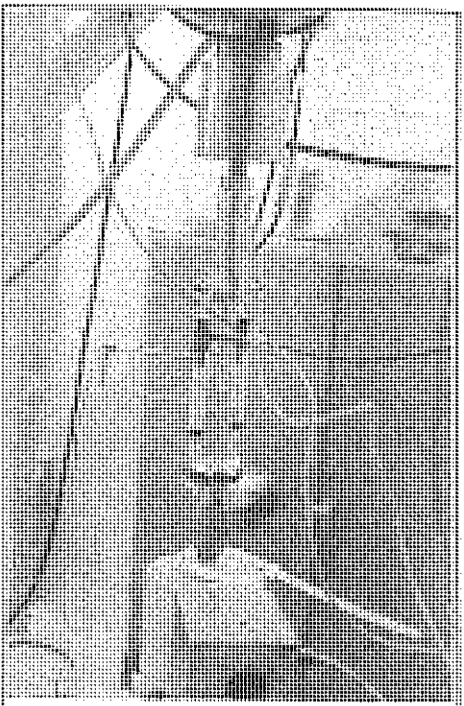

Figure 9: Test machine for the characterization of SMAs cables.

3.2 Tests on large-scale models

The model tested with the PsD method consists of three walls, one of which incorporating the cross-bracing system including the SMAs devices. The design of the model is shown in Figure 11. The tests matrix included the realization of a preliminary cyclic test in order to calibrate as best as possible a numerical model, based on finite elements, for the investigation of the dynamic behavior of the wall in both cases of bare and protected [3].

This 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 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 behavior 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 (see Figure 12). 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

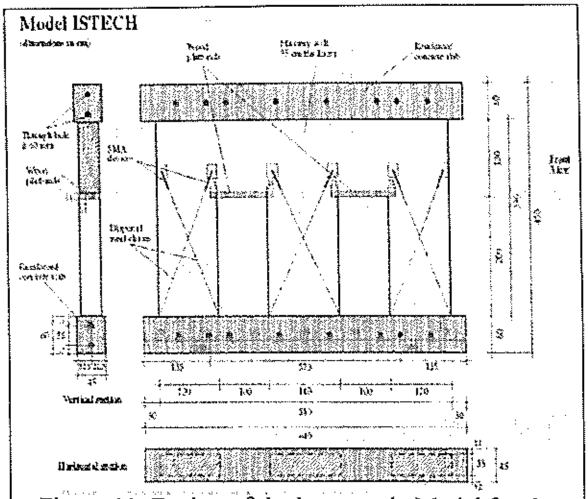

Figure 11: Design of the large-scale Model for the PsD tests

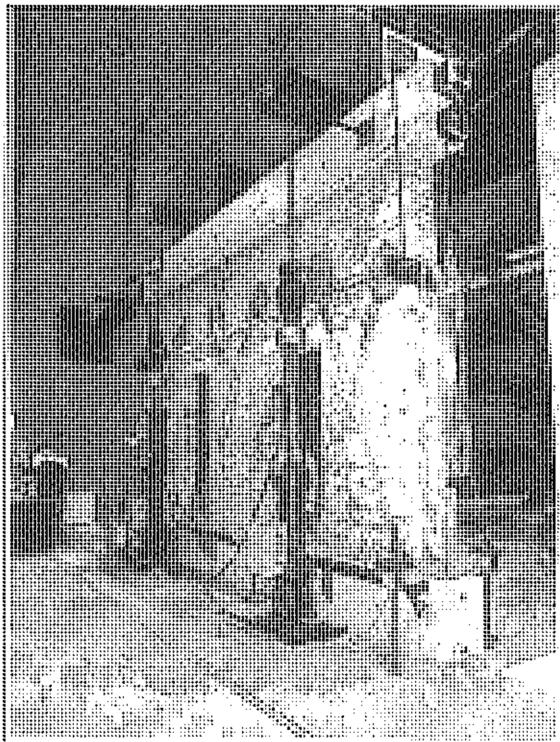

Figure 12: Masonry wall and SMAs devices tested at the ELSA laboratory

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. These last showed to contribute to the energy dissipation for about 30% of the total (see Figure 13) showing a good effectiveness in the improvement of earthquake resistance of the structure.

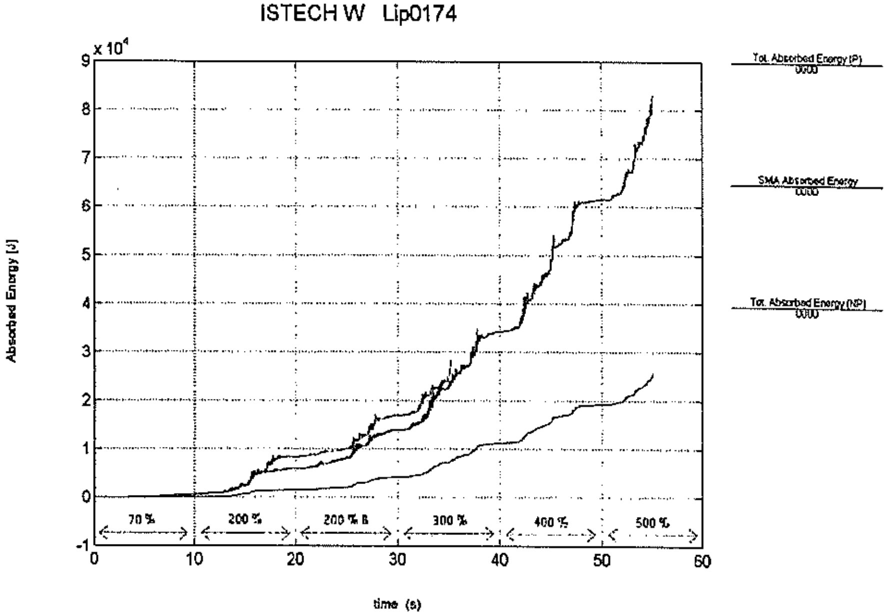

Figure 13: Energy dissipated for successive increasing earthquakes (Green = Unprotected; Blue = Protected; Red = SMAs devices)

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