Computational Methods in Applied Sciences

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Seismic Assessment, Behavior and Retrofit of Heritage Buildings and Monuments

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Prologue

A great range of structures qualify as heritage—today the term is used to classify any type of construction that coveys tractable information about technology, aesthetics, way of life, customs, religious practices, art, defense, and governance in former times. Protected by international treaties and conventions, historical constructions are precious as they form inseparable components of history, culture, and human evolution. For modern societies a noble pursuit is to restore the built cultural and historical heritage, to protect it from the deprecating influences of aging and exposure to the elements, and from such irreversible human intervention as would materially alter or eliminate the historical truth conveyed by their mere presence, so that it may be preserved for future generations.

Heritage structures are mostly non-engineered construction spanning from ancient times to the early twentieth century; their basic material is mostly unreinforced masonry, the ever-present milieu of builders from prehistorical times till the early twentieth century. Buildings vary greatly in terms of significance, size, aspect-ratio (slenderness), connectivity, morphology, structural form, materials, and condition, ranging from traditional dwellings to monumental edifices, ancient temples, towers and spires, abbeys, religious spaces, castles, fortresses and fortification walls, arenas, theaters, and tombs. In light of all the complexity presented by unreinforced masonry (URM), it is not surprising that the state of the art in Modeling and Analysis of URM buildings is hampered by particular difficulties when dealing with response calculation through computer simulation due to the complexity of the structural system and the material constituents. For this reason assessing the seismic response and vulnerability of the built heritage can be a formidable task, whereas simple methods are not readily available.

The advent in computational methods for the analysis and earthquake assessment of Structures has changed the engineering design practice in the last 30 years. Today it is considered routine structural engineering practice to use finite-element discretization and analysis in order to determine the effects of ground excitation on structures. This is particularly so for well-designed structures, with well-understood, resilient member behavior where the all-important positive-definiteness of the structural stiffness matrix may be relied upon—structures that satisfy these requirements, are for example, reinforced concrete or steel frames with ductile member behavior that is controlled by yielding. However the effort becomes a Sisyphean task when this type of analysis is attempted on URM Structures: nonlinear numerical procedures collapse and the problem becomes ill-conditioned due to the material-brittleness in the absence of the stabilizing influence of reinforcement. Structures are three-dimensional and continuous in form, so, shell or solid elements are needed for a faithful idealization and discretization, thereby increasing dramatically the size of the numerical problem. Mass is distributed throughout the URM system, whereas diaphragms are often too flexible or non-existent to enable the use of master-slaving options that are called on routinely in the analysis of frame structures in order to reduce the size of the numerical problem. Lateral forces cannot always be modeled by concentrated actions at the centers of storey masses. Constitutive relations for the material need to be defined in the more complex 3-D stress and strain space since the member state of stress in solid and shell F.E. cannot be defined through stress resultants in the context of linear members. Contact phenomena, gaps, and interactions that take place between the building components of a masonry structure prevail and tend to dominate the modeling issues, since the nonhomogeneous domain of unreinforced masonry does not lend itself to the application of continuum mechanics constitutive models. In light of all this difficulty, it is not surprising that the state of practice in simulation of URM structures lags behind that of more conventional earthquake resistant structures, whereas techniques that could be potentially useful require users with a high level of specialized expertise in order to lead to meaningful results.

Rehabilitation and retrofitting of historical and heritage structures is also an issue of paramount importance in countries with great built cultural heritage that also suffer from high seismicity, such as the countries of the eastern Mediterranean basin. In the effort of assessing the residual strength of historic structures due to damages caused by past earthquakes and of selecting the appropriate remedial measures, sophisticated finite element analysis programs combined with powerful computing means are a tempting opportunity for specialists. Yet, despite the capabilities that can derive from the use of advanced modern technology, the obtained results may be of limited reliability when important structural parameters are underestimated in the modeling process, or inappropriate strength criteria are adopted in the examination of the analyses results. As a result, during the process of seismic assessment of historic or heritage buildings the residual strength of the corresponding structure can easily be wrongly estimated, leading to the choice of rehabilitation methods that are not efficient or unnecessarily alter or destroy the unique historical or architectural characteristics of the building.

For this reason assessing the seismic response of historical constructions can be formidable, a situation that is exacerbated further by the great variability in structural forms, scale, and material encountered. Today, after extensive work in this area, simple methods are not readily available or fully corroborated with actual records of response. Interestingly, despite the challenge it poses and the societal significance it carries, preservation of the built heritage does not rank high in the industry-driven research priorities. Caring for cultural heritage must remain, therefore, in the hands of basic science, till the added value it carries for society receives proper attention and priority. It is in this spirit that several of the researchers who participated in this volume motivated on every opportunity the organization of dedicated mini-symposia with the objective to assemble, identify, and highlight the most recent developments in this challenging field.

The state of the art is represented in the volume by a number of invited contributions by several well-known experts in the field, who presented recent results in several dedicated sessions of the ECCOMAS conferences that took place in 2011 in Corfu and in 2013 in Kos, Greece, focusing on the Dynamic Response and Seismic Assessment of historical buildings and monuments, within the framework of the COMPDYN Conferences in the following mini-symposia:

(1) Seismic Assessment of Heritage Structures and Monuments through Simulation (MS24) in COMPDYN 2011 in Corfu, Greece;
(2) Seismic Assessment of Heritage Structures and Monuments through Simulation (MS18) in COMPDYN 2013 in Kos, Greece; and
(3) Seismic Behavior and Retrofitting of Monuments and Historical Buildings (MS21) in COMPDYN 2013 in Kos, Greece.

After considering the breadth and scope of the papers presented in these three sessions, but also in other related sessions of COMPDYN 2011 and COMPDYN 2013, the organizers along with the conference chairman have secured the consent of SPRINGER to publish this post-conference dedicated volume, where the most significant papers of the above sessions are included. The papers collectively provide a thorough cross-section of the field, reflecting the fertile activity going on toward resolving the "Seismic-Assessment of Cultural-Heritage" standing issue by addressing:

- Novel methods of Analysis and Response Simulation of Monumental structures with particular emphasis on methods that account for the discrete nature of masonry.
- Methods for computer simulation of URM historical 3-D building systems and benchmark calibration with test results.
- Methods guiding the retrofit design of historical monuments within the limitations of International Conventions for reversibility and noninvasiveness of the retrofit scheme.
- Fragility curves for quantifying the seismic risk of historical city neighborhoods in the event of the design earthquake.

Work is continuing in this area, and it is hoped that the volume will serve as a work of reference setting the background for many more exciting developments that exploit digital and simulation technologies in preserving our heritage, that are yet to come.

December 2014

Ioannis N. Psycharis
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Protection of Historical Buildings According to Prohitech

Federico M. Mazzolani

Abstract The FP6 EC PROHITECH research project "Earthquake PROtection of HIstorical Buildings by Reversible Mixed TECHnologies" (2004–2009) developed a wide experimental and numerical activity on structures, sub-structures, elements and devices, involving 16 academic institutions of 12 Countries, mostly belonging to the South European and Mediterranean area (AL, B, EG, GR, I, P, RO, SL, TR, ISR, M, MK). The final results were presented at the International PROHITECH Conference held in Rome on 21–24 June 2009. The main objective of this project was to develop sustainable methodologies for the use of reversible mixed technologies in the seismic protection of existing constructions, with particular emphasis to buildings of historical interest. Reversible mixed technologies exploit the peculiarities of innovative materials and special devices, allowing ease of removal if necessary. At the same time, the combined use of different materials and techniques yields an optimisation of the global behaviour under seismic actions. A challenging activity within the project was devoted to large scale models of monumental buildings, which were tested on shaking table for producing damage and then for evaluating the effectiveness of the proposed consolidation systems. In particular, the following monumental models were tested: the Mustafa Pasha Mosque in Skopje, the Gothic Cathedral in Fossanova, the St. Nikola Byzantine Church in Psacha and the Parthenon temple in Athens. Beside the experimental activity, appropriate numerical models were developed in order to both predict and interpret the testing results.

Keywords Seismic protection · Reversible mixed technologies · Shaking table tests · Large scale models · Monumental buildings · Numerical models

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1 Introduction

The seismic protection of historical and monumental buildings, namely dating back from the ancient age up to the 20th Century, is faced with greater and greater interest, above all in the Euro-Mediterranean area, its cultural heritage being strongly susceptible to undergo severe damage or even collapse due to earthquake. The cultural importance of historical and monumental constructions limits, in many cases, the possibility to upgrade them from the seismic point of view, due to the potential risk of using intervention techniques, which could have detrimental effects on their cultural value. Consequently, a great interest is growing in the development of sustainable methodologies for the use of Reversible Mixed Technologies (RMTs) in the seismic protection of the existing constructions. RMTs, in fact, are conceived for exploiting the peculiarities of innovative materials and special devices, and they allow ease of removal when necessary.

This paper deals with experimental studies, framed within the FP6 EC PROHITECH research project "Earthquake PROtection of HIstorical Buildings by Reversible Mixed TECHnologies" [7] on the application of RMTs to the historical and monumental constructions mainly belonging to the cultural heritage of the Euro-Mediterranean area [8, 12]. Within the range of the experimental research activities, shaking table tests were carried out on four large scale models of the following monumental constructions: the Mustafa Pasha Mosque in Skopje, the Gothic Cathedral in Fossanova, the St. Nikola Byzantine Church in Psacha and the Parthenon temple in Athens.

The large scale models of the Mustafa Pasha Mosque (scale 1:6), of the Fossanova Gothic Cathedral (scale 1:5.5) and of the St. Nikola Byzantine Church (scale 1:3.5) were tested on the shaking table at the IZIIS Laboratory in Skopje, Macedonia.

The seismic shaking table tests on the first two models were performed through three main phases with different loading intensities: (1) Testing under low intensity level earthquakes, causing minor damage in the model; (2) Testing under intensive earthquakes, producing a near collapse limit state to the structure; (3) Testing of the strengthened model until reaching heavy damage.

In the case of the third model, the particular consolidation system was able to fully protect the model under the maximum capacity of the shaking table and, therefore it was necessary to remove it for producing damage.

The tests on the large scale model of a part of the Parthenon temple (scale 1:3) was done on the shaking table of the Earthquake Engineering Laboratory of the National Technical University of Athens (NTUA). Three different configurations have been considered: namely three freestanding columns in a row with and without architraves and three columns in corner configuration. In all cases, the influence of metal connectors have been examined.

The carried out experimental activity [9], together with a systematically related numerical activity [10], has provided an important contribution to understand the seismic behaviour of monumental constructions, as well as to validate the consolidation interventions based on RMT systems.

2 Testing Equipments

The shaking table of the Laboratory of the Institute for Earthquake Engineering and Engineering Seismology in Skopje (IIZIS) was used for the Prohitech experimental activity [6]. It consists of a 5.0 × 5.0 m pre-stressed reinforced concrete plate, which is able to both sustain a maximum mass of 40 tons and simulate different types of dynamic/seismic load in horizontal and vertical direction, separately or simultaneously. The table is supported by four vertical hydraulic actuators located at four corners, at a distance of 3.5 m in both orthogonal directions. The table is controlled in horizontal direction by two hydraulic actuators at a distance of 3.5 m with a total force capacity of 850 kN. The four vertical actuators have a total force capacity of 888 kN.

The data acquisition and sequence generation system (DAC) for the shaking table is a computer based system, which allows simultaneous control of eight and data acquisition of 72 channels, storage of the acquired data to a computer recording device (HDD) as well as signal analysis and graphical presentation of the acquired data.

The shaking table of the Earthquake Engineering Laboratory of the National Technical University of Athens consists of a rigid platform and of a system controlling the input motion and the response of the specimen tested on the platform [9].

The material of the shacking table is steel and the dimensions are 4.0 × 4.0 × 0.6 m. The table can move in all six degrees of freedom (three translations and three rotations) independently or simultaneously. The maximum weight of the specimen can be up to 10 tons, if the centre of its mass is 2 m above the simulator platform. The maximum displacement, which can be achieved, is ±0.10 m in each direction and the maximum acceleration is 2.0 g in each horizontal direction and 4.0 g in the vertical one. The operating frequencies in each degree of freedom range from 0.1 to 50 Hz.

3 The Mustafa Pasha Mosque Model

3.1 Design Phase

The model of the mosque was built at the IZIIS Laboratory, in order to be tested on the biaxial seismic shaking table [6]. Considering the base dimensions of the prototype structure (20 × 20 m) and its height (22.0 m), the model was built into a scale 1/6. So, the model dimensions were 3.3 × 3.3 m in plan and 3.6 m in elevation, whereas the minaret was 6.3 m high (Fig. 1).

The model was designed according to "gravity forces neglected" modeling principle, using the same materials as in the prototype structure, namely stone (travertine), bricks and lime mortar. The main mechanical properties of this masonry were achieved by experimental tests.

The model was constructed on a RC foundation with strong hooks at the corners necessary to transport and lift the model on the shaking table.

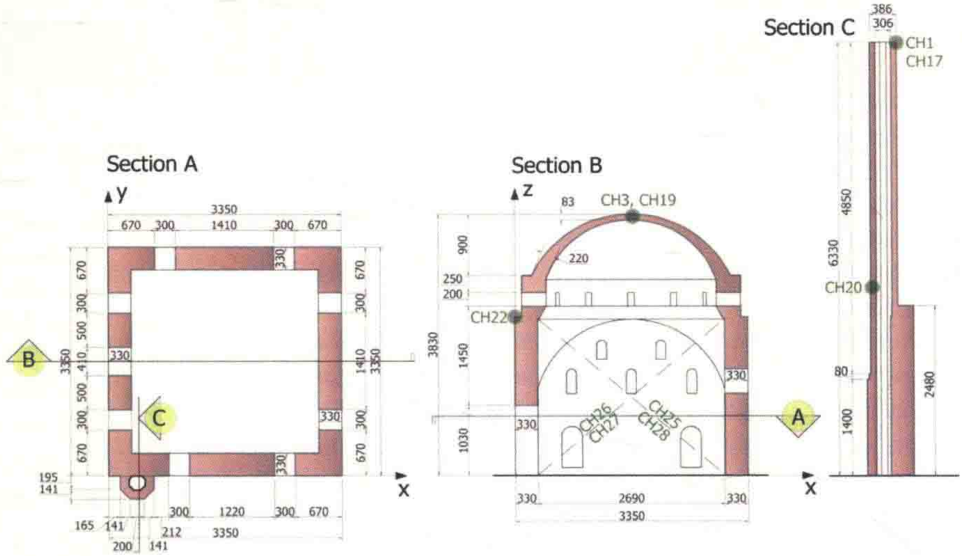

Fig. 1 Dimensions of Mustafa Pasha mosque large scale model

The walls of the model were conceived in accordance with the typical Byzantine design: two faces of stone and brick separated by an infill of stone and brick rubble set in lime mortar. Details related to both materials and constructive techniques were provided by the experts of the Institute for Protection of Cultural Heritage in Skopje. Wooden ties—two beams connected in transverse direction—were placed in horizontal mortar joints at each second layer. The construction of the model of the mosque and the completed model fixed to the shake table and ready for testing are shown in Fig. 2.

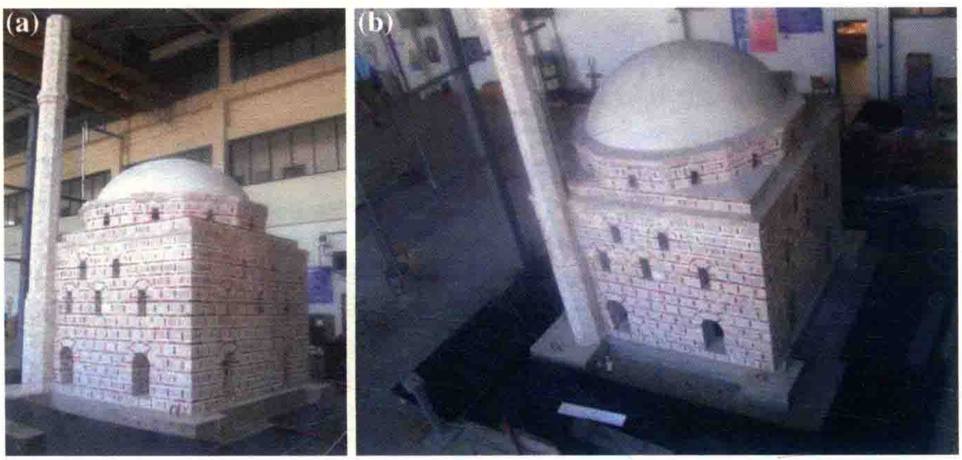

Fig. 2 The prototype of the mosque ready for testing

3.2 Testing Set-Up

In order to follow the dynamic response during the seismic shaking table testing, the model was instrumented at characteristic points with accelerometers and displacement transducers for measuring the absolute displacements as well as the relative diagonal deformation of the walls in the direction of the excitation (in-plane walls). 13 accelerometers (2 on the minaret, 9 on the mosque and 2 recording the input acceleration) were used. The number of displacement transducers—linear potentiometers and LVDTs—was 11 in total: 3 on the minaret and 8 on the mosque.

The main objective of the testing was to experimentally investigate the effectiveness of the reversible strengthening technology proposed for increasing the seismic resistance of such type of building. With this purpose, the seismic shaking table testing was planned in three main phases:

1. Testing of the original model under low intensity level, with the aim to produce damage to the minaret only;
2. Testing of the model with strengthened minaret under intensive earthquakes, with the aim to produce collapse of the minaret and damage to the mosque;
3. Testing of the strengthened mosque model until reaching heavy damage.

The testing procedure applied to the model consisted of several steps, consisting on the identification of the model dynamic characteristics and on seismic testing on selected earthquake records, whose period, according to the similitude requirements, was reduced 6 times. The excitation was applied in the horizontal direction only.

3.3 Testing Phases

3.3.1 Phase 1-Testing of the Original Model

After the model was located on the shaking table, its dynamic characteristics were defined by means of ambient vibration method as well as by low intensity random excitation in range 0.1–50 Hz.

In this phase the shaking table tests were performed by simulation of the Montenegro-Petrovac earthquake—N-S component, as well as of the El Centro earthquake, N-S component. During this testing phase, nine tests were performed with intensity of 0.01–0.10 g, in order to provoke damage only in the minaret. Under input intensity of 2 % g, the first horizontal crack appeared at the base of the minaret. In the next tests with intensities up to 10 % g, damage in the mosque was observed as well. The reason for this damage was the frequency content of the applied excitation, which was close to the self frequencies of both the minaret and the mosque.

The damaged model is shown in Fig. 3. During the last test with input intensity of 10 % g, the crack in the minaret was completely developed in the horizontal

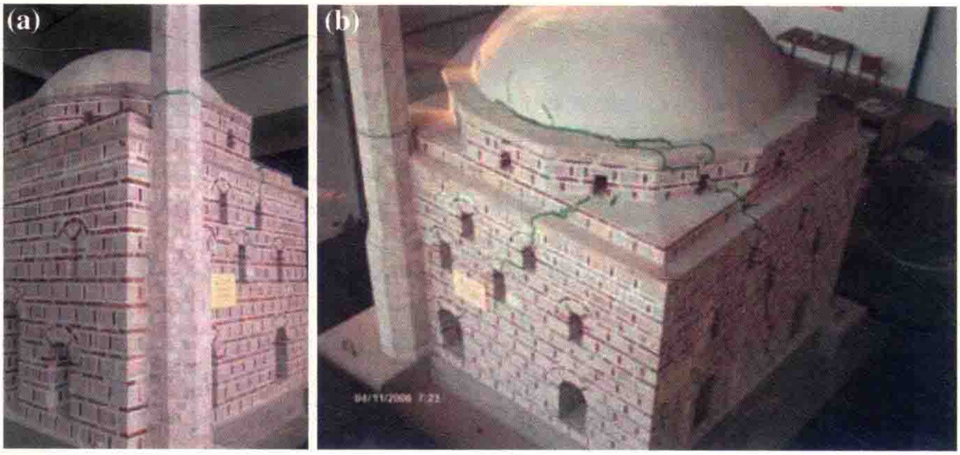

Fig. 3 The damaged model of the mosque after the first test

mortar joint and the minaret continued to vibrate completely freely, reaching the max absolute displacement of 9 mm, while the max displacement at the top of the mosque was 2.6 mm.

3.3.2 Phase 2-Testing of the Model with Strengthened Minaret

After the tests in phase 1, the model of the mosque was repaired by injection in cracks and the minaret was strengthened by application of C-FRP upon a layer of epoxy glue. The vertical strips with a width of 15 cm were placed on four sides along the length of the minaret up to the location of the balcony. They were confined by horizontal wraps, with a width of 10 cm, which were placed at four levels along the height of the minaret, while a strip of 20 cm was placed at its base. Such a strengthening enabled stiffening of the minaret and increasing of its bending resistance (Fig. 4a).

According to the preliminary analysis of the results obtained during the testing of the original model, it was decided to continue with seismic testing applying only the accelerogram of the Montenegro-Petrovac earthquake, N-S component.

Before the seismic tests, the dominant frequencies of the model were checked by random excitation. For the minaret, the dominant frequency was 4.7 Hz, while for the mosque, two frequencies were dominating: $f = 7.4$ Hz and $f = 9.6$ Hz.

During this phase of seismic testing, 11 tests were performed with an input acceleration of 0.2–1.5 g. The accelerogram of the Petrovac earthquake, N-S component was scaled by 6 as in the phase 1 testing.

The first cracks on the minaret were observed under an input intensity of 0.34 g, while on the mosque, the initial cracks appeared at 0.42 g input intensity. During the next tests, cracks developed and, at 0.49 g input acceleration, the upper part of the minaret totally collapsed (Fig. 4b).