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SEISMIC PROTECTION OF MONUMENTS AND HISTORIC STRUCTURES – THE SEISMO RESEARCH PROJECT

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Abstract. *The research has developed an integrated, interdisciplinary and innovative methodology to evaluate the seismic behaviour of monuments and historic structures. This methodology enables condition assessment of monuments, in a way that allows selection of effective preservation intervention techniques using appropriate materials. It also yields useful recommendations for engineers and authorities responsible for the procurement, realization and approval of studies and their subsequent applications to protect monuments and historic structures. Given the importance and complexity of historic structures in terms of design, construction techniques and materials, advanced computational tools and methods were utilized to meet the needs of the proposed research. In particular, implementation of the proposed methodology on selected case-study historic structures included: (a) documentation of the existing state through surveys and architectural studies; (b) recording of damage; (c) identification of the construction materials; and (d) monitoring of the monument and the evaluation of parameters, such as regional seismicity and soil conditions, that affect their seismic response. Static tests on wall specimens as well as shaking table tests were conducted, producing valuable data related to the true seismic behaviour of structures. Two well known monuments have been selected as case studies in order to be analysed using several types of analysis and failure criteria. Moreover, methodologies established for the study of monuments and historic structures were assessed in terms of their reliability, accuracy and effectiveness by comparing analytical results with experimental data.*

1 INTRODUCTION

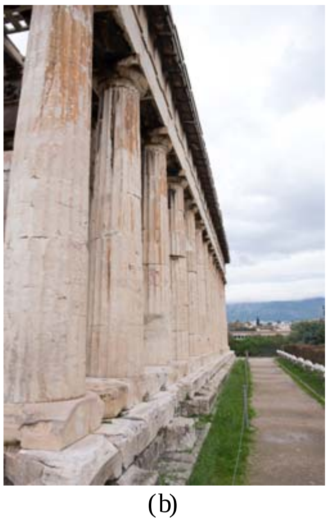
The interest of the scientific community involved in the protection of cultural heritage was rekindled at the end of the Second World War when many monuments across Europe showed irreparable damage [1-3]. This interest focused on the condition assessment of monuments, methods for more efficient maintenance, and development of simulation techniques to model their behaviour, facilitated by the evolution of computational tools and the parallel progress made in many scientific fields.

The study of the behaviour of a monument or a historic building is particularly difficult because of the complexity of the structure, construction method, age, and of course because of its historic significance [4]. These parameters limit the choice of means and methods of monitoring and intervention for these types of structures. Detailed data collection, use of advanced computational methods and development of complex models is usually required [5-7]. Assessing the status of a historic building becomes even more difficult when the structure is prone to seismic activities [8]. In this case the risk of partial or total collapse should be studied [7, 9]. Furthermore, the existence of seismic activity in the vicinity of an aging monument usually suggests that the structure has already suffered damage, which must be considered in the study, and in addition, any proposed interventions should be targeted to protect the structure from future earthquakes [10-13].

Therefore, it is evident that the seismic protection of monuments involves a great number of parameters that should be investigated thoroughly and systematically. Although the surveying of a historic structure is a prerequisite for its study and protection against seismic actions, current practice has demonstrated deficiencies, as demonstrated by several current examples of failures reported in the literature, such as the Tower in Pavia, Italy, an important monument that collapsed without any indication of damage. A similar case- study is a Cathedral in the south of Sicily that was partially propped after an earthquake in 1990, and then collapsed in the 1996 without another seismic event. Use of suitable investigation methods and testing would have allowed an accurate assessment of the status of the above monuments and early detection of damage.

This research develops a methodology for thorough documentation of the geometry, assessment of structural condition and calculation of seismic response through experimental and analytical methods, as well as application or enhancement of innovative preservation techniques to monuments and historic structures.

(a)



(b)

Figure 1: The temple of Hephaestus in the Ancient Agora, Athens: (a) western façade; (b) southern view.

(a) (b)

Figure 2: The Catholikon of Kaisariani Monastery, Hymettus Athens: (a) western façade; (b) southern view.

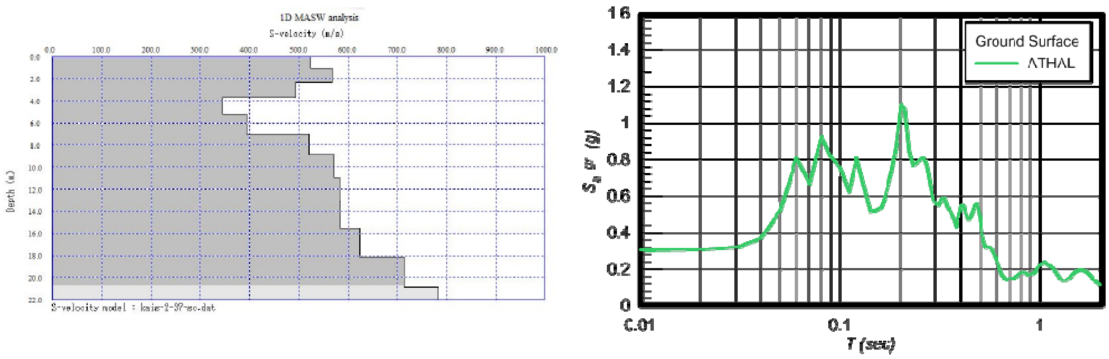
Two monuments of major importance were selected, representing the classical and the byzantine era: (a) the Temple of Hephasteus in the ancient Agora in Athens; (b) the Catholicon of the Kaisariani Monastery. The temple of Hephaestus was probably erected between 460 and 420 BC by a yet unknown architect on top of Agoraios Kolonos hill, which is delimiting the Ancient Agora of Athens to the west. It is one of the best preserved ancient temples, partly because it was transformed into a Christian church. The central church (Catholicon) of the Monastery of Kaisariani is located on a hillside at the foot of Mount Hymettus on the east of Athens, Greece. The Catholicon is a Byzantine crossed-dome church constructed during the 11th/12th centuries. The two monuments are shown in Figures 1 and 2.

2 CONDUCTED RESEARCH

The geometric survey of monuments is a sophisticated and demanding process, as regards to the use of suitable equipment (simple tools, photogrammetry or laser scanners surveys), software, expertise, time and effort. The importance of accuracy in monument surveying is obvious. The need for a detailed record of the architectural elements of the bearing structure, deformation and damage is often a catalyst for the choice of retrofitting methods. A full documentation of the main structure, including the main horizontal, vertical and inclined structural elements that transfer the imposed stresses and strains at the foundation elements, has been performed for the two monuments. In Figure 3 the final 3D model for the temple of Hephaestus derived with the use of a Leica ScanStation 2 laser scanner is shown [14].

Figure 3: Documentation of temple of Hephaestus with laser scanner: View of the 3D model from the northeast corner [14].

Local soil conditions have a profound influence on the structural response. In this context, site surveying includes the study of local topography (i.e., slopes, valleys), nature of the bedrock and nature and geometry of the deposited soils. These factors may contribute to the qualitative interpretation of the observed damage. The role of soil behaviour and site characteristics on the seismic response is now internationally recognized. A Geophysical investigation has been performed for the Kaisariani Monastery to evaluate the velocities for P and S waves along depth, as depicted in Figure 4a. Based on the geological and geotechnical data available at the positions of the two monuments, the soil profiles have been derived and analysis of soil response has been conducted to estimate maximum acceleration, maximum velocity and design spectra at the top of the soil. An indicative elastic acceleration spectrum at the ground surface is shown in Fig. 4(b) [15].



(a) (b)

Figure 4: Soil investigation: (a) determination of S-waves velocity in Kaisariani Monastery; (b) elastic spectral acceleration at ground surface in Hephaestus temple [15].

A detailed study of seismic hazard is also completed, that is, assessment and evaluation of seismic loads resulting from the seismicity of the area in which the monument is located, considering possible nearby active faults and near-fault phenomena. The significance of the monuments requires the probabilistic assessment of seismic risk, which is based on regional seismicity including historic earthquakes and the establishment of the probability distribution of occurrence for seismic events. The combination of the regional seismicity and attenuation relationships of ground motion result in the formation of seismic hazard curves that provide the expected ground acceleration, depending on soil type, for different annual frequencies of exceedance and return periods. Based on typical values of acceleration, appropriate pairs of earthquake magnitude and distance were determined, and used for seismic analysis. In Figure 5 the annual frequency of exceedance of peak ground acceleration for stiff soil conditions is depicted [16].

Another important parameter, necessary for the complete documentation of the structure and for understanding its behaviour, is the identification of material properties, which may have different characteristics depending on construction phases of the structure. Beyond identifying these components, namely the structure and the mechanical properties of the materials, the scientific community interest focuses on the modeling approach of historic mortars, since application of inappropriate mortars for the preservation of monuments in the past resulted in devastating effects, i.e., cracks, failure of the original materials, surface staining or spalling. A thorough and organized survey of the two monuments has been conducted including the implementation of various non-destructive techniques (NDTs) [17-19]. In the case of Kaisariani monastery, after a thorough in-situ macroscopic investigation, a variety of NDTs where applied: Ground-penetrating Radar (GRP), Infrared Thermography (IR), Fiber Optics Microscopy (FOM) and Schmidt rebound hammer.

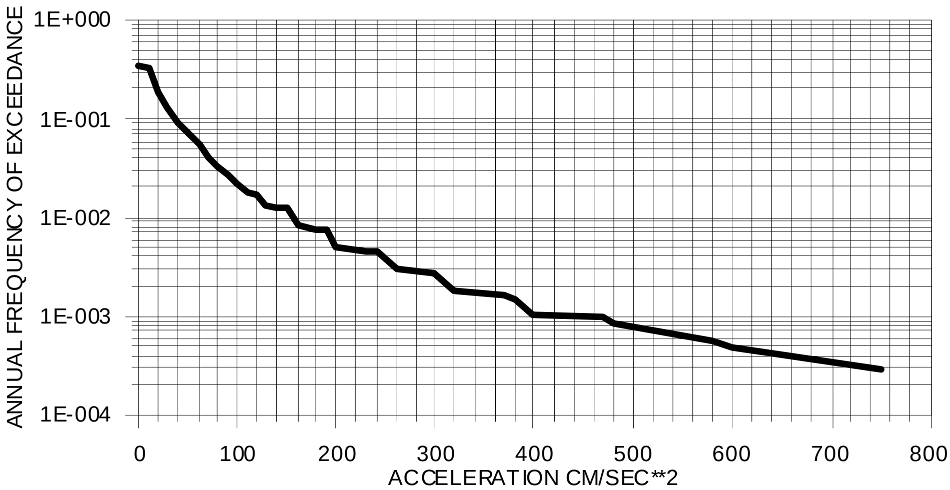


Figure 5: Seismic hazard curve [16].

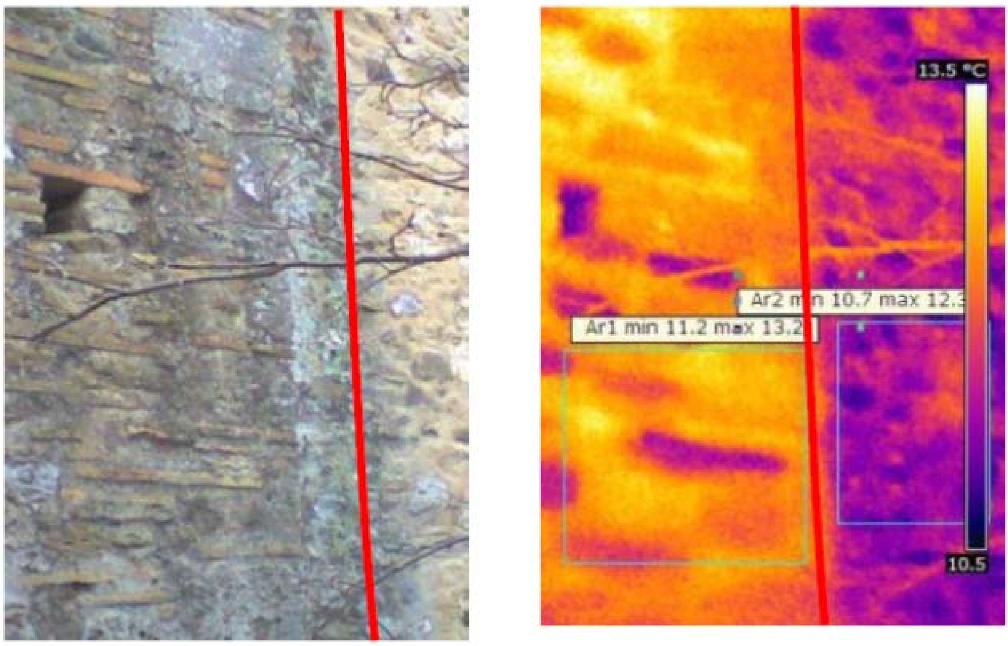


Figure 6: Results of Infrared Thermography at the Catholikon. Detection of different structural phases [17].

The results were analyzed and combined in order to extract information regarding the original building materials, the type of masonry construction, as well as information regarding non-documented different construction phases and problematic areas. In Figure 6 indicative results of infrared thermography are shown regarding the Catholikon. A series of NDT tests have been conducted also at the Hephaestus temple including the use of ground penetrating radar, endoscopy and rebound hammer testing. In Figure 7 the results of radar are shown regarding a wall of the south façade.

Monumental and historic buildings are generally constructed with masonry walls. These construction materials present significant variances of the mechanical and dynamic characteristics, which are very difficult to identify. The identification of these variances is required in order to perform the analysis of the monument and assess its behaviour. The large dispersion of these characteristics is mainly attributed to the fact that the monument during its life has been strained by several actions, including subsidence, temperature changes, environmental vibration and seismic loads. The impact of these actions is partly depicted in the form of cracks. The existence of severe cracking could result in separating the monument in different parts; thus, increasing the difficulty to assess its behaviour under seismic excitations.

For these reasons, a thorough understanding of the behaviour of the monument is achieved through structural monitoring under small-intensity earthquakes in order to assess the effects of cracking on the behaviour of individual parts. The information from structural monitoring can be a basis for developing numerical and analytical models that will be validated according to the results of a monitoring program in order to approximate the real behaviour of the structure with acceptable accuracy. In Figure 8 the positions for the placement of six triaxial accelerometers are depicted for the Catholikon. The accelerometers are connected with a central data acquisition system.

Another important source of information is through testing of models. These experiments allow simulation of the seismic action by selecting the intensity, frequency spectrum and most parameters that characterize an earthquake motion. The specimens are constructed to satisfy, in as much as possible, the actual construction and to facilitate the study of specific parameters. However, there are few experiments in the literature related to historic structures because of the many implementation difficulties. A number of masonry specimens have been constructed at the Laboratory for Earthquake Engineering of the National Technical University of Athens, LEE-NTUA, to be tested under compression as shown in Figure 9.

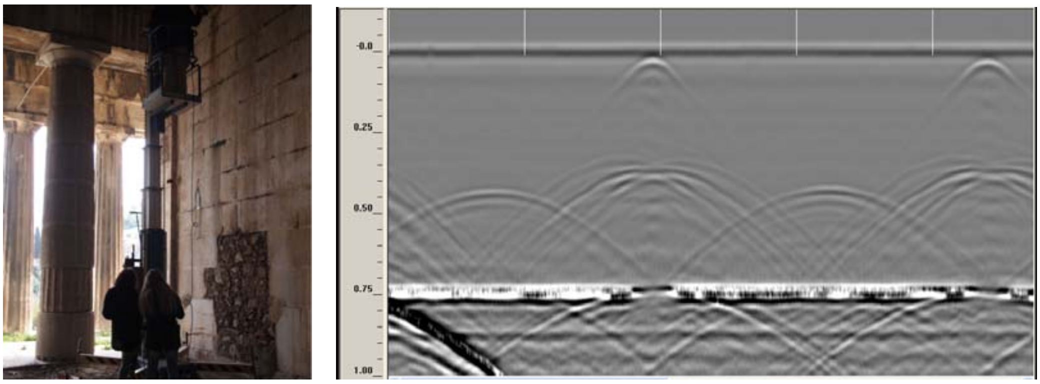


Figure 7: Results of ground penetration radar testing at the Hephaestus temple [19].

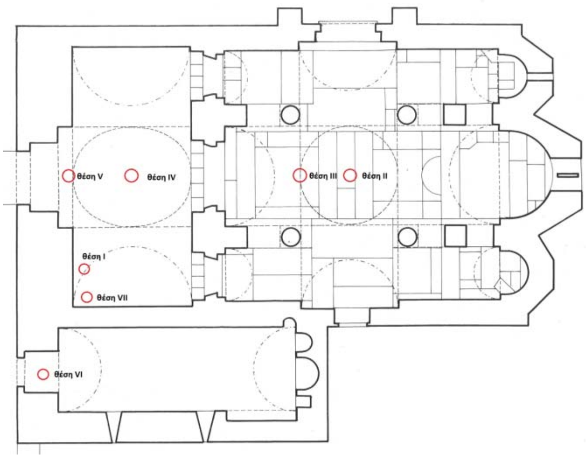
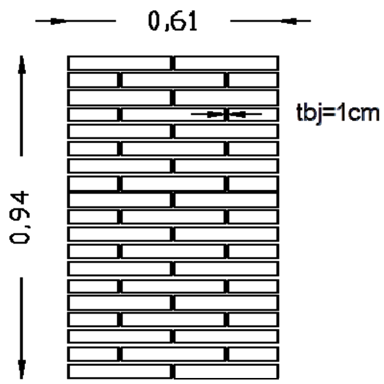


Figure 8: Monitoring scheme for the Kaisariani monastery. Placement of recording devices.

Identifying potential failure modes of a monument or a historic building requires understanding of its structural behaviour. This can be aided by examining the response of pertinent subsets of the structure based on the method of macroelements, or the finite-element method, using linear or non-linear analysis [20, 21]. Development of reliable macroelement and finite element models is necessary to perform elaborate analyses, including nonlinear static and dynamic time-history analysis. In Figure 10(a) and 10(b) the finite element models of the Hephaestus temple and the Catholikon are depicted, respectively [22]. In Figure 11(a) the central apse of the Catholicon is selected as a macroelements in order to study a local mechanism of failure governed by overturning. The transversal behaviour is assessed by means of a macroelement that isolates three arches and the supporting pillars of the central nave as shown in Figure 11(b) [9].

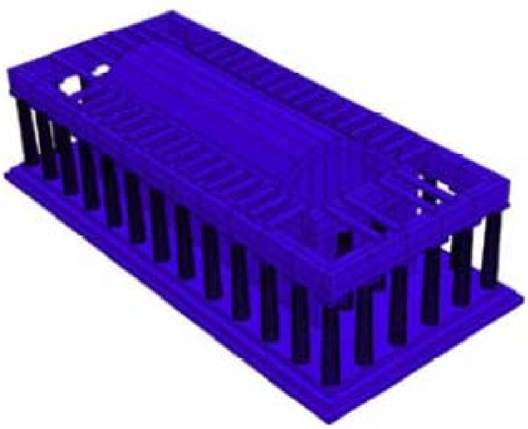
Common practice in describing failure is the application of criteria based on stress distribution. Successful use of an analytical mathematical model that incorporates the particular geometric, mechanical and structural features of a historic structure can provide information on the type, extent and location of damage. The results from such an analysis can be used in a deterministic way or alternatively, following a probabilistic approach with which parametric analyses are performed for a range of values of a critical parameter. The statistical evaluation of the results has led to the development of fragility curves that correlate the estimated damage to the seismic intensity based on a given type of probability. Indicative fragility curves for the Kaisariani monastery are shown in Figure 12b referring to the failure criterion depicted in Figure 12a [18, 23].



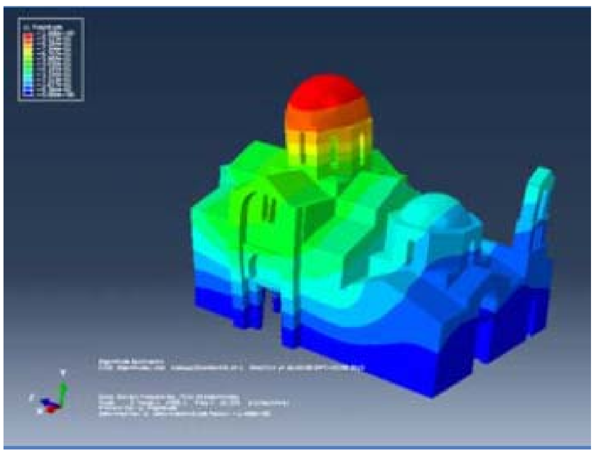
(a)

(b)

Figure 9: Masonry specimens to be tested for compression: (a) drawing; (b) as build.

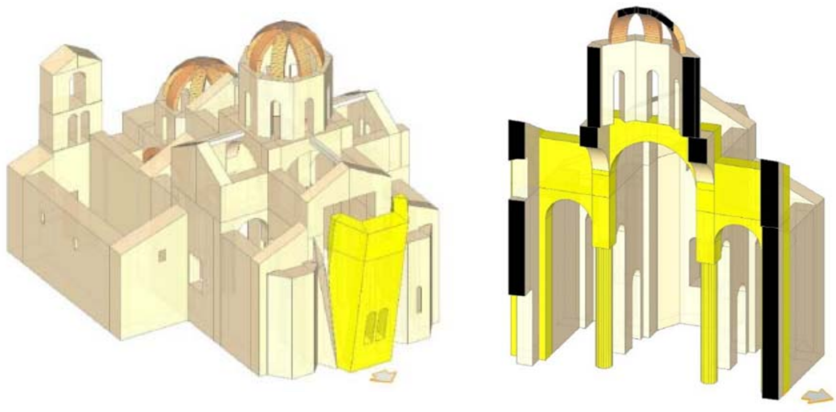


(a)



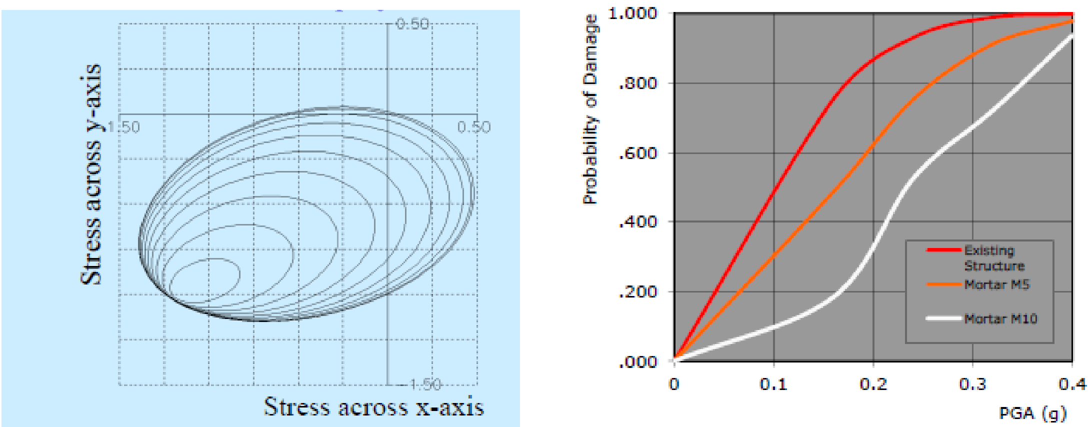
(b)

Figure 10: Finite element models: (a) Hephaestus temple; (b) Catholikon [9, 22].



(a) (b)

Figure 11: Macroelement analysis for the Kaisariani monastery: (a) Overturning of the central apse; (b) Transversal behavior.



(a) (b)

Figure 12: Vulnerability the Kaisariani monastery: (a) development of failure criterion; (b) fragility curves for moderate damage [23].

The main purpose of the analysis of a monument or a historic building is to assess its seismic risk in order to propose specific intervention measures for an effective seismic upgrade and protection of such structures. In addition to conventional treatments, application of seismic base-isolation is an efficient engineering methodology designed to reduce or even eliminate damage caused by dynamic excitations. In fact, seismic isolation is a type of support that separates the structure from the soil response and results in a reduction of seismic energy input rather than enhancement of structural resistance. The application of this technology leads to structures that continue to behave elastically even during major seismic events [24]. The effectiveness of using base isolation is also studied at LEE-NTUA with the aid of a masonry specimen depicted in the drawing of Figure 13 [25-26].

3 MANAGEMENT STRUCTURE AND PROJECT TEAMS

The conducted research was organized in thirteen Work Packages (WP):

WP 1: Coordination of the project including synchronization of the research groups and financial management;

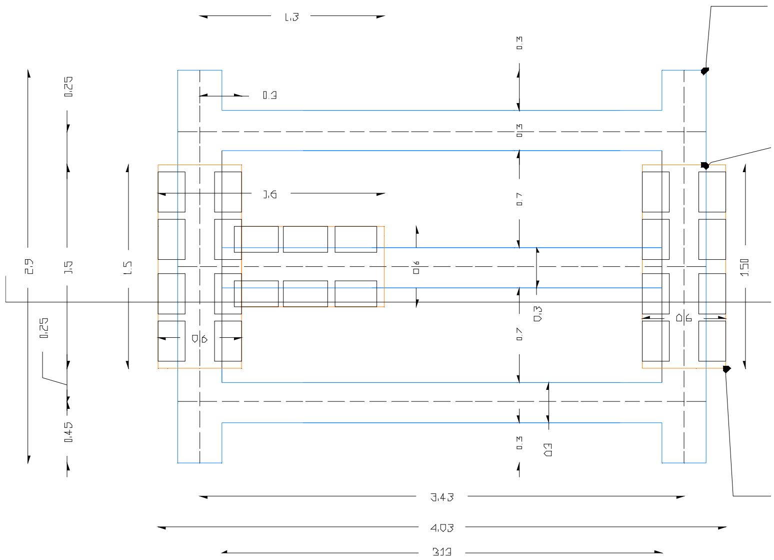


Figure 13: Masonry specimen for the study of base-isolation application in historic structures.

WP 2: Development and implementation of the methodology including development and documentation of the methodology and derivation of instructions for proper application;

WP 3: Geometrical documentation including surveying of the case-study structures, geometrical and damage documentation;

WP 4: Seismic hazard assessment including study of historic seismicity, derivation of Guttenberg-Richter curve, investigation of near-fault phenomena and development of seismic hazard curve;

WP 5: Assessment of the soil influence on seismic response including literature review, geological mapping and geotechnical investigation, seismic response analyses and soil failure analyses;

WP 6: Selection of proper monitoring system including assessment of the effectiveness of the system and installation on a case-study structure;

WP 7: In-situ surveying of materials and characterization of mechanical properties in the laboratory including application of non-destructive techniques, sampling and mapping of materials, damage and mechanical resistances, characterization of structural materials applying laboratory tests, correlation of in-situ results with laboratory results, design and construction of compatible mortars;

WP 8: Experimental evaluation of masonry characteristics including construction and testing of representative masonry wallets and assessment of their behaviour under static and seismic loading;

WP 9: Testing on the shaking table of LEE including construction of specimens, installation of base isolation and testing on shaking table until failure and comparison with the non-isolated behaviour to assess the effectiveness of base-isolation;

WP 10: Development of probabilistic models, fragility curves, evaluation of the results and preparation of recommendations/ instructions;

WP 11: Implementation of probabilistic methodology including application of the methodology on selected monumental and historic structures, correlation of analytical with experimental results and implementation of failure criteria for masonry;

WP 12: Numerical modeling and application of methodologies to determine the seismic response including correlation of the experimental results with analytical linear and non-linear deterministic methodologies and implementation on case-study structures;

WP 13: Application of seismic isolation including dynamic analysis of shaking table tested structures with and without base isolation, correlation with experimental results, analysis of case-study structure with and without base-isolation and preparation of recommendations/ instructions for seismic isolation.

Dr. Constantine Spyrakos, Professor NTU Athens, is the Project Coordinator responsible for the completion of the several stages of the work within the submitted timetable, as well as for the financial management of the project. The First Research Team coordinated by Dr. E. Vintzileou, Professor NTUA, has been responsible for the methodological development that determined the priorities of other groups and provided the theoretical framework of the activities. It has provided data to the other two research teams, through either field measurements or experimental results. The Second Research Team coordinated by Dr. A. Moropoulou, Professor NTUA has been responsible for the study and evaluation of critical parameters affecting the determination of the seismic response of monuments and historic structures. The results of the second group were essential for the continuity and reliability of the other research teams, since they were used by the first group during the experiments and by the third group as input data to complete their work packages. The Third Research Team coordinated by Dr. I. Psycharis, Professor NTUA has been responsible for the evaluation of experimental results from the shake table testing at LEE-NTUA, the development and validation of analytical models that simulated the seismic behaviour of the monuments as well as the evaluation of various methods that calculate the seismic response and estimate structural damage. Substantially, the third team was the receiver of information that was produced by the first and second teams aiming at the formulation of conclusions regarding the seismic behaviour of monuments and historic structures.

4 LEE INFRASTRUCTURE

In LEE an Earthquake Simulator with six degrees-of-freedom has been installed and used in this program. The equipment was initially calibrated and started its operation at the beginning of 1986 and has been operating ever since. The shaking table consists of a rigid steel platform with dimensions 4x4x0.6 (m) and 100 kN weight. It is capable of simultaneous vibration in all six degrees-of-freedom (6 DOFs), with vertical load capacity of 640kN and a horizontal reference at 320 kN. The maximum acceleration in both horizontal directions that can develop is 2g, while in the vertical direction is 4g. The operating frequency rate of the simulator ranges from 0.1 up to 50 Hz. The generation and processing of seismic excitations and analysis of the experimental results is performed by special signal processing programs available in the library of LEE.

An independent reaction wall is also available at the laboratory. Its capacity is 10 MNm, is 6m in height and consists of two sections each 4 and 5 m long, 1.1 m width. Several jacks are installed and may function with independent control. The jacks have capacities of 500 kN, 300 kN, 200kN and 100kN. A mobile data multi-channels acquisition system is supporting this facility. An innovative testing apparatus is also functioning at the laboratory in order to test specimens under recyclic loads horizontally applied, such as walls with up to 1.5 m height, 1.0 m long and 0.5 m thickness. The vertically applied load may be up to 1000 kN and can be kept constant without any variation throughout the tests. Innovative testing apparatus are also functioning at the Laboratory in order to measure mechanical characteristics (compression strength, modulus of elasticity, Poisson's ratio, stress-strain curve) of masonry specimens.

Diverse instrumentation is also available for in-situ testing such as flat jacks, ambient testing, displacement strain measurements, pull-out tests, etc.

In 2000 the LEE-NTUA was certified by TUV CERT (TUV Austria Hellas), for Dynamic and Seismic Tests using the earthquake simulator, according to ISO 9002/1994. Starting on 12/1/2007, it implemented a Quality Management System for DYNAMIC SEISMIC TESTS certified by TUV Austria (the Austrian Organization of Inspection and Certification). The current relevant certification of the LEE by this organization is according to standard EN ISO 9001:2008.

In addition, LEE-NTUA has a highly experienced staff in preparing, testing and analyzing of the experimental results. The staff has over twenty five years of experience and participation in the successful completion of a multitude of national and international research programs. A representative number of international projects relevant to the proposed research are listed:

- New Integrated Knowledge based approaches to the protection of cultural heritage from Earthquake-induced Risk – NIKER (DCT - Università degli Studi di Padova).
- Seismic Engineering Research Infrastructures for European Synergies – SERIES (University of Patras/ European Commission/ Framework Programme 7).
- Performance of Innovative Mechanical Connections in Precast Building Structures under Seismic
- Conditions – SAFECAST (FP7-SME-2007-2).
- Seismic Resistance of new Reinforced or Isolated Perforated- Brick Masonry Housing Construction in Low
- Seismic Region (ECOLEADER Access to Research Infrastructures).
- Seismic Behaviour of Capacity designed masonry Walls in low Seismicity regions (ECOLEADER Access to Research Infrastructures).
- Experimental evaluation of technical interventions for reduced seismic vulnerability of old existing buildings.
- Experimental evaluation of technical interventions to reduce seismic vulnerability of masonry buildings.

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