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SYSTEMIC IMPROVEMENT OF OVERALL SEISMIC RESPONSE

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ABSTRACT

Subassemblies and building models at reduced scale are tested on shaking table facilities. This experimental program is part of the project NIKER and constitutes the Work Package 7 (WP7): "Systemic improvement of overall seismic response". The purpose of this WP is to define global intervention strategies through shaking table tests on both substructures and entire structures before and after intervention in order to check the performance of single elements and to characterize the seismic behaviour of whole buildings. The obtained results will also allow data for FE and analytical modelling to be obtained for both single elements and whole structures. The design and the testing protocol of both subassemblies and building models were based on the results obtained from the experimental campaigns carried out on individual vertical members (quasi-static tests), on horizontal elements (e.g. floors and roofs) and on connections between bearing elements, all these performed within the same project. The experiments summarized in this paper proved the efficiency of the investigated intervention techniques and provided fundamental data to calibrate analytical models, developed within the same project, in order to describe the seismic behaviour of historic structures both in unstrengthened and strengthened conditions. This paper provides a brief overview of the whole dynamic experimental campaign and introduces some key experimental results.

Keywords: *Historic structures, Shaking table tests, Subassemblies, Scaled models*

1. INTRODUCTION

The seismic behaviour of masonry structures has been investigated in the past through (in- or out-of-plane) testing on individual masonry walls [e.g. 1-5], on planar subassemblies [6, 7], as well as on scaled models of entire buildings [8-15]. The available experimental results from the state-of-art provide valuable information on several aspects of the seismic behaviour of masonry structures, such as on the shear capacity and deformability of masonry walls, on the behaviour of panels subjected to out-of-plane bending, on the performance of colonnades supporting masonry arches, on the failure mode of subassemblies made of one longitudinal wall connected to two transverse ones, etc., as well as on the efficiency of various intervention techniques. Nevertheless, the available experimental data do not always cover the behaviour of the tested specimens before and after an intervention or the interventions applied to the specimens do not necessarily comply with the requirements set for the preservation of cultural heritage assets. Furthermore, data available from the state-of-art could not serve the needs of the project NIKER, since they refer to a variety of materials and to masonry typologies that are not necessarily typical for historic structures. Based on these reasons, the decision was taken to design and to carry out within NIKER a testing program consistent with the experimental work carried out within the previous WPs of the project. It should be mentioned that previous WPs comprise testing (before and after repair/strengthening using various techniques) on vertical elements (WP4), on floors, roofs and vaults (WP5), as well as on connections between structural members

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(WP6). Thus, the testing program carried out within WP7 constitutes the final step of the entire experimental work.
The program is divided into two parts: (a) tests on substructures and (b) tests on building models at reduced scale. The assessment of the seismic response of structures through experiments on subassemblies offers the advantage to test specimens at real scale. Scaling down real structures to investigate the seismic behaviour of whole buildings poses several problems of similitude that cannot be simultaneously solved [10]. For this reason it is desirable to pass from real scale individual elements (tested within previous WPs) to reduced scale entire building, through an intermediate step of practically real scale subassemblies. Testing subassemblies is very useful for several reasons since (a) it allows for the interaction between structural elements to be reproduced, (b) it makes possible to quantify relative levels of vulnerability and identify collapse mechanism in relation to various constraint conditions and different conditions of connections between structural elements. Therefore, this task allows combining the information obtained in previous experimental tasks and thoroughly investigating the ways the interactions occur, whereas (at the same time) the obtained results can be interpreted more easily than those obtained on entire structures.
On the other hand, testing building models allows to get immediate and reliable information on the interaction of several factors (conditions of vertical elements, quality of connections, stiffness of floors, building geometry) affecting the seismic response of buildings. Due to smaller geometrical dimensions of the models, buildings typical of urban nuclei can be more easily scaled to models for shaking table testing purposes, and yield meaningful results. Therefore, shaking table tests on model buildings aim to cover also this category of constructions.
Subassemblies as well as scaled models of entire buildings are in general tested initially in their as-built state until they suffer significant but repairable damages. Subsequently, they are repaired and re-tested up to failure or to an advanced state of damage. In some cases both subassemblies and building models are strengthened before testing with the aim to evaluate the effects of the considered intervention techniques if applied to an undamaged structure, that represents the best achievable result.

2. WP 7 RESEARCH PROGRAM

Ten partners were involved in this Work Package, namely: National Technical University of Athens (NTUA, Greece), University of Padova (UNIPD, Italy), Institute of Theoretical and Applied Mechanics (ITAM, Czech Republic), University of Bath (UBATH, United Kingdom), Gazi University (GUNI, Turkey), Politecnico di Milano (POLIMI, Italy), Ecole Nationale d'Architecture (ENA, Morocco), Bozza Legnami srl (BOZZA, Italy), Interprojekt d.o.o. (IPM, Bosnia-Herzegovina) and Federal Institute for Material Research and Testing (BAM, Germany).
The contribution of each participating partner is schematically shown in Tables 1 and 2. It should be noted that some of the participating partners do not appear in the Tables, since they did not contribute to the experimental work. They did contribute, however, in the analytical work that follows the experimental campaign.

3. TESTING OF SUBSTRUCTURES

The experimental work performed on substructures (Table 1) covers the cases listed in the following, for which the available literature is scarce. (1) Testing on shaking table walls under out-of-plane excitations. It is well known that historic structures are very vulnerable to out-of-plane actions. This is because of the defective connection between horizontal and vertical elements, of the flexible diaphragms at the level of floors and roofs, as well as due to the effect of curved elements (e.g. arches, domes and vaults) supported by the vertical elements (walls and piers). Two commonly used types of masonry are considered: three-leaf stone masonry and adobe. The experimental results are used for the interpretation of the overall behaviour obtained from testing three-leaf stone masonry buildings and adobe buildings (Table 2). They also provide data for the modelling of structures, for the analytical interpretation of the experimental results, as well as for the design of interventions applied to the specimens. (2) Testing on uniaxial shaking table of adobe brick walls and columns, with either plain or reinforced with polyethylene nets mortar joints. This is an easy to apply and low cost intervention that does not increase significantly the mass of the bearing elements. Out-of-plane loading was imposed. (3) Testing on shaking table of a brick cross vault, supported by two three-leaf stone masonry walls.

Table 1 Experimental work on substructures

	Type of Specimen	Specimen	Materials – Description of the structure	Partner	Testing	
					Type of tests	Strengthening
1	Element		Three-leaf stone masonry	UNIPD	Shaking table tests. Out-of-plane input motion	(a) As built (b) Transverse steel ties (c) Grouting (d) Combined (b) and (c)
2	Element		Adobe	ITAM	Shaking table tests-uniaxial	Plain/reinforced wallsPlain/reinforced columns
3	Subassembly		Three-leaf stone masonry piers + brick arches and cross vault	NTUA	Shaking table tests. Motion along two axes	(a) [As built] (b) Grouting, timber struts, steel ties, external vertical prestressing
4	Subassembly		Three-leaf stone masonry piers + timber floor	NTUA	Shaking table tests. Motion along two axes	(a) As built (b) Grouting, enhance-ment of diaphragm action of floor

This type of structure is very vulnerable even under normal actions, especially in its weak direction (i.e. perpendicular to the walls). Actually, the vertical loads are applied eccentrically to the walls, due to the smaller thickness of the vault, and out-of-plane bending moments are imposed to the walls, due to the horizontal component of the thrust line, whereas the low level of vertical loads yield to a limited out-of-plane bending moment capacity of the wall. The situation may become critical, when seismic actions are acting. The as-built behaviour is studied, whereas the efficiency of various intervention techniques (such as grouting, external vertical prestressing, timber struts/steel ties) is investigated. The analytical work that is being carried out is supported by the data obtained experimentally under (1) (4). Two parallel three-leaf stone masonry walls (one of rectangular cross-section, the other with T-shaped cross-section), connected by a timber floor: This test provides information on the effect of in-plan irregularities on the behaviour of masonry structures; it also examines the efficiency of intervention techniques (grouting of walls and enhancement of the diaphragm action of the floor) in alleviating the detrimental torsional effects. It also provides data regarding the out-of-plane behaviour of masonry walls (compare with tests described in (1)), as well as on the connection between longitudinal and transverse walls (compare with work carried out in WP6).

4. TESTING OF SCALED MODELS OF ENTIRE BUILDINGS

This part of the experimental work (see Table 2) examines the seismic response of entire buildings both at their as-built state and after interventions. It is obvious that, due to space limitations, details about the design of the models and the design of the testing procedure cannot be given in this paper. It should be noted however, that due consideration of similitude laws was taken, whereas preliminary analyses carried out before testing, provided information about the expected behaviour, thus assisting also the selection of adequate instrumentation.

This part comprises: (1) One two-storey building (scale 1:2) made of three-leaf stone masonry and having flexible in their-plane timber floors. After damage, the model was strengthened (grouting of all walls and enhancement of the diaphragm action of the floors through the addition of a second planking+connection of the floors to the walls) and retested to advanced damage, (2) One two-storey building, identical to the previous one with one exception: Timber laces (consisting of two parallel timber elements running along the perimeter of the walls, transversely connected using timber elements every 0,5 m approx.) are arranged at various locations along the height of the building. This system is typical for historic structures in most of the earthquake prone areas around the globe and it is the first time that it is experimentally investigated on a building model. This model too is tested before and after interventions (identical to those applied to the first model), (3) One two-storey building (scale 2:3) made of three-leaf stone masonry having stiff in their plane diaphragms, thus limiting the vulnerability of walls to out-of-plane bending. The model is tested as-built and re-tested after damage and strengthening through grouting. (4) An identical model is tested after grouting, before the occurrence of any damage, thus providing data about the efficiency of grouting in a non damaged buildings as opposed to its application to a damaged one, (5 to 7) Three models of scaled adobe buildings (scale 1:5) differing in the stiffness and the weight of the roof. This part aims to provide data about the seismic behaviour of adobe buildings (including consideration of the earth block-mortar bond properties) that are quite vulnerable to seismic actions, both because of their poor mechanical properties and because of the heavy roofs provided to them in many cases (for insulation purposes, under adverse climatic conditions). Samples prepared by BAM were tested at the laboratory of ITAM.

5. SOME EXPERIMENTAL RESULTS

It is obvious that even a brief presentation of the experimental setups, of the instrumentation, as well as of the obtained experimental results is beyond the scope of this paper. Thus, only few representative experimental results are presented in the following sections. It should also be noted that, to complete the presentation of the work carried out within WP7 of the NIKER project, one should also refer to the analytical work (interpretation of the observed behaviour and parameter analyses) that is being carried out. That analytical part, as well as the detailed experimental results and their assessment will be the subject of further publications by the partners of the project.

Table 2 Experimental work on scaled models of entire buildings

	Type of specimen	Specimen	Materials – Description of the structure	Partner	Testing	
					Type of tests	Strengthening
1	Model building		Three-leaf stone masonry + timber floors	NTUA	Shaking table tests. Motion along two axes	(a) As built (b) Grouting of masonry and enhancement of diaphragm action of floors
2	Model building		Three-leaf stone masonry + timber floors + timber laces	NTUA	Shaking table tests. Motion along two axes	(a) As built (b) Grouting (c) Enhancement of diaphragm action
3	Model building		Three-leaf stone masonry + timber floors (double planking and steel ties)	UNIPD	Shaking table tests. Motion along two axes	(a) As-built (b) Grouting
4	Model building		Three-leaf stone masonry + timber floors (double planking and steel ties)	UNIPD	Shaking table tests. Motion along two axes	Grouting
5	Model building		Adobe + light timber floor	BAM	Unidirectional sliding table tests	As-built
6	Model building		Adobe + heavy timber floor	BAM	Unidirectional sliding table tests	As-built
7	Model building		Adobe + light roof with stiff diaphragm	BAM, ITAM	Unidirectional sliding table tests	As-built

5.1. Tests on substructures

5.1.1. Tests on multi-leaf stone masonry panels strengthened through grout injection and steel ties

The experimental campaign performed by UNIPD aimed at deepening the study about the influence of two different strengthening techniques widely adopted when intervening on historical structures: injection of hydraulic lime based grout and insertion of transversal steel ties. The specimens are 8 multi-leaf stone masonry panels: 2 in unstrengthened conditions (1-2), 2 strengthened through steel ties (3-4), 2 strengthened through injection (5-6) and 2 strengthened combining both techniques (7-8). The specimens were tested with a dynamic excitation on the out-of-plane direction, this being the most vulnerable condition. The signal of the Montenegro earthquake (15/4/1979, Ms 7,0; PGA = 0,22 g) was selected as seismic input for the tests. The experiments were carried out with an increasing of PGA equal to 0,05 g at each succeeding step up to the failure of specimens (Fig. 1).
The panels tested in unreinforced conditions manifested a failure mechanism similar to that observed on real cases, namely separation of layers due to the out-of-plane action. The insertion of transversal steel ties allowed the area involved by failure to be limited and resulted in an increased ultimate PGA, even if the mechanism was similar to the previous one. Differently, tests on injected panels showed both any separation between external layers and a higher ultimate seismic load. Finally the use of a combined intervention clearly manifested the best behaviour being avoided both the collapse up to 0,67 g and the separation between the external layers. The PGA levels suffered by each panel are summarized in Fig. 1e.
The use of each technique has also a different influence on the dynamic characteristics of specimens, namely on frequency, mode shape and damping trends. Furthermore, also the way and the quality of execution of interventions (position of ties, uniformity of injection) have a large influence on the failure modes and on the overall behaviour of panels.

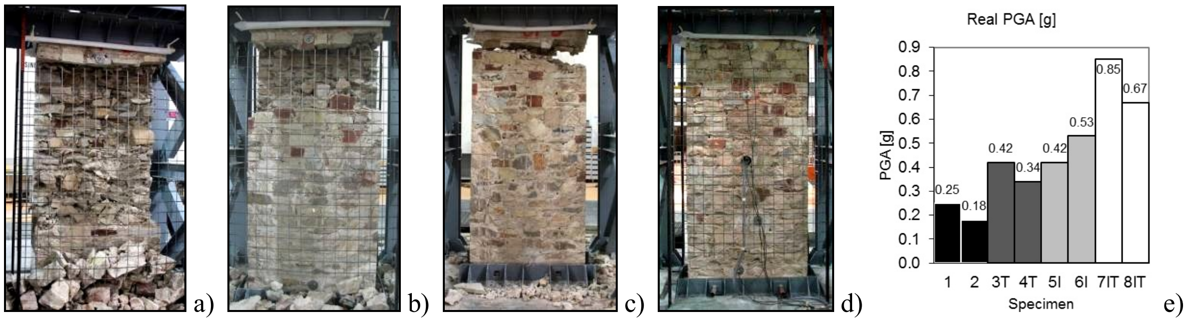

Fig. 1 Example of failures: (a) unreinforced, (b) steel ties, (c) grout injection, (d) steel ties and grout injection; (e) maximum PGA suffered by each panel

5.1.2. Tests on walls and columns made of earth-blocks and strengthened using polyethylene nets in the joints

In order to investigate the performance of the developed strengthening technique in terms of ultimate capacity, energy absorption and deformability, two walls and two column specimens were constructed. Each specimen was tested (Fig. 2) under a series of simulated earthquake ground motion, generated by random signals with frequencies from 0,1 Hz to 40 Hz.

Fig. 2 Wall specimens (SAWV and SAWR) on shake table

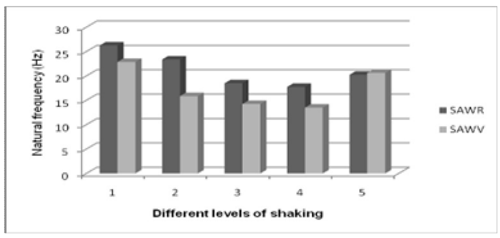

Fig. 3 Variation of natural frequency of wall specimens obtained from shake table tests

Figure 3 shows, in case of walls, the variation of natural frequency for each level of shaking. The histograms show that there is a general trend of decrease in the natural frequency as the amplitude of shaking increased. It is noted that the cracking, which appeared during higher shaking level propagated and has caused dislocation of a block of bricks in the final shaking level. This has changed the mode shape and fundamental natural frequency, as the height of the wall was reduced. In case of columns, the linear increase of the imposed acceleration did result to non-linear increase of displacements. This is attributed to the fact that the tensioned side of the columns is non-linearly deformed (Fig. 4) after cracking.

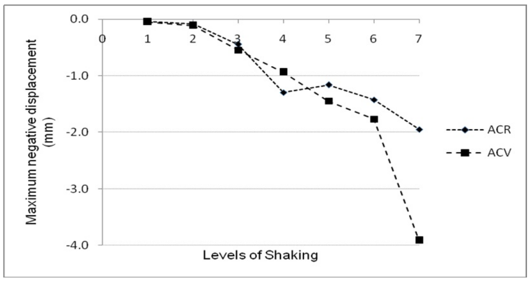

Fig. 4 Variation of tensile deformations for various levels of shaking – columns

Strengthening the joints of walls and columns with polyethylene nets has improved significantly their behaviour. Actually, the dislocation of bricks was prevented, whereas the specimens behaved linearly, up to cracking. This suggests that the reinforced mortar layer becomes active and takes part in the load transfer after the cracking of the bricks or mortar joints. The reinforced specimens underwent smaller deflection at the top than the unreinforced ones. Changes in frequency were recorded as higher intensity motions were imposed. Such changes are more sudden in unreinforced specimens than in reinforced ones, thus indicating a more gradual development of damages in the reinforced specimens.

5.1.3. Test on cross vault

The subassembly was subjected to a series of input motions along two axes. For that purpose, the Calitri record (Irpinia earthquake, 1980, Ms = 6.9) was used. The maximum input acceleration of the adequately scaled motions was gradually increasing. After the occurrence of severe damages, the subassembly was strengthened: All cracks were grouted, the three-leaf masonry piers were grouted, timber struts/steel ties were placed at the base of the two arches, whereas vertical prestressing was applied to the piers, using CFRP plates. The prestress force has increased the compressive stress in the piers by 0,20 MPa. Fig. 5 shows the strengthened subassembly on the shaking table, as well as the damages observed after the completion of the test. It is important to note that the damages recorded after strengthening were of the same nature as those observed in the as-built case, namely: Cracks in the vault and in the arches (due to the out-of-plane movement of the supporting piers), as well as horizontal cracks in the piers (at the top and the bottom of the openings, again due to their out-of-plane

Fig. 5 (a) The strengthened cross vault; (b) Damages in the arch;
(c) Damages in the vault [input motion: 450% Irpinia earthquake]

bending). This is a positive result, in the sense that the applied techniques do not alter the structural behaviour of the structure. On the other hand, the strengthened subassembly was able to sustain three times higher maximum acceleration than the unstrengthened one, and significantly larger deformations (40,6 mm at the top of the piers vs. 11,4 mm for the unstrengthened specimen) for the same level of damages.

5.2. Tests on models of entire buildings

5.2.1. Tests on multi-leaf stone masonry buildings strengthened through grout injection

The experimental program on multi-leaf stone masonry buildings can be considered the continuation and the extension of the tests presented in section 5.1.1. The experiments presented in the following

allow an in-depth study on the influence of lime grout injection when intervening on whole structures and not only on single elements. Two models were realized with the same geometry and the same details: two storeys, double planking wooden floors and insertion of steel ties to prevent out-of-plane mechanisms on masonry piers (Figure 6a and 6b).
The first model (URM) was tested in unstrengthened conditions and could suffer a maximum PGA of 0,45 g. The damages surveyed on the models reflected those typically observed on real cases, namely local separation of external layers and a widespread crack patter. Since this model was not led to the collapse, it could be repaired through injection of lime grout and tested again (RM). In this case a maximum PGA of 0,60 g could be attained. The damages could be limited, even if the reopening of several cracks occurred. The second model was strengthened through lime grout injection before the test (SM), thus allowing the influence on an undamaged structure to be evaluated. This specimen manifested the highest strength, being attained a maximum PGA of 0,70 g. Furthermore any separation between external layers could be seen and only limited and localized damages occurred to the model.
Intervening through injections also influenced the dynamic behaviour of models, allowing a limited decreasing of frequencies and a restrained variation of mode shapes, while the damping factors appeared to be increased. Figure 6c also highlights the ability of both injected models to sustain higher seismic loads and to widen the linear behaviour up to higher PGA. The analyses confirmed the improved dynamic behaviour of both injected models, even if the best overall result could be observed on the strengthened model (SM).

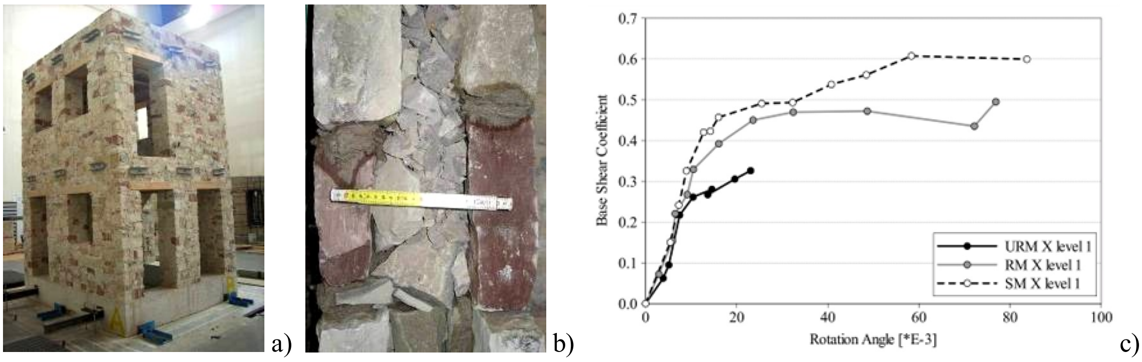

Fig. 6 View of a building model (a) and detail of the multi-leaf wall (b). Example of base shear trend (c)

Fig. 7 (a) In-thickness layout of longitudinal and transverse timber elements, (b) Connection of timber elements in the corners of the building, (c) Timber ties and timber frames of openings

5.2.2. Test on timber laced building

Some construction details of the system of timber reinforced masonry adopted for one of the models tested at NTUA are shown in Fig. 7. The aim of this test was to obtain quantitative data about the positive effect of timber laces on the seismic behaviour of historic structures. For this purpose, the model was subjected to three series of seismic tests along two axes, namely: (a) In the as-built state, in order to compare its behaviour with that of the plain masonry model, (b) After the application of grouting, in order to check whether grouting alone (in presence of timber ties) is able to improve the seismic response of the building and (c) after the enhancement of the diaphragm action of the roof alone (as tests on the plain masonry model have proven that the diaphragm action of the roof is decisive for the seismic response).

The model, at its as-built state has sustained the 120% of Kalamata earthquake (Kalamata, Greece, 1986, Ms = 6,2) with repairable damages (Fig. 8), whereas the respective plain masonry model underwent more severe (still repairable) damages under 90% of Kalamata earthquake. It was observed (see Fig. 8), that the cracks were closing at the vicinity of the timber ties. Similarly, the separation between the exterior leaves of masonry (very pronounced in the case of plain masonry model) was very limited in the timber laced building.

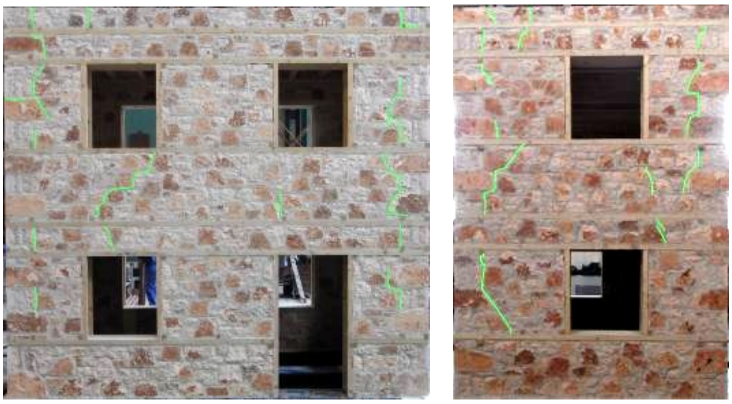

Fig. 8 As built specimen. Observed damages at a) the long wall 1 (LW1) and b) the short wall 2 (SW2); at 120%R of Kalamata earthquake

The grouting of masonry has led to significant improvement of the behaviour, as under the maximum motion imposed to the unstrengthened model (120% of Kalamata earthquake) the grouted model was free of damage. The subsequent enhancement of the diaphragm action of the roof alone has led to a box-like behaviour of the building, preventing out-of-plane damages and allowing the model to sustain significantly higher seismic actions.

5. CONCLUSIONS

The experimental program referred to in this paper has provided data that are still to be evaluated. Moreover, the analytical part of the work is still going on. Although the work is not yet completed, on the basis of the tests on subassemblies, as well as on scaled building models one may draw the following conclusions:

(a) The structure of the experimental program, the selection of the specimens, as well as of the interventions techniques applied to them were proven to be successful, as they have provided data consistent with those obtained within previous WPs, data that can be compared with those on individual structural components.

(b) The results obtained within this WP7, in combination with those obtained within previous WPs can provide sufficient and reliable data for the modeling of historic structures, for the calibration of the models and for the formulation of Guidelines for end-users that constitute the final Work Package of the NIKER project.

(c) The tests on subassemblies-for which it is more difficult to simulate the boundary conditions than in case of entire buildings-have shown that the behaviour of the specimens was compatible with that observed on entire building models (e.g. separation between leaves of masonry in testing individual walls and in testing three-leaf masonry buildings). Thus, the vulnerability of the real structures, as repeatedly observed during earthquakes, was successfully reproduced in-laboratory. Finally,

(d) The intervention techniques, selected on the basis of the criteria of both efficiency and acceptability for cultural heritage assets, were proven to be efficient (i) in terms of reducing the vulnerability of the structures, without (ii) altering drastically the original bearing system. Furthermore, (iii) they have made the strengthened structures to resist significantly higher seismic actions before damage and failure occur.

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