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SEISMIC RETROFITTING OF STRUCTURES, HISTORIC BUILDINGS AND MONUMENTS - IZIIS’ APPROACH

The impact of present building code requirements for seismic design in new buildings can readily be acknowledged, however applying regulation to existing buildings is an area less well defined. Presently, there is a diverse list of existing code references which could be interpreted to require seismic upgrades of existing structures. Unfortunately, these references do not provide a clear path toward addressing the hazards, evaluation and retrofitting of existing buildings. And when it comes to existing historic buildings and monuments, the topic becomes much more complex and challenging.

The problem of earthquake protection of historic buildings and monuments is radically different from that of other existing structures, due to the priority given to preservation of aesthetic, architectonic and historic values instead of keeping the structure operational. In providing the protection of these structures in a manner that requires the least intervention and the greatest care to preserve authenticity, the experts are permanently challenged by the fast development and the improved performance of new materials and techniques. However, the implementation of retrofitting methodology depends on the extent it has been investigated.

Within the frames of IZIIS ’research activities, in addition to seismic design of modern structures, particularly noteworthy is also the experience gathered in the field of protection of cultural historic structures. Important scientific research projects, involving analytical and unique experimental investigation and extensive research activities resulted on developing of a procedure for seismic retrofitting of valuable historic monuments. This paper present the integrated multidisciplinary approach to seismic protection of structures pertaining to cultural heritage that has been developed by the Institute and implemented in the process of seismic upgrading or reconstruction of important historic buildings and monuments in the country and beyond.

Keywords: seismic retrofitting, historic buildings, monuments, multidisciplinary approach

1. INTRODUCTION

1.1 HISTOIC BACKGROUND

Protection from earthquakes begins with the appearance of early, now missing, civilization although in these periods of human society development the phenomenon of earthquakes has been considered as God's will or the product of mystical powers. During the 19th and early 20th centuries, interest in earthquakes and their effects increased in Japan, Italy and United States. This was mainly because of major earthquakes such was: in Japan, the 1855 Edo and 1923 Kanto earthquakes, in United States, the 1906 San Francisco and 1925 Santa Barbara and in Italy, the 1908 Messina earthquake. This growing interest results with the establishment of important institutions: the Structural Engineers Association following by Earthquake Engineering Research Institute (EERI) in California, the Earthquake Research Institute within Tokyo Imperial College, as well as Special Committee for investigation of the Messina earthquake in Italy, which report was evaluated as the birth of practical earthquake design of structures since it contains engineering recommendation for earthquake resistant structures by means of equivalent static method, which was gradually used in earthquake countries around the world and was later adopted for building codes too, [1].

However, the beginning of the modern approach to earthquake protection can be considered the First World conference on earthquake engineering, (1st WCEE, Fig.1) held in 1956 to commemorate the 50 anniversary of the San Francisco earthquake, since it was the first proceedings on earthquake engineering. The formation of the International Association for Earthquake Engineering, (IAEE) in 1960 during the Second World Conference in 1960 held in Japan, was a very important for earthquake engineering development especially for the countries that did not have their own national association. Since then World Conferences, (WCEE) held every four years have successfully brought together many researchers, practitioners and public officials and contributed significantly to the process of earthquake knowledge. While the *repair and strengthening* appears as a topic for the first time in 1976 during 6th WCEE, the theme of the next 17WCEE which will be held in Sendai, Japan is "*toward resilient society*" aiming to contribute to the goal of earthquake engineering - to control the seismic risk at socio-economically acceptable levels.

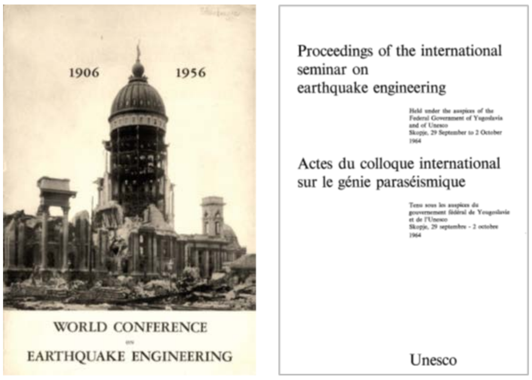


Fig. 1. Proceeding of the 1st WCEE and 1st ECEE

Similarly, the key event for the beginning of earthquake engineering in Europe was the Skopje 1963 earthquake, the most destructive earthquake in the history of ex-Yugoslavia, causing losses of about 15% of the gross national product for the year 1963. This earthquake was unique among the catastrophic earthquakes in Europe and the Mediterranean region, since it triggered a high level of awareness and activity by the government, population, scientists and engineers to the need for organized and sustained efforts to be implemented in earthquake disaster management. Dominated by the activity and financial support by UNESCO and its agencies, seismic zoning map and a network of seismological stations of Yugoslavia have been developed, the Institute of seismology, earthquake engineering and urban planning, (later Institute of earthquake engineering and engineering seismology, IZIIS) has been created in Skopje, code for seismic design and standardization of construction materials and improvement in the quality of construction have been elaborated and it was among the first aseismic codes in Europe.

Following the earthquake in Skopje the members of the UN Consultative Board for the Reconstruction of the City of Skopje signed an agreement, sponsored by UNESCO, for the establishment of a European Commission for Earthquake Engineering, (later European Association for Earthquake Engineering, EAEE). The first symposium was held in Skopje on 1st October 1964, and it was followed by regular conferences (ECEEs) every four years.

The traces of growth, advances and developments of earthquake engineering can be followed by following the milestones of both WCEEs and ECEEs. During these conferences great lessons have been, and will be, learned about the nature of earthquakes, characteristics of ground motion, performance of geotechnical, structural, non-structural and lifeline systems during earthquakes, and their social and economic aspects, increasingly emphasizing the need for multidisciplinary approach.

Majority of these developments have reached the modern building seismic codes and their impact in new buildings can readily be acknowledged. However, applying regulation to existing buildings is an area less well defined. Presently, there is a diverse list of existing code references which could be interpreted to require seismic upgrades of existing structures. Unfortunately, these references do not provide a clear path toward addressing the hazards, evaluation and retrofitting of existing buildings

1.2 SEISMIC UPGRADING OF EXISTING BUILDINGS

The older existing buildings that were constructed with low or no seismic consideration represent the largest risk to most communities. In general, the needs for their structural strengthening are in case of: errors in designing or construction, load increases, damage to structural parts, modification of structural system, improvements in suitability for use or upgrading of standards or national technical provisions. However, the *seismic retrofitting* of existing earthquake damaged or earthquake-vulnerable buildings is needed when the existing structures should be made more resistant to seismic activity, ground motion or soil failure due to earthquakes and it necessarily means modification of existing structural system. The main problems the structural engineers are faced are the lack of standards for risk assessment, evaluation and retrofitting methods as well as the variability of the effectiveness of each retrofitting method depending on type and importance of structures, type and condition of built-in materials and their conditions, amount of damage etc.

Extremely important role in overcoming these problems in the Balkans had UNESCO and UNDP, primarily through actions and financial support for IZIIS' development (1965-1982), and especially for implementation of several subsequent projects (1968 – 1985) on the seismicity, earthquake risk reduction and seismic resistant building construction in the Balkan region. This was for sure initiated by the several deadly earthquakes in the region in that period: in Yugoslavia, 1963 Skopje, 1967 Debar, 1969 Banja Luka and 1979 Montenegro; in Romania, 1977 Bucharest; in Greece, 1978 Thessaloniki earthquake. The final regional project "*Building Construction under Seismic Conditions in the Balkan Region*" UNDP/UNIDO REP/79/015 has been carried out with the participation of the Governments of Bulgaria, Greece, Hungary, Romania, Turkey and Yugoslavia and with UNIDO acting as executing agency for the UNDP. A set of seven Manuals has been produced within this project, reflecting to considerable extent the experience of the participating nations in earthquake resistant design and construction, [2].

1.3 METHODOLOGY FOR STRUCTURAL REPAIR AND STRENGTHENING IN BALKAN REGION

The fifth project volume *"Repair and Strengthening of Reinforced Concrete, Stone and Brick-Masonry Buildings*", [2], prepared by the *working* group E convened by Prof. Gavrilovic from IZIIS, was aimed to give qualitative instructions for the step by step repair and strengthening procedure, drawn on the experience gained following recent earthquakes. Without going in details, what follows are the main steps of this post-earthquake repair and strengthening procedure, agreed and adopted by all the Balkan countries:

- *Emergency damage evaluation,* which should be done for each structure by official inspection teams to quickly determine the general level of damage and level of safety for continued occupancy (presented in detail in fourth Manuel, (fig. 2).

Fig. 2. Volumes 4 and 5, UNDP/REP/79/015

- *Preliminary investigation*, as an independent and more thorough evaluation which should be performed by a design engineer. The first phase of this preliminary investigation is to determine in detail the nature, cause and extent of damage and consequently the need for emergency, temporary bracing or shoring. Further phases of investigation involve detailed inspection of the damage so repair and strengthening procedures can be designed and detailed.

- *Definition of seismic parameters* for the region as a prerequisite for successful accomplishment of repair and strengthening of damaged structures. This study should include the expected maximum acceleration of bedrock for different return periods, the amplification factors of soil deposits and to propose adequate time histories and average spectra for design of structures to be strengthened. For important structure or group of typical structures it is necessary to determine the seismic parameters for considered sites and to perform field, soil investigation and geophysical studies to be used as input design parameters.

- *Definition of criteria for repair and strengthening*, as correlation of the seismic force design parameters with the structural characteristic in terms of its strength, deformability, ductility etc. Each country should establish its own criteria based on specific condition related to its seismicity. In our country they are as they were set for ex-Yugoslavia, as follows:

  o *Design Level I:* for slight and moderate earthquakes with return period of 50-100 years, the structure is assumed to perform in linear range up to the yield point, with maximum relative story displacement of h/600 and required displacement ductility $D \leq 1$.

  o *Design Level II:* for more severe earthquakes with return period of 200-500 years, the structure could suffer nonlinear deformations but without disturbance of its global stability, with maximum relative story displacement of h/150 and required displacement ductility $D \leq 3\text{-}4$ for reinforced concrete, $D \leq 1.5\text{-}2$ for plain and $D \leq 2\text{-}2.5$ for confined masonry.
  The designer must use the criteria established or to use the existing Code for new buildings of the area as the minimum standard for repair and strengthening projects. For selected projects, like special or important structures, or structures form traditional materials, the designer may have to use additional criteria based on circumstances regarding the project.

- *Additional investigations* for completion of the detailed site inspection to develop knowledge of as-built conditions. First, if documents regarding original construction are available, (drawings, specifications, construction details, material strength data, previous repairs or alterations, code under which original design was prepared), the information gathered should be compared with the actual structure, and if there are deviations they should be recorded. If information is not available, the field measurements and observations must be taken to establish the condition of the original structure, usually with removing the finishes or covers to determine the composition of structural elements. Second, each structural member must be inspected, and the damage or lack of damage should be noted and recorded, as repairs will be based on these data. Third, characteristics and strength of original construction materials must also be estimated, which could be accomplished by various methods, taking samples for laboratory testing and/or using in-situ strength evaluation methods.

- *Damage analysis and evaluation* which should be done by the designer by analyzing the damaged structure, thoroughly understanding why the damage occurred, if the structure suffered due to discontinuities in strength or stiffness, due to torsion moments or improper connection or details, etc. The effects of non-structural elements on the structural performance must be considered. Calculation and analysis must be performed in order to evaluate the existing strength and stiffness capacity of damage structure, following by the decision of the need for its strengthening. If the repaired structure only meets the design criteria, then strengthening will generally not be required. The strengthening will generally be appropriate in addition to repairs of damage if the repaired strength is less than the required one.

- *Selection of a repair and strengthening* based on feasibility evaluation of alternative solutions for repair and strengthening, defined as follows:

  o *Repair* is the reestablishment of the initial strength of damaged structural members and reestablishment of the function of damaged nonstructural elements. Properly repaired structural members will possess approximately the same strength as before they were damaged but will probably have a somewhat reduced stiffness due to very fine cracks which are impossible to restore.

o *Strengthening* is a judicious modification of the strength, stiffness and/or deformability of structural members or the structural system to improve the structure's performance in future earthquakes. It generally includes increasing the strength or ductility of individual elements or introducing new structural elements to increase the structure' lateral force resistance. On occasion, strengthening can also involve making selected structural members weaker to improve the interaction of the members and prevent premature failure of a week adjacent member. Anyhow, strengthening should bridge the gap between the required and existing strength, stiffness and deformability. While repair usually follows the damaging earthquake, strengthening can be done either prior to or following an earthquake.

A complete listing of all strengthening techniques is beyond the scope of this paper. It becomes a treatise on structural engineering because all materials and systems used in new construction can also be used in retrofit. The selection of the specific type of element is dependent on local cost, availability, and suitability for the structure in question. Calculation for each alternative solution must be performed in enough detail to ensure that the criteria will be satisfied, to evaluate the effects and to provide a reasonable basis for comparison with other proposed schemes. For the selected solution complete analysis must be performed with the appropriate mathematical model and according to the design criteria, with studies for determine the dynamic response of structural system for defined seismic parameters

- *Final design procedures* which include a completion of the detailed calculations of the strengthening solution including dynamic time history analysis for the defined seismic parameters, then preparation of drawings, specifications, detailed procedures and instructions so the work can be accomplished successfully. Regardless of the level of investigation done in the evaluation or design phases, unexpected conditions will be discovered during construction of strengthening. Therefore, it is important that the design engineer is available during the construction phase to provide consistent and acceptable adjustment of details. In certain cases, discovery during construction can be used as a strategy to confirm unknown or vague conditions while minimizing disruption from pre-construction investigation.

Further reading of this manual on *"Repair and Strengthening of Reinforced Concrete, Stone and Brick-Masonry Buildings"* gives complete information about the materials and construction techniques for repair and strengthening, separately for reinforced concrete, stone and brick-masonry buildings, emphasizing that each structure is a unique system and its damage in an earthquake will be different from other structures, requiring custom repair and strengthening solutions and details. The decision of the rehabilitation method and the appropriate construction technique depends on many factors, such as local soil conditions, type and age of structures, type and degree of damage, available time, equipment and staff, architectural requirements, cost and, last bet not the least, the required level of seismic safety.

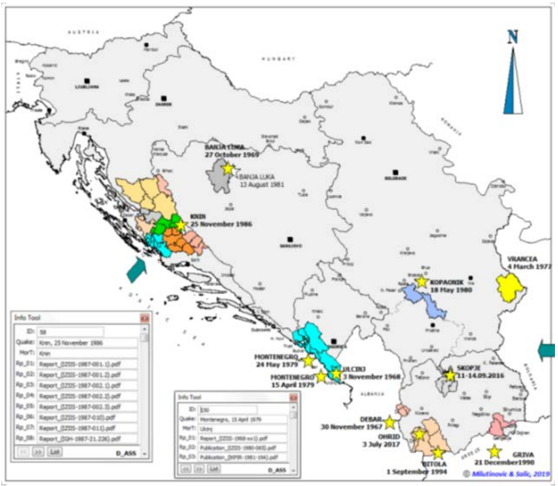


Fig. 3. Damage evaluation, strength assessment and strengthening of buildings after occurrence of major earthquakes in ex-Yugoslavia, [3]

To date, this manual has been regarded in the region as unmatched in defining the necessary steps of strengthening procedure. In keeping with the philosophy of this procedure, IZIIS has implemented a seismic strengthening of a great number of structures, different in their function, main bearing system and built-in materials, prior- or post-earthquake repair and strengthening, (fig. 3). For all of them step by step process of presented strengthening procedure has been thoroughly followed.

2. SEISMIC RETROFITTING OF HISTORIC BUILDING AND MONUMENTS

The problem of seismic retrofitting 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 solution, [4]. 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:

• *A monument* is a structure having an important "cultural value" so high that it is necessary to guarantee its preservation, generally with its architectural, typological and material characters;

• *A historical building* is a building of an urban area, which has a "cultural value" as a whole (historical urban area), while a single building is not a monument, meaning that preservation concerns the general character of construction techniques typical in the whole area.

Historic 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 the techniques that have so far been developed, (injection, grouting, jacketing, confining, base isolation). Since 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 minimum intervention – maximum protection and/or preservation of the monument's identity should be adopted.

Retrofitting of masonry structures is elaborated in numerous books, publications and individual reports. However, from the aspect of conservation and restoration of monuments, historic buildings and sites- 1964 ICCOMOS' Venice Charter could be considered a basic document and a beginning of a systematic approach to general protection of these structures. Since then, the seismic protection of monuments, historic buildings and sites with all their structural and specific characteristics has intensively been developed throughout the last several decades within the frameworks of the scientific discipline of earthquake engineering - typically multi-disciplinary, including other related scientific spheres.

Materials for Retrofitting: The key for selecting materials and techniques is classification of retrofitting 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, (as externally applied ties or as reinforcement incorporated into the existing masonry is a very frequently applied material in the strengthening processes of both historic buildings and monuments, [4].

Retrofitting Methods: The main problem imposed in masonry structures is to provide structural integrity at story level because of 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 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.

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, position and 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. Vertical reinforced concrete belt courses are used to increase the ductility of the considered element. 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, [4].

3. INTEGRATED APPROACH FOR SEISMIC RETORFITTING OF HISTORIC BUILDINGS AND MONUMENTS DEVELPED BY IZIIS

In providing the protection of these structures in a manner that requires the least intervention and the greatest care to preserve authenticity, the experts are permanently challenged by the fast development and the improved performance of new materials and techniques. However, the implementation of particular retrofitting methodology depends on the extent it has been investigated. The delicate problem of proving the effectiveness of the selected consolidation system can be successfully overcome by using the methodology of design assisted by testing.

Within the frames of the IZIIS' research activities, in addition to seismic design of modern structures, particularly noteworthy is also the experience gathered in the field of protection of structures pertaining to the cultural historic heritage. During a period of more than forty years of activities in this field, the Institute has realized important scientific research projects involving analytical research, unique experimental shaking table test and field surveys of historic structures.

Applying the knowledge from repair and seismic strengthening of structures presented in previous chapters and deepening the existing methodology, it can be said that an integrated approach to seismic protection of extraordinarily important cultural historic structures has been adopted by the Institute and used in the process of reconstruction or seismic upgrading of important monuments. This approach that complies with the restoration and conservation requirements as well as procedures and legislative for high category structures, should encompass the following:

- Definition of seismic potential of the site through detailed geophysical surveys for definition of geotechnical and geodynamic models of the site to consider the expected earthquake effect through a probabilistic approach, including also the local soil effects through nonlinear dynamic analysis of a representative geotechnical model;
- Determination of structural characteristics and bearing and deformation capacity of existing structure including investigation of the built-in materials, definition of structural dynamic characteristic through ambient vibration method, developing the corresponding mathematical model and determination of dynamic response for defined seismic parameters;
- Definition of criteria and selection of concept for seismic retrofitting respecting the country regulative as well as guidelines in the ICCOMOS and ISHARCH documents;
- Definition of structural methods, techniques, materials in accordance with defined criteria and positive national and international construction and conservation practice;
- Analysis of dynamic response of retrofitted structure and verification of their seismic stability;
- Definition and documentation of field works, and their execution by constant supervision by professionals from different fields.

Although the above stated seems to be the "normal procedure", it is the only way of providing high quality in protection of cultural heritage. This task is certainly much more than simply listing of what is to be done since it requires a lot of knowledge and efforts.

Further in the paper are presented some of the most characteristic case studies of applying different, previously experimentally verified, seismic retrofitting of historic buildings and monuments that have so far been carried out in IZIIS in accordance with the presented integrated methodology.

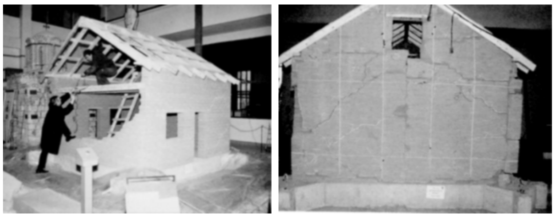
4. SEISMIC RETROFITTING OF HISTORIC BUILDINGS - IZIIS' EXPERIENCE

Old towns along Mediterranean coast: The old towns of Budva, Kotor, Dubrovnik, etc. were severely damaged due to the April 1979 Montenegro earthquake. Considering the cultural value of most of the buildings in the old towns, extensive investigations for the purpose of searching for the optimum conditions and methods for reconstruction, repair and strengthening of structures were performed, thoroughly applying the methodology presented in chapter 1.3. Firstly, the buildings were classified into structural units and then the methodology for structural retrofitting was determined based on detailed studies of structural characteristics, the damage level, the built-in materials, the foundation conditions as well as local seismicity. Since the injection was the most frequently applied method, for its testing and verification, 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 model suffered less damage, (Fig. 4). Using the acquired knowledge on the technique application, the consumption of material and the effect of applied injection, more than three hundred buildings within the old towns along Mediterranean coast have been repaired at the same time, including structural repair, repair of facade walls and the interior of each individual building, [5].

Fig. 4. Repaired Model of a typical building for the old town of Budva, [5]

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, dynamic testing of small scale model buildings (scale 1:10) at the Stanford University, and the preparation of an Engineering Guide for designing seismic retrofit measures. As an extension of GSAP, tests were conducted on two large-scale models (scale 1:2) on the seismic shaking table in IZIIS.

The first model was a control model while second was retrofitted with a combination of horizontal and vertical straps, center cores, and partial plywood diaphragms. The applied retrofitting proved very effective in improving stability and preventing collapse, (Fig. 5). Based on all the results and the GCI' Engineering Guidelines a number of historic adobes structures in south California were seismically upgraded applying this experimentally verified methodology, [6].



Unretrofitted UAB   Retrofitted RAB

Fig. 5. Gable end wall of UAB and RAB model

The Parliament building in Skopje: The Parliament Building of the Republic of North Macedonia was more than 70 years old, (Fig.6). As a historic building, it is protected by the Law on Protection of Cultural Heritage. Throughout its existence, a lot of changes, enlargements, adaptations, damaging during 1963 Skopje earthquake as well as post-earthquake repair and strengthening of this building have been done. Within the project on Enlargement, Building of Another Storey and Adaptation of the Building, the necessity for increasing the seismic safety of main structural system has been defined, [7].

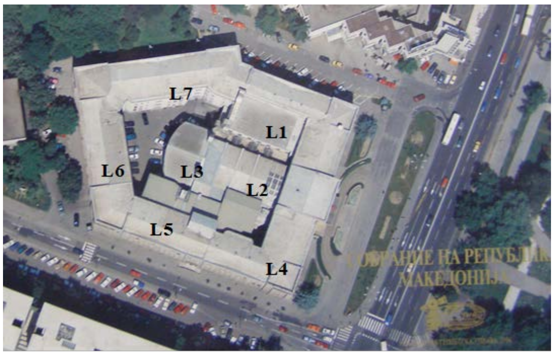
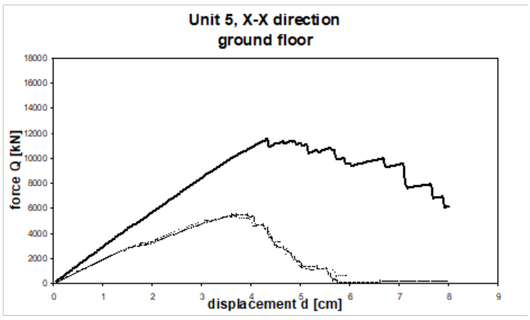


Fig. 6. Individual structural units L1–L7, Parliament building, [7]

Starting with the essential difference between "plain" and "confined" masonry, the most important phase was in-situ technical investigations performed to identify the principal structural system of the pentagonal outline, evaluated as the oldest and most critical part for the planned building of another storey. The analysis of the bearing and deformation capacity of the structure shows that the shear base coefficient for the seven structural units is in the range of 6-18%, much smaller than that required one by the regulations for plain masonry, (30%), while the relative storey displacements do not satisfy the requirements for earthquakes that may occur in this area. Thus, the need for strengthening of the structure becomes even more topical and economically justified.



--- existing state, ▬ strengthened structure

Fig. 7. Comparative Q-d diagrams for unit L5, [7]

The strengthening solution has been defined to improve the integrity and the seismic stability of the structure. Subsequent final analysis of strengthened system has been made up to ultimate states of strength and deformability for each unit taken separately. Comparison for selected unit gives a very clear insight into the effect of the selected strengthening solution, as is shown on Fig. 7, pointing to a considerable increase of both the bearing and deformation capacity of the system. The process of strengthening of the structural system, while continuously functioning of the Parliament, was carried out quite successfully despite a number of limitations in the period 2010-2014.

5. SEISMIC RETROFITTING OF MONUMENTS - IZIIS' EXPERIENCE

Monuments in Pagan - Burma (1978-1980): The Pagan plateau in the central part of Burma, is a worldwide known place for the high concentration of magnificent historic monuments like temples and pagodas. Unfortunately, most of these have severely been damaged by natural disasters, including earthquakes. The 1975 earthquake with a magnitude of 6.8 destroyed or heavily damaged many of them.

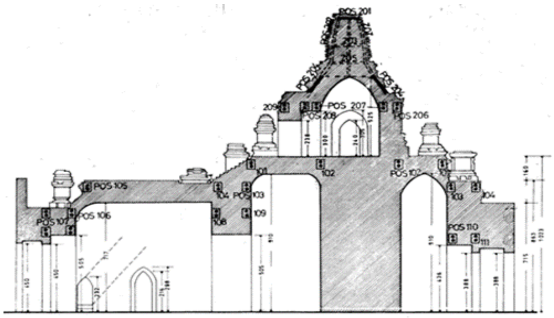


Fig. 8. Strengthening of South Guni Temple, [8]

Based on the defined seismic design criteria, the developed methodology for seismic retrofitting of this type of structures has been applied under the Project – UNSECO/UNDP project Burma 78/023, [8]. Considering the material and structural properties, its dynamic characteristics and the expected possible earthquakes, the method of strengthening and repair has been proposed anticipating injection and inserting of steel bracing or RC belt courses, (Fig. 8). Later fifteen monuments were seismically upgraded according to presented methodology and none of them experienced damage during the recent 6.8 magnitude earthquake in 2016.

Byzantine Churches: Within the long-term research project entitled "Study for Seismic Strengthening, Conservation and Restoration of Churches Dating from the Byzantine period in the Republic Macedonia" realized jointly by IZIIS, Skopje, Macedonian National Conservation Center (NKC) and GCI, Los Angeles, [4, 9], ample experimental and analytical investigations were performed to verify an original methodology for the repair and seismic retrofitting of Byzantine churches. For the first time in the world, shaking table testing of 1:2.75 scaled model of St. Nikita church, simulating the existing and the strengthened state, (Fig. 9), was realized at IZIIS to investigate its behaviour in elastic, nonlinear and heavily damaged state. The tests approved that applied methodology, consisting of horizontal and vertical belt courses, increases the bearing capacity and deformability of the structure up to the level of the designed protection.

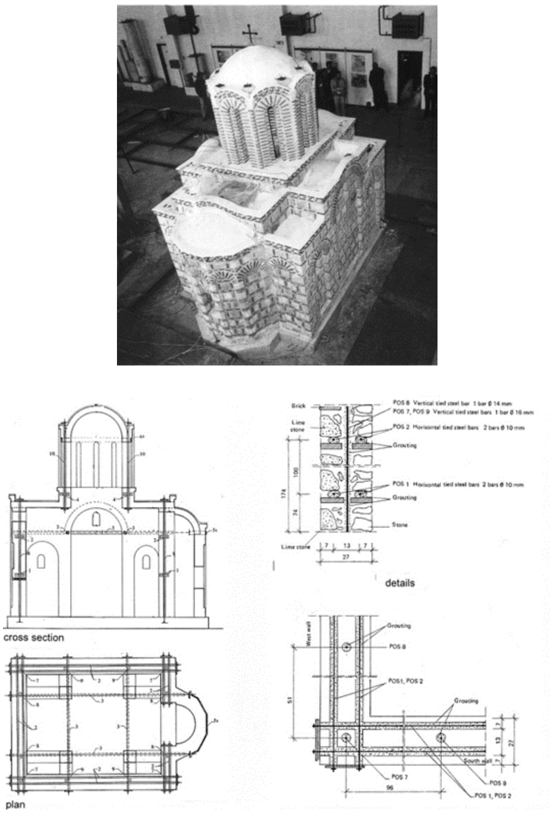


Fig. 9. The 1:2.75 scaled church model and the applied strengthening method, [4, 9]

After the realization of the project on Byzantine churches and gained unique and incomparable knowledge, IZIIS became a partner of the National Conservatory Center, which enabled direct application of the gained knowledge in actual conditions and for specific historic monuments. The most characteristic examples of application of the developed methodology in the process of reconstruction and seismic upgrading of monuments were: (1) reconstruction of blown-up St. Athanasius Church in Leshok, (2) consolidation and reconstruction of the church St. Panteleymon in Ohrid, and (3) reconstruction of the blown-up church of the Holy Trinity in Mostar, [10], (Fig. 10).

St. Athanasius Church in Leshok

St. Panteleymon in Ohrid

The church of the Holy Trinity in Mostar

Fig. 10. Implementation of the developed methodology in the reconstruction of three churches, [10]

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REFERENCES

[1] Bozorgnia Y., Bertero V. (2004). Earthquake Engineering from Engineering Seismology to Performance-Based Engineering, CRC Press, Taylor & Francis Group.

[2] UNDP/UNIDO REP/79/015. (1980). Building Construction under Seismic Conditions in the Balkan Region/Volume 5.

[3] Milutinovic Z. (2019). Overview on Systematic Management of Seismic Risk in SFR Yugoslavia – experience and contribution of IZIIS, SERA Balkan Seismic Workshop, Belgrade.

[4] Shendova V. (1998). Seismic Strengthening and repair of Byzantine Churches in Macedonia. Doctoral dissertation, IZIIS, Skopje.

[5] Gavrilovic P., Stankovic V. (1984). Design for Repair and Strengthening of the Old City of Budva. Doctoral Dissertation, IZIIS, Skopje.

[6] Tolles L., Kimbro E., Webster F., Ginell W. (2000). Seismic Stabilization of Historic Adobe Structures. Final Report of the Getty Seismic Adobe Project, Los Angeles.

[7] Bozinovski Z., Shendova V., Cvetanovska G., Garevski M., Apostolska R. (2008). Analysis of Seismic Stability with Technical Solution for Repair and Seismic Strengthening of the Structure of the Parliament of Republic of Macedonia, Report IZIIS 2008-53, Skopje.

[8] Gavrilovic P., Pichard P. (1983).Methodology for Repair and Strengthening of the National Monuments in Pagan –Burma, Report IZIIS 83-30/1-6, UNESCO/UNDP Project BUR 78/023.

[9] Gavrilovic P., Shendova V., Ginell W. (1999). Seismic Strengthening and Repair of Byzantine Churches, JEE, Imperial College, London, Volume 3, No.2, pp: 199-235.

[10] Shendova V., Rakicevik Z., Garevski M., Apostolska R., Bozinovski Z. (2014). Implementation of Experimentally Developed Methodology for Seismic Strengthening and Repair of Historic Monuments", A. Ilki and M.N. Fardis (eds.), DOI 10.1007/978-3-319-00458-7_8, © Springer International Publishing, Switzerland.