REPAIR AND SEISMIC STRENGTHENING OF HISTORIC BUILDINGS AND MONUMENTS

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SUMMARY

This paper presents some methods and techniques for repair and strengthening of historic buildings in urban areas and historic monuments in seismically active regions on the basis of a detailed study and assessment of seismic hazard, local soil conditions, definition of seismic parameters and criteria. The results from the performed experimental investigations as well as the applied method of seismic strengthening and repair are presented separately for historical masonry buildings and historical monuments. Particular attention is paid to different approaches to achieving successful protection of historical buildings on one hand and monuments on the other, i.e., preserving the "cultural value" of historical urban areas or of particular monuments.

INTRODUCTION

The problem of seismic strengthening and repair of historic structures is radically different from that of other structures, due to the priority given to preservation of esthetic, architectonic and historic values instead of keeping the structure operational. The specific character of seismic protection of historical buildings and monuments resulting from the variety of structural systems, built-in materials, periods and techniques of construction, stability criteria and contemporary requirements incorporated in the modern principles of conservation and protection needs systematical and scientific approach to achieving a successful

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solution. Although there is a similarity between historical buildings and historical monuments, there also exist differences, for which each of these groups should be considered separately, as emphasized in the latest Eurocodes [1].

Historical buildings usually present shear wall masonry structures that are basically non-ductile and insufficiently resistant to seismic effects. The problem of interaction between the "old" and the "new" materials and/or elements that arises in their strengthening requires experimental verification of all techniques that have so far been developed, (injection, grouting, jacketing, confining, base isolation).

Since historic monuments are also masonry structures, same basic principles and requirements hold for them also, but are specific. The characteristic structural entity, the variability of the built-in materials, the complex history of successful modifications done in the past, as well as the degree of deterioration, makes each historic monument a case for itself. Therefore the basic principle of minimal intervention – maximal protection and/or preservation of the monument's identity should be adopted.

CRITERION, STRATEGY, ETHICAL AND PHILOSOPHICAL ISSUE OF SEISMIC PROTECTION OF MONUMENTS AND HISTORIC BUILDINGS

From the aspect of conservation and restoration of monuments, Historic Buildings and Sites - Venice Charter could be considered a basic document and a beginning of a systematic approach to general protection of historic monuments (Venice Charter - ICCOMOS - International Charter for the Conservation and Restoration of Monuments and Sites" (ICCOMOS 1966 - I). The seismic protection of monuments, historic buildings and sites with all their structural and specific characteristics has intensively been developed throughout the last 15 - 20 years within the frameworks of the scientific discipline of earthquake engineering - typically multi-disciplinary including other related scientific spheres and activities. It is important to mention some particular conferences, scientific meetings, projects etc. that have played a crucial role in the establishment of an individual branch within the frames of earthquake engineering and conservation of monuments.

Analyzing the development of this field with the intention of presenting the state-of-the-art", it can rightfully be pointed out to the great progress made which is not only due to the general progress of scientific knowledge but also the greater cooperation among experts of different professions (engineers, architects, archaeo-logists, art historians, conservators, etc.). Prior to reviewing the achievements made and practice, it is necessary to state some definitions (officially adopted or to be officially adopted) which are in use:

- A monument is a structure having an important "cultural value" so high that it is necessary to guarantee its preservation, generally with its architectural and typological characters;
- A historical building is a building of an urban area which has a "cultural value" as a whole, while a single building is not a monument. This means that preservation concerns the general character of the construction techniques typical in the whole area.
- The sites of monuments must be an object of special care in order to safeguard their integrity and ensure that they are cleared and presented in a seemly manner. The work of conservation and restoration carried out in such places should be inspired by the general principles of conservation.
- The concept of a historic monument embraces not only the single architectural work but also the urban or rural setting in which is found the evidence of a particular civilization, a significant development or a historic event. This applies not only to great works of art but also to more modest works of the past which have acquired cultural significance with the passing of time.
- The conservation and restoration of monuments must have recourse to all the sciences and techniques which can contribute to the study and safeguarding the architectural heritage.

ANALYSIS OF STRUCTURES AND MODELING OF THEIR DYNAMIC RESPONSE

The review of available literature (Page '78, Clough, Mayes, Gulkan '79, Arya '80, Benedeti & Castoldi '82, Tassios '84, Tomazevic '87, Mengi '89, Gavrilovic '88, '89, Tomazevic '90, etc.) provides an insight into a large number of analytical methods for analysis of masonry structures under the effect of different kinds of loads, however their application is limited to concrete specific problems. These analytical methods can roughly be classified into phenomenological methods on one hand (these methods describe and are based on the different characteristics of constitutive materials, linear or nonlinear behaviour of structural elements, elastic or inelastic response of structures, etc) and methods that are different according to the scope and the complexity involved in computations in respect to types of external effects. In his state-of-the-art report entitled "Design, Construction and Research in Masonry: Current Status in Selected Regions of the World" Dr. Noland ('88) reviews applied materials, recent investigations and methods of design in several countries, based on the questionnaires sent by certain investigators from Australia, Canada, China, Denmark, Ireland, Japan, Mexico, Hungary, Norway, Peru, USA, Germany and Yugoslavia as well as available literature and personal experience. The author concludes that various methods for repair and strengthening of masonry structures as well as different methods for their design (ranging from usage of empirical formulae through linear elasticity

/allowable stresses up to ultimate states) have been used, whereas recent investigations in most of the countries most frequently refer to improvement of the methods of strengthening and calibration of existing regulations.

The behaviour of historical building structures under an earthquake is much more realistically evaluated by dynamic analysis, which apart from the other parameters, takes into account the material nonlinearity and its effect upon modification of the dynamic characteristics of the analyzed structure. The experimentally defined values of mechanical characteristics of masonry are applied as input parameters, whereas the redistribution of seismic forces from one wall to another is done considering that the walls as a whole (not their critical cross-sections) behave as ductile structural elements.

From the aspect of mathematical modeling of structural elements and systems, as mentioned before, there are numerous methods ranging from macroscopic (method of concentrated masses or storey mechanism) to microscopic methods (consideration of masonry and mortar layers as separate finite elements), i.e., modeling of the behaviour of a storey within a structure (Clough, Mayes, Gulkan '79, Arya '80, Benedeti & Castoldi '82, Tomazevic 87) or a particular element (Page '78, Tassios '84, Mengi '89) with a different level of sophistication of the applied hysteric model.

However, modern finite element methods are often less accurate than simple mathematical models and, although the time and economic aspects allow these methods, efforts should be made in analysis of historic buildings (taking into account all the partialities) to develop a corresponding simplified model, that, paradoxically, shall require more skill in presenting the analyzed structure than that required by the finite element method (Gulkan '93). In any case, the analysis of the response of each historical building should be considered as an individual case due to the large diversity in design, construction, incorporated materials, state of damage and deterioration, soil conditions and expected seismic effects.

REPAIR AND STRENGTHENING OF HISTORIC STRUCTURES

Repair and strengthening of masonry structures as are the structures of historic buildings and historic monuments is an exceptionally large field of work elaborated in numerous books, publications and individual reports. However from the aspect of conservation and restoration of historic monuments, historic buildings and sites - Venice Charter, [2] could be considered a basic document and a beginning of a systematic approach to general protection of these structures. The seismic protection of monuments, historic buildings and sites with all their structural and specific characteristics has intensively been developed throughout the last 15 - 20 years within the frameworks of the scientific discipline of earthquake engineering - typically multi-disciplinary, including other related scientific spheres.

Repair and strengthening as part of modern protection of structures of historic monuments located in seismically active regions should be planned based on a detailed study of the expected seismic hazard, the local soil conditions, the dynamic characteristics of the structure, the strength and deformability of structural elements and built-in materials, as well as on the dynamic response of the structures under expected seismic motions, Gavrilovic [3]. Repair and strengthening should enable an economically justified and technically consistent seismic protection through providing of the necessary bearing capacity and deformability for an acceptable level of damage in case of future earthquakes.

- Materials for Repair and Strengthening

The key for selecting materials and techniques is classification of repair and strengthening techniques into two main categories: reversible and irreversible. In selecting materials to be used in reversible interventions, there are usually only a few limitations. However, the materials used in irreversible interventions as are for example the unavoidable injection of cracks, do impose two additional limitations: compatibility of new with old materials and their durability. The best way of assuring compatibility and durability is usage of traditional materials, (stone, bricks, lime mortar and cement), which on the other hand, is not always possible. In selecting injection mixtures, advice should be asked from experts as to preventing separation of the old and new parts. Modern cement mixtures should carefully be applied particularly in the process of jacketing because of the irreversible modification of the surface of existing masonry. Steel, either in the form of externally applied ties or in the form of reinforcement incorporated into the existing masonry is a very frequently applied material in the strengthening processes of both historic buildings and monuments.

- Repair and Strengthening Methods

To define an adequate concept of repair and strengthening, it is necessary to carry out a detail analysis of the existing structure of the historical building or monument, the type and the physical-mechanical characteristics of masonry., dynamic properties of structure, criteria and expected seismic action, [3, 4]. If this analysis proves that the structure has a sufficient bearing and deformability capacity, taking of measures for its *repair* shall be sufficient enough. In case the analysis proves that the bearing and deformability characteristics of the structural elements are not sufficient enough, depending on the vulnerability level, the *strengthening* should be done to increase the strength of the existing structure and its deformability. In local and/or global strengthening of structures of historic structures, numerous methods and techniques are used. These are presented in the subsequent text.

The main problem imposed in masonry structures (taking into account the low tensile and shear bearing capacity of masonry and the massive cross-sections of the elements) is to provide structural integrity at story level which is due to two reasons: enabling of distribution of seismic forces according to the stiffness of individual elements and avoiding of individual vibration of the elements after the occurrence of the first cracks. The most commonly used procedure to achieve structural integrity and joint behaviour of structural elements is to incorporate *horizontal steel ties* into the existing masonry (at the top of the existing walls in order to be made invisible - churches and mosques), incorporate *reinforced concrete belt courses or reinforced concrete slabs* into structures where possible - structures in old towns, [4, 5, 6].

To improve the bearing characteristics of the walls and the columns as structural elements sustaining horizontal seismic forces, several techniques are used: *injection of masonry, injection with jacketing, incorporation of vertical reinforced concrete columns, or even incorporation of new reinforced concrete walls* (in the structures of the old towns). The injection technique, the material to be used, i.e., the pressure under which the prepared mixture will be injected are selected depending on the size (up to 10 mm), the position and the shape of the cracks. To increase the bearing and deformability capacity of the walls, jacketing of the walls with concrete on both their surfaces, i.e., incorporation of reinforced concrete belt courses is anticipated. However, irreversibly covering of the existing masonry reduces jacketing usage to internal walls or walls which are not of a particular importance for the historical building, mainly in strengthening of structures in old towns. Vertical reinforced concrete belt courses are used to increase the ductility of the considered element, [4, 5, 6] .

Strengthening of the structural elements taken separately or of the whole structure increases its ultimate bearing capacity wherefore it is necessary to control the bearing capacity of the foundation and the soil. The techniques of strengthening of the foundation structure mainly consist of *extending the proportions* of the foundation and their connection to the vertical elements, *modifying the foundation structure and consolidating and improving of the characteristics of soil conditions*.

Seismic isolation is a new approach to earthquake-resistant design that is becoming widely accepted in earthquake-prone regions of the world. To date, this technology has been applied mostly to new buildings. The advantage of this method in strengthening of historical buildings consists in minimal interventions on the existing structure and protection of the architectonic integrity. Because of the many advantages and the accelerated technology of development of different types of seismic isolators, the number of historic monuments strengthened in this way is expected to increase.

Further in this paper will be presented some of the most characteristic case studies of applying different methodologies for repair and/or strengthening of historic buildings and monuments, that have so far been carried out in IZIIS.

REPAIR AND STRENGTHENING OF HISTORIC BUILDINGS

Old Towns along Mediterranean Coast

The old towns along Mediterranean coast (Budva, Kotor, Dubrovnik, etc.) were severely damaged due to the April 1979 Montenegro earthquake. In the process of renovation of earthquake affected old towns, extensive studies were performed along with the experimental and analytical investigations. Considering the cultural value of most of the buildings in the old town of Budva, which are typically stone masonry structures with one or several stories, investigations for the purpose of searching for the optimum conditions and methods for reconstruction, repair and strengthening of structures were performed, [7].

Firstly, the buildings were classified into structural units and then the methodology for structural repair and strengthening was determined on the basis of detailed studies of structural characteristics, the damage level, the built-in materials, the foundation conditions as well as local seismicity. The anticipated concept for repair and strengthening of sacral structures consists of rebuilding of the demolished and heavily damaged parts, introducing of horizontal and vertical ties, injection of emulsion based on cement and lime, and strengthening of foundation. For residential and other buildings the following is anticipated: inserting of RC floor, belt courses, strengthening the lower stories by RC jackets, injection of walls using cement emulsion and strengthening of foundations. In order to evaluate the main characteristics of stone masonry, which was necessary during the design and construction, in-situ tests on wall fragment, both for the original and injected wall, were performed and increase of bearing and deformability capacity were confirmed.

Considering the fact that injection was the most frequently applied method, a 1:2 scaled model of a typical single story building was constructed of the same original stones and mortar and tested on the seismic shaking table in IZIIS applying the 1979 Petrovac earthquake. After testing and occurring of diagonal cracks, the model was repaired by injection and tested again, in which case the failure mechanism was not modified, but the model suffered less damage, Figure 1. After these experimental and analytical investigations, rationalization of construction was made and the input data were verified. The whole old town of

Budva was repaired at the same time (structural repair and repair of facades) and the interior of each individual building was repaired separately.

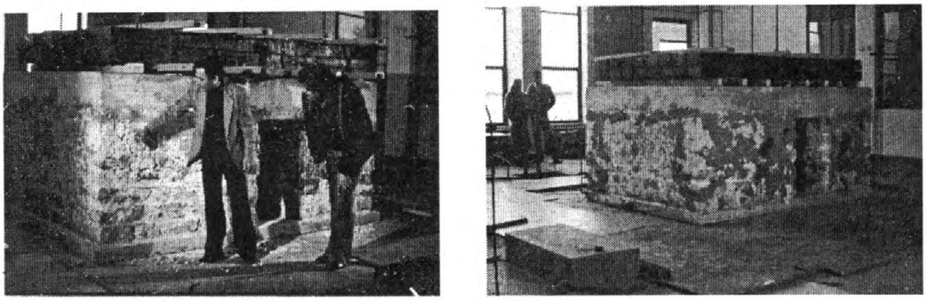
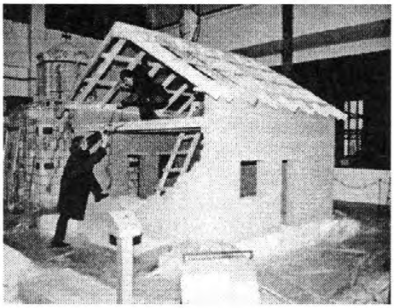


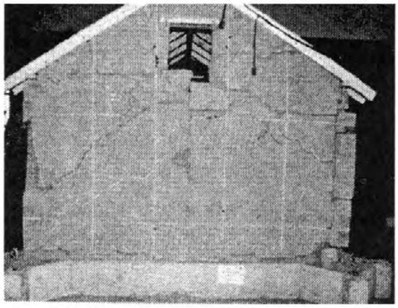
Figure 1. *Original and Repaired Model of a typical building for the old town of Budva*

Historic Adobe Structures in California

Since 1990, the Getty Conservation Institute (GCI) carried out a multi-year, multi-disciplinary project, the Getty Seismic Adobe Project, (GSAP), including a survey of existing historic adobe buildings in California, performance of dynamic testing of scale model adobe buildings at the Stanford University shaking table, and the preparation of an Engineering Guide for designing seismic retrofit measures for adobe buildings. As an extension of GSAP, tests were conducted on two large-scale models (1:2 scale) on the seismic shaking table in the dynamics laboratory in IZIIS, [8, 9]. The two models were of the same design as the last two 1:5 scale models tested at Stanford University, i.e. *tapanco*-style building, a typical southwestern American design that includes floor and roof systems and highly vulnerable gable end walls. The first model was a control model and the second model was retrofitted with a combination of horizontal and vertical straps, center cores, and partial plywood diaphragms. The first part of the research program included tests of adobe materials and brick/mortar assemblies, as well as dynamic tests on the model buildings.

Retrofitted and unretrofitted tapanco-style models were built to a scale of 1:2 and had walls 3.7 meters long and 3 meters high at the gable end of the building. They were tested under selected intensities of the simulated time history of the Taft earthquake in order to investigate the linear and nonlinear model behaviour and the behaviour in the heavily damaged state. In these tests, the gable end wall of the unretrofitted building collapsed, while in the retrofitted building, the straps and, especially, the center core rods proved very effective in improving stability and preventing collapse, Figure 2. Since an increase in the size of the scale models did not change the test results, gravity does not appear to be a significant factor.





Unretrofitted Adobe Model -UAB   Retrofitted Adobe Model – RAB

Figure 2. *The gable end wall of the UAB and RAB model*

Using a survey of 19 historic adobes in the Los Angeles area that was conducted after the 1994 Northridge earthquake, the behavior of real and model structures was compared. It was found that many of the structures suffered damages similar to those seen in the test of unretrofitted models.

REPAIR AND STRENGTHENING OF HISTORIC MONUMENTS

Strengthening and Repair of Earthquake Damaged Monuments in Pagan – Burma

The Pagan plateau, in the central part of Burma, is a worldwide known place for the high concentration of magnificent historic monuments from the distant past like temples and pagodas. Unfortunately, most of these have severely been damaged by natural disasters, including earthquakes. The earthquake of 8th July 1975, with a magnitude of 6.8 destroyed or heavily damaged many monuments - temples and pagodas. Based on the defined seismic design criteria, a methodology for repair and strengthening of this type of structures has been developed under the Project – UNSECO/UNDP project Burma 78/023, [10].

Two types of historic monuments mainly characterize the Pagan region: temples and pagodas. The structural systems of the temples consist of bearing massive walls combined with massive central pillars, which form corridors or halls. The pagodas are constructed as massive solid stupas with changeable form along the monument height. All the monuments are constructed of solid bricks in mud mortar with or without plastering.

Taking into account the modes of failure, the material properties and the structural systems, the dynamic characteristics and the expected possible earthquakes, the following method of strengthening and repair of Pagan monuments has been proposed:

- Preserving of the structural system integrity at each story level by inserting of steel bracing for small and medium size temples and/or by construction of reinforced concrete belt courses around the structure and at each story as defined by the free height of corridors and halls in the case of medium size temples, Figure 3.
- Strengthening of the upper slender parts of the monuments (shikaras) by inserting of horizontal R/C belt courses and injection, Figure 3.

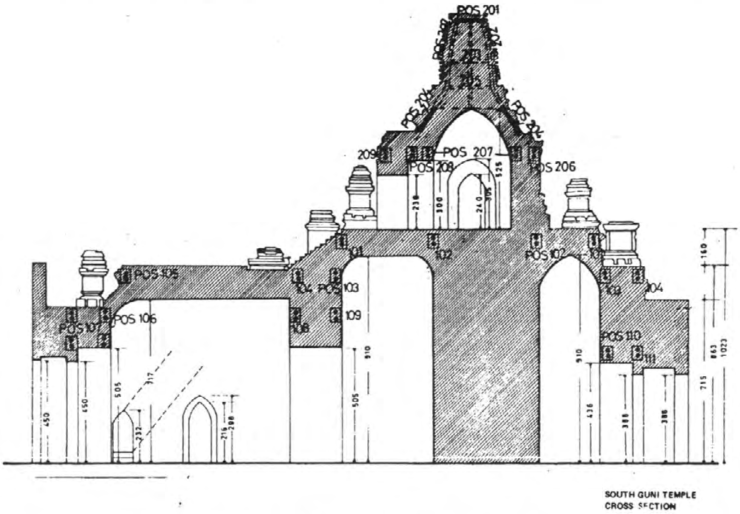


Figure 3. *Strengthening of South Guni Temple*

For the purpose of development of appropriate methodology and techniques for repair and strengthening, two types of filed experimental investigations have been performed:

- Full scale ambient vibration testing on 15 selected monuments for determination of dynamic characteristics including soil media;
- Structural testing of wall 'in situ' for determination of existing and repair (after jacketing) structural properties and definition of bearing capacity before and after strengthening.

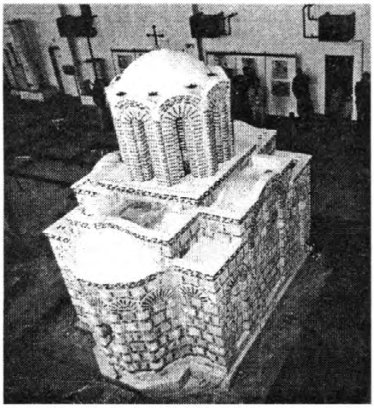
Seismic Strengthening and Repair of Byzantine Churches in Macedonia

Experimental and analytical investigations were performed to verify an original methodology that was developed for the repair and seismic strengthening of Byzantine churches. This work was part of the long-term research project entitled "Study for Seismic Strengthening, Conservation and Restoration of Churches Dating from the Byzantine period (9^{th}-14^{th} century) in the Republic Macedonia realized jointly by the Institute of Earthquake Engineering and Engineering Seismology (IZIIS) - Skopje, the Republic Institute for Protection of

Cultural Monuments (RZZSK) - Skopje and the Getty Conservation Institute (GCI) -Los Angeles, California, [6, 11].

The churches dating from the Byzantine period located in Macedonia are important architectural structures and contain extraordinary collections of highly important frescoes. The walls of these churches are constructed in a typical Byzantine style - a wall with two faces between which there is an infill of lime mortar and pieces of bricks and stone.

A model of St. Nikita church selected as representative church, was constructed to a scale of 1 : 2.75 and tested on a seismic shaking table simulating the existing and the strengthened state, (Figure 4) to investigate the linear behaviour, nonlinear behaviour, and behaviour in the heavily damaged state (close to failure). The applied methodology for repair and strengthening is in compliance with the principle of "minimum interventions - maximum protection" and increases the bearing capacity and deformability of the structure up to the level of the designed protection.



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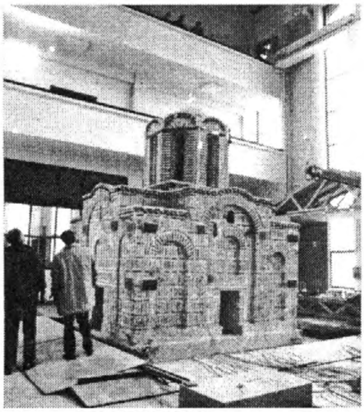

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Figure 4. *Models on shaking table*

To investigate the nonlinear dynamic response of the structure, an original trilinear model of stiffness degradation and pinching of the hysteretic loop was developed on the basis of the experimental results obtained for the original and the strengthened model as well as from the results of the quasi-static testing of wall elements.

Earthquake Protection of Byzantine Churches Using Seismic Isolation

As a continuation of previous activities, experimental and analytical investigations as well as shaking table testing of isolated church model were performed to develop a methodology for application of seismic isolation as a way of seismic protection of a large number of similar cultural monuments. These investigations were realized at the Institute of Earthquake Engineering and Engineering Seismology (IZIIS) within the framework of the joint US-Macedonia research project and PHARE Cultural development program. [12].

To experimentally verify the methodologies for seismic isolation of Byzantine churches, a base isolated model of the church of St. Nikita was tested on the seismic shaking table in the Dynamic Testing Laboratory of IZIIS. For the needs of testing the isolated church model, 8 seismic isolators of the type of rubber bearings were specially designed and produced in the Republic of Macedonia, (Figure 5).

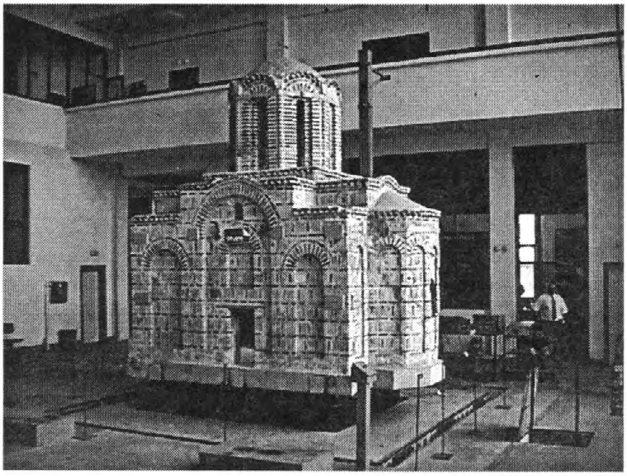


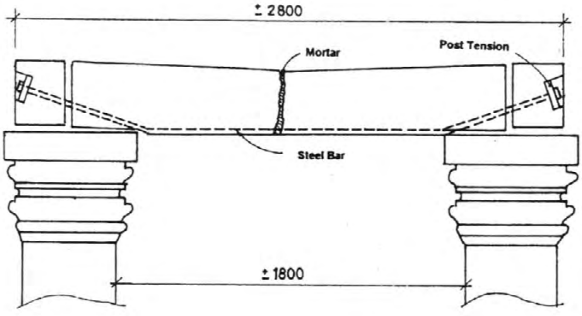
Figure 5. *Base isolated church model on shaking table*

The results from the tests, especially compared with the results from the previously tested strengthened model by use of "ties and injection", pointed to a decrease of input acceleration in the model structure for 50-60%. The base isolated model did not suffer damage under low and moderate earthquake intensities and the damages under maximum expected accelerations with a return period of 1000 years were minimal and absolutely allowable and repairable. Finally, to conceive the efficiency of the applied seismic isolation system, the model was tested under earthquake intensity greater than the expected one. Under this intensity, the monument was evidently stable and safe, with the exception of some minor damage.

The main result of the project is demonstration of the efficiency, as well as technical, economical and conservatory justification of the applied technique of base-isolation on the structure of the church model. The tests undoubtedly proved that the new technology of seismic base isolation of historic monuments offers absolute safety and protection and that its application should become an imperative in earthquake protection of historic monuments in future.

Structural Consolidation and Conservation of the Monuments at Preah Khan - Historic City of Angkor – Cambodia

Amidst the lush tropical jungle in northwest Cambodia near the great lake called the Tonle Sap lies Angkor, the ruins of a grand civilization that flourished between the 9th and 15th centuries A.D. Today it represents a ruined structure - reminiscent of the devastation caused by ground motion, although the actual reasons for damages have been the tropical vegetation, harsh climatic conditions and other factors. Within the frameworks of the project "Preah Khan Conservation Project - Historic City of Angkor Seam Reap, Cambodia" undertaken by the World Monuments Fund, [13], a methodology for structural stabilization and architectural conservation was developed through careful analysis of the style, structural systems, construction methods and conditions of the complex. Methods for permanent and temporary protection have been developed for all the structural components of the Preah Khan complex and the historic city of Angkor including: beams, columns, vaults, roof structures, towers, enclosure walls, and objects of artistic value such as lanterns, frontons and gorudas. Being in full compliance with modern principles and applications in architectural conservation practice, the achieved results satisfy the previously set goal of "minimum intervention for maximum protection" including invisible interventions, reversibility and preservation of original structural systems and architectural components.



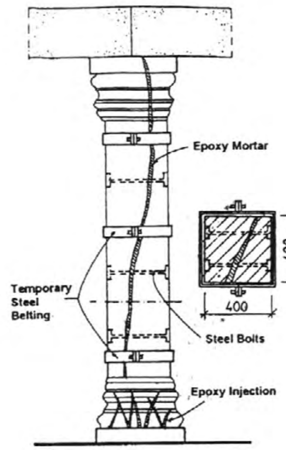


Figure 6. *Repair and strengthening of bearing beam* *Figure 7. Strengthening of columns*

The Preah Khan complex is constructed of two basic materials: sandstone and laterite. The buildings of Preah Khan are constructed of dry masonry in large stone blocks that form structural components. Based on an analysis of the various types of beam and column failure, the most suitable methods of structural intervention are proposed using stainless steel and epoxy mortar or/and epoxy resin. A very simple and effective method for repairing failures due to bending moments was developed, Figure 6. A combination of different methods of repair, strengthening and consolidation is recommended for splitting columns depending on the degree of damage and whether a temporary or a permanent solution is sought. For consolidation and strengthening, steel belting is presented on Fig. 7.

The use of a multidisciplinary approach which recognizes a carefully developed set of conservation priorities for a given site has proven to be the best procedure to follow at complicated architectural and archaeological conservation projects such as those found at Angkor.

CONCLUSIONS

Repair and seismic strengthening of historic buildings and especially the historic monuments is a task requiring a multi-disciplinary approach in solution. The invaluable value of these monuments and the duty to preserve them for the future generation require their permanent protection against possible destructive effects of future earthquakes but preservation of their authenticity at the same time. In fulfilling this task, one must get a detail insight into the problems related to a certain structure and the causes of these problems as well as the effect of future interventions and the application of techniques, in the sense of their reversibility. Also, particular attention should be paid to selection of materials and knowledge of their durability and chemical compatibility with the existing masonry.

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