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SEISMIC RETROFITTING OF BUILDING STRUCTURES AND MONUMENTS IN NORTH MACEDONIA – NECESSITY, SOLUTIONS AND CONSTRUCTION

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Abstract

The impact of present building code requirements for seismic design of 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 old buildings and monuments, constructed with low or no seismic consideration, 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. This paper presents the integrated multidisciplinary approach to seismic protection of important structures that has been developed by the Institute of Earthquake Engineering and Engineering Seismology, IZIIS, Skopje, and implemented in the process of seismic upgrading or reconstruction of historic buildings and monuments in the country and beyond.

Keywords: seismic retrofitting, historic buildings, monuments, multidisciplinary approach, analytical and experimental investigation

1. Introduction

Seismic retrofitting of historic structures is radically different from that of other structures, due to the priority given to preservation of aesthetic, 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 systematic and scientific approach to achieving a successful 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:

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- 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. This means that preservation concerns the general character of the 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 all 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 as are the structures of historic buildings and 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 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. 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.

Retrofitting Methods: The main problem imposed in masonry structures is to provide structural integrity at story level to avoid individual vibration of the elements after the occurrence of the first cracks. The most 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.

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2. Integrated Approach for Seismic Retrofitting of Historic Buildings and Monuments Developed 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 research activities of the Institute of Earthquake Engineering and Engineering Seismology, IZIIS, 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. These resulted in an integrated approach to seismic protection of extraordinarily important cultural historic structures that has been adopted by IZIIS and used in the process of reconstruction or seismic upgrading of important monuments. This approach 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.

The particularly important part of the IZIIS' experience in the field of earthquake protection of cultural heritage are the numerous shaking table testing of models for investigation of structural behaviour of historic building and monuments and methodologies for their repair and seismic strengthening, that have been carried out in the IZIIS' Dynamic Testing Laboratory, [1]. The most important seismic shaking table investigations of models of historical buildings and monuments are presented further, followed by their implementation in real structures, [2]. The considered structures have relatively low levels of axial stresses at the base which justifies the adoption of a model with neglected gravity forces, i.e. "gravity forces neglected" modelling principle, using the same materials as in the prototype structures.

3. Shaking Table Testing of Models of Historic Buildings and Monuments

3.1. Historic Buildings

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 2. Firstly, the buildings were classified into

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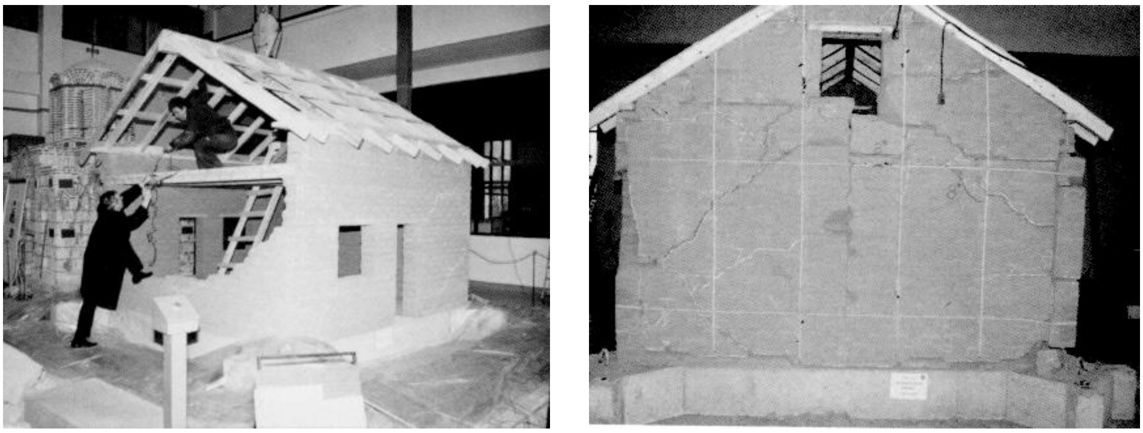
structural units and then the methodology for structural retrofitting was determined based on detailed studies of structural characteristics, the damage level, the built-in materials, the foundation conditions as well as local seismicity. Since the injection was the most frequently applied method, for 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 IZIIS' seismic shaking table 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. 1). 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, [3].

Figure 1. Original and repaired model of a typical masonry building in Budva

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, [4].

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. 2). 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, [5].



Unretrofitted Adobe Model -UAB Retrofitted Adobe Model – RAB

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

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3.2. Monuments

Byzantine Churches in Macedonia**:** Within the long-term research project entitled *"Study for Seismic Strengthening, Conservation and Restoration of Churches Dating from the Byzantine period (9th-14th century) in the Republic Macedonia"* realized jointly by IZIIS, Skopje, National Conservation Center of R.N. Macedonia and GCI, Los Angeles, [6, 7], ample experimental and analytical investigations were performed to verify an original methodology that was developed for the repair and seismic retrofitting of Byzantine churches. For the first time in the world provided was shaking table testing of a model of St. Nikita to a scale of 1 : 2.75, simulating the existing and the strengthened state, (Fig. 3) to investigate its behavior in elastic, nonlinear and heavily damaged state (close to failure). The applied methodology for repair and retrofitting, consisting of incorporation of horizontal and vertical belt courses, significantly increases the bearing capacity and deformability of the structure. The tests approved that applied methodology increases the bearing capacity and deformability of the structure up to the level of the designed protection.

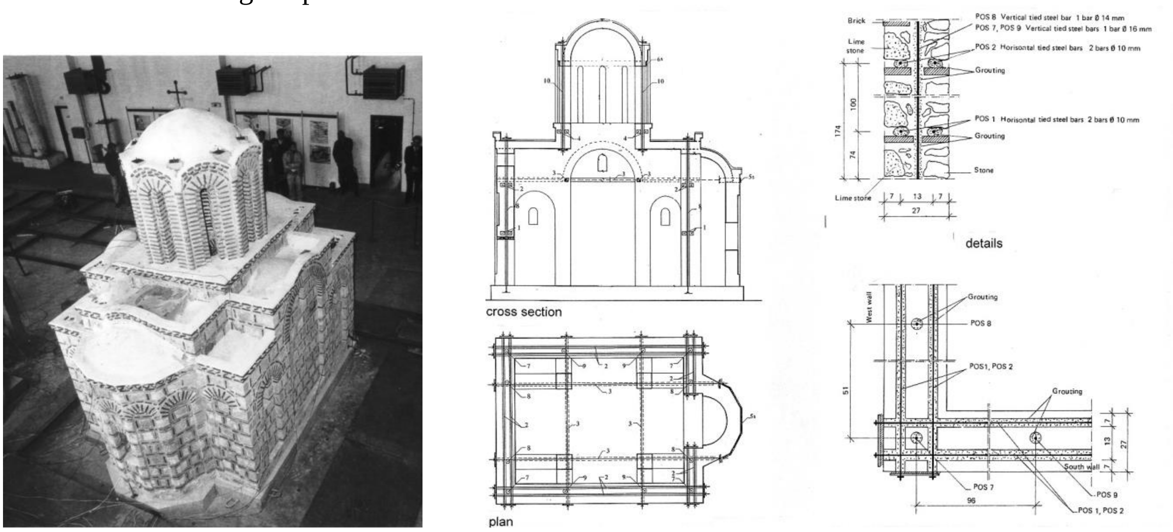

Figure 3. The 1:2.75 scaled church model (left) and the applied strengthening method (right)

Mustafa Pasha mosque in Skopje: Within the frames of FP6 PROHITECH project *"Earthquake Protection of Historical Buildings by Reversible Mixed Technologies*", experimental shaking table tests on the models of three important historical monuments, mosque, cathedral and church, were carried out in IZIIS. Mustafa Pasha's Mosque, one of the biggest and the best-preserved monuments of the Ottoman sacral architecture in Skopje and the Balkan, was selected as representative mosque for shaking table testing, (Fig. 4).

Figure 4. Mustafa Pasha Mosque: prototype (left), 1:6 scaled model (middle), phase 3 – damages (right)

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Experimental investigation was performed in three main phases: (1) testing of the original model under low intensity level, with the aim of provoking damage to the minaret only; (2) testing of the model with strengthened minaret, with the aim of provoking its collapse and damage to the mosque, and (3) testing of the strengthened mosque model until reaching heavy damage. The applied strengthening solution, consisting of formation of a horizontal belt course around the bearing walls by CFRP rods as well as around the tambour and at the base of the dome by CFRP wrap, has significantly improved the seismic resistance of the monument, [8].

4. Implementation of the Developed Retrofitting Methodologies in North Macedonia

After the realization of these projects and gained unique and incomparable knowledge, IZIIS became a partner of the Republic Institute for Protection of Cultural Historic Monuments of R.N. Macedonia, which enabled direct application of the gained knowledge in actual conditions and for specific historic monuments. Presented further are the most characteristic examples of application of the developed methodologies for seismic upgrading of monuments and historic building.

4.1. Reconstruction of St. Pantelymon Church in Plaoshnik, Ohrid

In the process of conservation and rebuilding of the St. Panteleymon Church in Ohrid, having in mind the importance and specific nature of the structure representing a historic monument classified in the first category, it was necessary to design a building structure that will satisfy the stability conditions in the process of application of the conservation principles regarding shape, system, and materials, [9]. The principal structural system of the church consists of massive stone and brick masonry in lime mortar. Seismic strengthening was provided in accordance with the previously developed and verified methodology for Byzantine churches, (chapter 3.2). i.e. the horizontal and vertical steel ties were proportioned and a solution for consolidation of the foundation was given. The church was reconstructed in the course of 2001, (Fig. 5).

Figure 5. St. Panteleymon church: during reconstruction, (left, middle), rebuilt church (right)

4.2. Reconstruction of St. Athanasius Church in Leshok

On August 21, 2001, during the armed conflict in R. Macedonia, the monastic church of St. Athanasius in Leshok experienced strong detonation, which resulted in its almost complete demolition, (Fig.6). Based on previous knowledge, there have been two approaches taken in the reconstruction of the church: (i) repair and strengthening of the existing damaged part and (ii) complete reconstruction of ruined part with strengthening elements, [10].

The solution for repair and structural strengthening of damaged existing part of the structure anticipates injection of all the cracks and incorporation of horizontal and vertical RC strengthening elements on certain levels. For the demolished part of the structure, a concept of complete reconstruction by maximum possible use of selected material has been adopted, whereat elements for structural strengthening for providing the designed level of seismic safety have also been anticipated: (i) RC belt course below the floor level, in the existing foundation walls, for anchoring the vertical strengthening elements, (ii) vertical strengthening steel elements at the ends of the massive walls and around openings, (iii) vertical strengthening steel elements into the tambour columns, (iv) horizontal steel elements along

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the walls, in the base of the tambour and the dome. Due to the different treatment of the structural units constituting the integral structure, an expansion joint between them is anticipated to be constructed.

Figure 6. St. Athanasius church: after detonation, (left) during reconstruction, (middle), rebuilt church (right)

The church was reconstructed according to the designed methodology during 2005-2007. The results from the analysis show that both structural units constituting the integral structure possess a sufficient bearing and deformability capacity up to the designed level of seismic protection.

4.3 Repair and Seismic Retrofitting of Mustafa Pasha Mosque in Skopje

Respecting the modern requirements in the field of protection of historical monuments, as is the application of new technologies and materials, reversibility and invisibility of the applied technique, concept of repair and strengthening involving the use of composite materials was used for seismic upgrading of Mustafa Pasha Mosque in Skopje, [11]. It has been selected based on investigations of the: characteristics of the built-in materials, main dynamic characteristics, shaking table testing of the mosque model, (chapter 3.2); investigations of the soil conditions as well as detailed geophysical surveys for definition of geotechnical and geodynamic models of the site.

The accepted solution of structural strengthening, (Fig. 7), consists of incorporation of CFRP wrap in a layer of epoxy glue along the perimeter of the dome base, placement of CFRP bars in an epoxy mortar layer in horizontal joints of bearing walls, and construction of RC wall along the perimeter of the foundation walls, below the terrain level. Strengthening of the mosque structure in accordance with the designed system started in the fall of 2008.

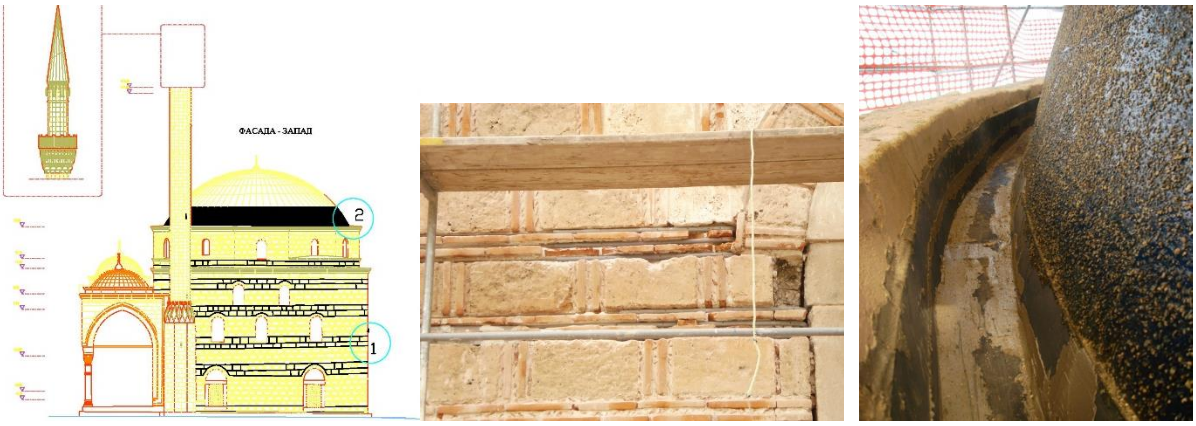

Figure 7. Mustafa Pasha Mosque: proposed retrofitting, (left), CFRP bars in the walls, (middle), CFRP wrap around the dome (right)

Following the successful seismic upgrading of Mustafa Pasha Mosque, the same or slightly modified retrofitting methodology by using CFRP has been so far implemented in several other mosques on the territory of North Macedonia and Kosovo, all of them from the Ottoman period: Isaki and Gazi Hajdar Kadi Mosques in Bitola, Ali Pasha Mosque in Ohrid, Yashar Pasha and Fatih Mosques in Pristina, as well Sinan Pasha Mosque in Prizren, while for Orta Mosque in Strumica the process of construction is currently under way.

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4.4. The Parliament building in Skopje

The Parliament Building of the Republic of North Macedonia was more than 70 years old, (Fig.8). 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, [12].

Figure 8. Parliament of Republic of North Macedonia (north facade – left, aerial view – right)

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.

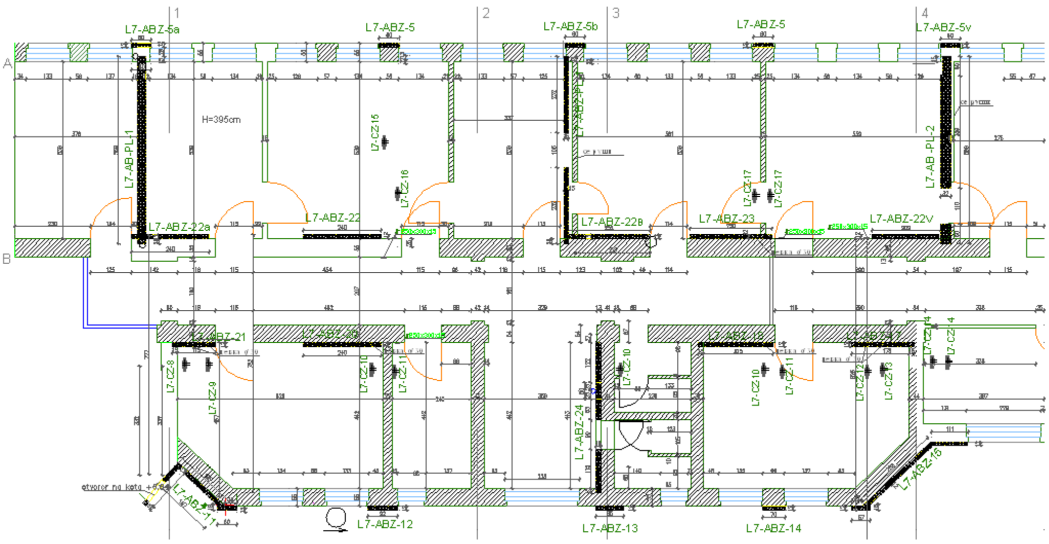

Figure 9. Strengthening of representative unit – L7

Based on the required strength and deformation characteristics of the elements and the system as a whole on one hand, and the possibilities for adding new elements in the structure, on the other hand, the most appropriate (from the aspect of stability and economy) technical solution for strengthening has been selected. During the selection, particular attention has been paid to the possibility of achieving optimal strength, stiffness and deformability by minimal interventions. It has also been endeavoured to

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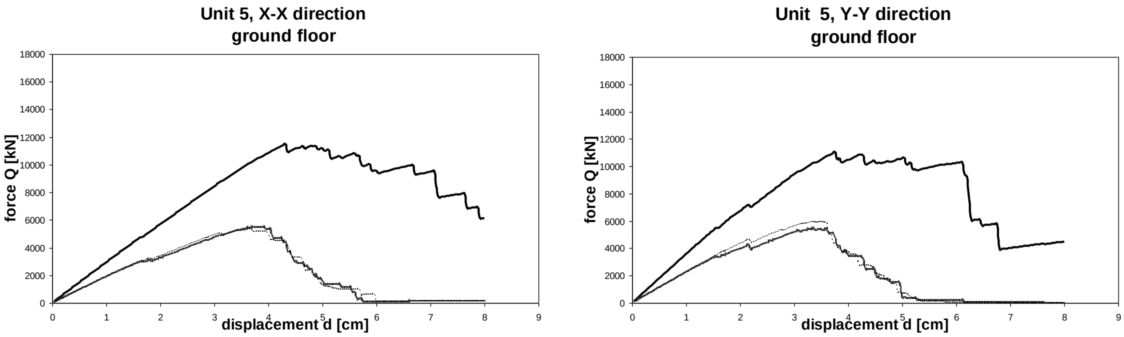
avoid structural intervention in the functionally necessary premises and premises with interior of particular value and importance. With the solution of strengthening of the principal structural system, classical methods and strengthening elements have been anticipated for the purpose of use of materials with characteristics like the existing ones. Fig. 9 shows the strengthening solution for the representative unit, L7. Generally, by selected strengthening the existing structural system was converted form plain to confined masonry.

Subsequent final analysis of strength and deformability of the elements and the system as a whole has been made up to ultimate states of strength and deformability for each unit taken separately. Comparative force-displacement storey relationships for the three analysed conditions (existing, existing with additional storey, and strengthened structure) for selected unit gives a very clear insight into the effect of the selected strengthening solution, (Fig. 10), pointing to a considerable increase of both the bearing and deformation capacity of the system.



--- existing state, ___ with additional storey, ▬ strengthened structure

Figure 10. Comparative Q-d diagrams for characteristic units

Figure 11. Strengthening of a characteristic column with a plastic hinge, unit L3

Figure 12. The Parliament building after seismic retrofitting, adaptation and building of another storey

The process of strengthening while continuously functioning of the Parliament, was carried out quite successfully despite number of limitations in the period 2010-2014, (Fig. 11, 12).

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5. Conclusion

The paper presents successful implementation of previously developed and experimentally verified retrofitting methodologies in seismic upgrading or reconstruction of important buildings in the country and beyond, which followed the modern principles for seismic protection of historical buildings and monuments. The delicate problem of proving the effectiveness of the selected retrofitting has been successfully overcome by using the "*design assisted by testing*" methodology. This methodology, which has been recently codified in all Eurocodes, represents a very powerful tool especially in the case of a complex structures, which are difficult, and therefore unsafe, to analyse using traditional methods. The knowledge gained through shaking table testing is unique and incomparable and hence necessary for design of seismic strengthening of individual important cultural-historic structures where it is important to have an insight into the effect of the interventions upon the authenticity of the monument.

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