SMAR 2015 – Third Conference on Smart Monitoring,
Assessment and Rehabilitation of Civil Structures

Seismic retrofitting of 15th century mosques using CFRP composites

Veronika Shendova[1], Predrag Gavrilovic [2], and Goran Jekic2[3]

[1, 2, 3] Institute of Earthquake Engineering and Engineering Seismology, IZIIS, Skopje, Republic of Macedonia

ABSTRACT: The applied concept of structural retrofitting has been selected respecting the modern requirements in protection of historical monuments, as is application of new technologies and materials, reversibility and invisibility. The starting point in making the decision for using of CFRP composites for seismic retrofitting of three mosques dating back form 15th century was the selected methodology for seismic retrofitting of the 1:6 scaled mosque model, the experimental investigation of which were performed within the framework of EU FP6 project PROHITECH. The paper deals with the design, analysis and implementation of experimentally verified methodology for seismic retrofitting of Mustafa Pasha Mosque in Skopje, Sultan Mehmet Fatih Mosque in Pristina and the Sinan Pasha Mosque in Prizren.

1 INTRODUCTION

Modern approach to protection of cultural heritage should be multidisciplinary and should introduce criteria for protection against earthquake effects considering all the specificities of the site, the expected level of seismic effect as well as the specific characteristics of the monuments, their historic, cultural importance, their structure and characteristics of materials used for their construction. In providing all this, the experts are permanently challenged by the fast development and the improved performance of new materials and techniques. However, the implementation of particular strengthening methodology depends on the extent it has been investigated as well as its analytical and experimental verification.

Extensive research activities have been performed by the Institute of Earthquake Engineering and Engineering Seismology, IZIIS, Skopje, for the purpose of evaluation of an integrated approach for repair and seismic strengthening of valuable historic monuments. Considering that the seismic analysis of these structures cannot be performed using seismic design codes for modern buildings, IZIIS' approach includes determination of criteria, methods and techniques for structural retrofitting, restoration and preservation based on detailed studies, including experimental investigations and taking into account the cost effectiveness of the alternative solutions by using advanced and innovative technologies and materials, (Gavrilovic et al, 1999, 2007).

2 DESIGN OF SEISMIC RETROFITTING BY TESTING

The design process for seismic retrofitting presented in this paper was accurately developed as far as possible according to the modern principles for the seismic protection of historical buildings, which require the use of reversible, low intrusive and possibly invisible technologies.

The delicate problem of proving the effectiveness of the selected consolidation system has been successfully overcome by using the methodology of design assisted by testing.

A technology involving application of composite material, encouraged by the satisfying results from experimental investigations of the model of Mustafa Pasha Mosque in Skopje and wishing that these results could be applied in practice in the process of conservation and seismic retrofitting of monuments in seismically active regions, has been applied for three particularly important monuments.

2.1 Shaking table testing of the Model of Mustafa Pasha Mosque

Shaking table tests on a model of the Mustafa Pasha Mosque in Skopje were carried out in IZIIS Laboratory within the frames of EU FP6 project "Earthquake Protection of Historical Buildings by Reversible Mixed Technologies"- PROHITECH, (Mazzolani et al, 2007). The 1:6 scaled model has been subjected to the effect of a series of earthquakes that caused damage (Fig. 1a). Then the model was strengthened by application of CFRP elements and subjected to iterative tests, (Fig. 1b). The strengthening solution consisted 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.

a) Damage to the model b) Retrofitting of the model

Figure 1. The 1:6 scaled model of Mustafa Pasha Mosque.

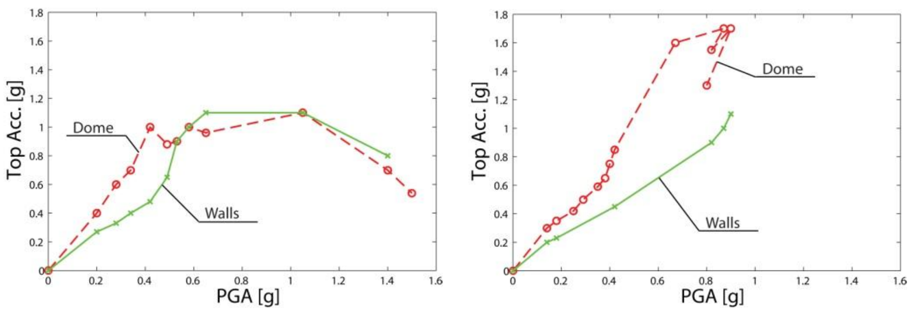

Figure 2. Response of the model: acceleration measured at the top of the shear walls and of the dome as a function of input acceleration, original and retrofitted model.

Shaking table testing showed that the strengthening of the minaret by application of a CFRP wrap enabled stiffening and increasing of its bending resistance. Push-over curves were constructed based on the different intensity level of the repeated seismic test, within an input acceleration of 0.05g - 1.50g, (Fig.2). Comparing the obtained results it can be concluded that the applied strengthening technique has significantly improved the seismic resistance of the monument. The results from the investigation, although obtained for small geometrical scale, have shown that the system is efficient, which was the starting point in making the decision about the concept of seismic retrofitting of the prototype.

3 REPAIR AND SEISMIC RETROFITTING OF MUSTAFA PASHA MOSQUE

Mustafa Pasha's Mosque is one of the biggest and the best preserved monuments of the Ottoman sacral architecture in Skopje and the Balkan. The building style belongs to the early Constantinople period at the beginning of the second half of the 15^{th} century.

The structural system of the mosque consists of massive peripheral walls in both orthogonal directions with a thickness of about 170 cm constructed partially of hewn stone and brick. The catastrophic Skopje earthquake of 1963 inflicted damage to the mosque structure that dominantly affected the central dome and the domes of the porch, the east facade and the minaret. In 1968, these damages were repaired by injection of cement mortar based mixtures as well as incorporation of RC belt courses, (Fig 3).

Figure 3. Mosque after Skopje earthquake: east facade damage (1963) and strengthening of dome (1965)

Today, Mustafa Pasha’s Mosque represents a cultural historic monument of an extraordinary importance for the city of Skopje and Republic of Macedonia. The authors of this paper had the opportunity and the challenge to design a system for seismic strengthening of the structure, (financed by the Turkish foundation TIKA) for the needs of the conservation project on the architecture of Mustafa Pasha Mosque prepared by the Foundation, University of Gazi in cooperation with the Ministry of Culture and Tourism of Turkey, the Ministry of Culture of Republic of Macedonia and the National Conservation Centre 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, the authors have decided to choose a concept of repair and strengthening involving the use of composite materials, (Shendova et al, 2007).

3.1 Concept for seismic retrofitting of Mustafa Pasha Mosque

Based on these investigations and the defined seismic parameters, as well as detailed analysis of the seismic stability of the structure, the solution of structural retrofitting has been accepted, that complies thoroughly with the conservation principles for repair and strengthening of cultural historic monuments. It consists of incorporation of strengthening elements in the process of conservation of the architecture of the structure and in accordance with the existing project on conservation of the structure.

3.2 Analysis of the structure

An analysis has been carried out in accordance with the valid existing regulations and the European standards Two methods were used: analysis of the bearing and deformability capacity of the structure and performance of a nonlinear dynamic analysis for the defined seismic parameters, static and equivalent seismic three-dimensional analysis of the structure by means of the computer package SAP 2000.The results from the analysis show that the structure possess a sufficient bearing and deformability capacity up to the designed level of seismic protection. It satisfies the prescribed requirements and criteria for such type of historic structure

3.3 Project realization

Strengthening of the mosque structure in accordance with the designed system started in the fall of 2007 with strengthening of the foundation structure, (Fig.4). After removal of the cement mortar layer over the dome placed in 1968, the following was carried out on the dome structure: (1) coating of the formerly constructed reinforced concrete ring in the base of the main dome with an injection mixture based on lime mortar and (2) placement of a CFRP strip in a layer of epoxy glue along the perimeter of the dome base within a width of 2.9 m. Then the entire dome was externally coated with a protective layer of lime mortar and covered in accordance with the project on the conservation of the architecture, (Fig. 4).

Figure 4. Strengthening of Mustafa Pasha Mosque: foundation strengthening; preparation for incorporation of CFRP rods into bearing walls; CFRP wrap in a layer of epoxy glue over the dome

The realization of the project continued on the bearing walls. After cleaning of all the joints on the outside with a depth of ~8 cm, it is anticipated to place CFRP bars of defined mechanical characteristics (tensile strength ft=1800–2000 MPa) in an epoxy mortar layer and connect them in the vertical joints. Then, the joints were filled with pointing lime mortar in accordance with the project on conservation of the architecture. In the entire part of the structure extending above the terrain level, the cement mortar injected in the cracks after the 1963 earthquake was removed. With the project on conservation of the architecture, it is anticipated that these cracks as well as all the cracks detected after the opening of the external joints be injected with lime mortar with defined mechanical characteristics.

4 SEISMIC RETROFITTING OF MOSQUES IN KOSOVO

The monuments in Kosovo dating back to the Ottoman period are of a special interest having in mind their significance from historic and artistic point of view. The Kosovo authorities in cooperation with the Turkish foundation TIKA supported the conservation projects for two important mosques in Kosovo, i.e., the Fatih Mosque in Prishtina and the Sinan Pasha Mosque in Prizren, (Fig. 5).

The Mosque of Sultan Mehmet Fatih is located in the centre of the ancient city of Prishtina, close to the big Hamam (XV century), the Clock Tower (XIX century) and the building of the Academy of Science and Arts of Kosovo (XIX century), listed as monuments of cultural heritage.

Figure 5. 15th century mosques in Kosovo: Sultan Mehmet Fatih Mosque, Sinan Pasha

It was constructed upon the order of Sultan Mohammed II Fatih –the Conqueror. An inscription, written in the Arabic alphabet in six rows, located above the main portal gives the construction date as 1461, according to the Gregorian calendar. At the end of the 17th century, during the Austrian-Turkish wars, it was converted into a Catholic church. During the Second World War, the German Army refurbished the interior of the mosque, as it's highlighted by the swastikas painted above the main gate. For its monumentality, method of construction and decorative elements, this monument is listed among the most important buildings of the Islamic architecture in South-Eastern Europe. The wall thickness reaches 180cm.The cupola is one of the biggest cupolas of the XV century and is one of the best architectural examples in South-East Europe. The damage to the Sultan Mohammed Fatih's Mosque is caused by climatic changes, ravages of time and permanent vibrations caused by traffic. The damage is manifested by separation of sandstones, vertical cracks in the walls indicating separation of rigid blocks as the first mode of failure, cracks in the arcade columns, vertical cracks in the corners and the dome.

The second mosque is Sinan Pasha in Prizren, with its huge elegant minaret; it is one of the dominant architectural features of Prizren. The mosque has a square plan about 14 x 14m covered by a dome, with a projecting mihrab area 4.1 x 4.5m. covered by a semi-dome. The dome is resting on walls with a thickness of 1.65 m. The deep recessed mihrab with its semi-columns has a stalactite hood and is also painted. The mosque still has its original stone flooring as well as podium and carpentry. The traditional portico was demolished in 1939. It consisted of four pillars carrying arches supporting small domes (traces can still be seen on the site). There are no evident cracks in the structure and the structural elements except for the vertical cracks in the south-east corner, which can be treated as local. Some degradation of stone has occurred due to the ravages of time, water penetration and lack of maintenance. Due to rain and water infiltration through the roof of the praying hall and the mihrab area, the plaster is detached and fallen down and some original paintings have been lost.

4.1 Analysis of structures in their existing condition

Analysis of the structures has been carried out in accordance with the valid existing regulations and the European standards and codes for existing and strengthened conditions. Two methods were used: (i)-Static and dynamic three-dimensional analysis of the structural system by using the SAP 2000 computer program and (ii) Analysis of the bearing and deformability capacity of the main structural system and performance of nonlinear dynamic analysis, (Gavrilovic, 2007).

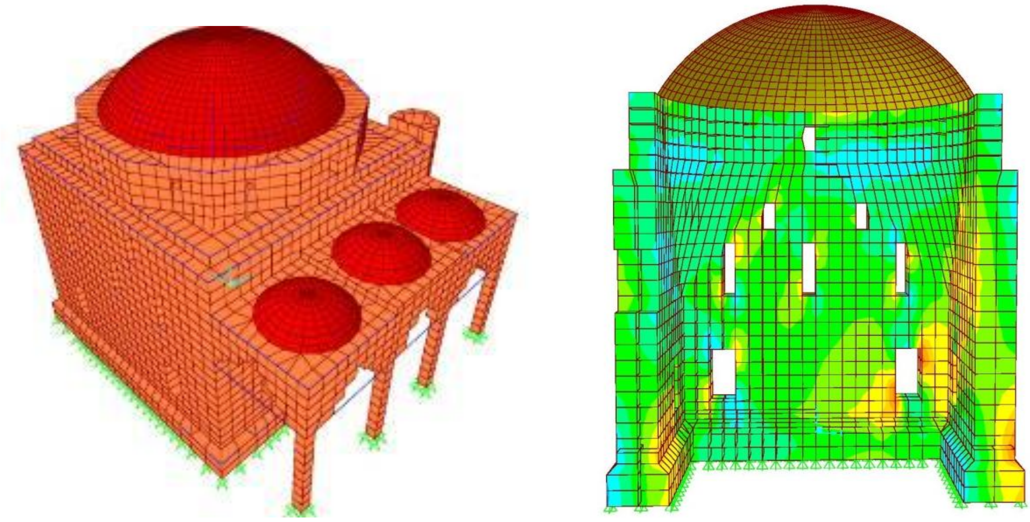

Figure 6. Sultan Mehmet Fatih Mosque: 3D analytical model and Stress distribution for dead load

For analysis of the existing structure under gravity and seismic load, the finite element method has been used, modeling the structure as 3D, the walls as solid elements and the domes as shell elements. In the case of the strengthened structures, the strengthening elements have been modeled as frame tied elements with own characteristics, (Fig. 6). The natural period of vibrations being Tx=0.263 sec, Ty=0.249 sec for the Fatih Mosque and Tx=0.289 sec, Ty=0.253sec for the Sinan Pasha Mosque, with appropriate mode shape. The analysis of stresses due to gravity load for both mosques points to maximum vertical stress of 4.-4.5 kg/cm^2 in the upper part, with some areas under low tensile stresses of 0.1-0.2 kg/cm^2. According to the observations and investigations of the structural conditions and stability, it is evident that the structure and the structural system is safe and satisfies the criteria for gravity and serviceability load. Having in mind that the monuments represent masonry not-ductile structures located in zones of high seismicity, representing monuments of the first category of importance, their seismic stability should be increased. As to seismic conditions, there are evident tensile stresses at the end of the walls and on the domes in the range of 1.2-1.5 kg/cm^2, meaning overstress and potential damage. The analysis shows large tensile zones, below the domes and in the upper part of the structures. Consequently, the structures are not safe under seismic loads, meaning that, in the case of an earthquake; they will be damaged and will experience partial collapse. Strengthening of the structures is therefore a prerequisite.

4.2 General concept for structural retrofitting of mosque structures

The general concept of seismic retrofitting follows the original idea but using composite materials, (Gavrilovic et al, 2007) and consists of: (i) strengthening of the domes in the lower part by carbon wrap to improve their tensile strength; (ii) construction of a ring at the domes using a carbon fiber laminate and carbon bars; (iii) strengthening of the walls by using carbon bars to sustain tensile stresses that develop in the walls under seismic actions; (iv) rebuilding of the entrance part in its original shape and its strengthening by stainless steel ties in the case of the Sinan Pasha Mosque and strengthening by a system of carbon reinforcement in the case of the Faith Mosque; (v) consolidation of the bearing walls by injecting cracks and strengthening of the foundations.

The analysis of retrofitted structures show that the level of tensile stresses is minimized and acceptable; in the case of the maximum expected earthquakes, the motions will produce controlled level of damage but not collapse of the elements and the structures.

4.3 Structural consolidation and retrofitting

Structural consolidation and retrofitting works started as the first phase of the field works before the conservation activities by the Akcayalar Restorations Company from Afion, Turkey and continue. Consolidation and retrofitting of the dome started after removal of the roof cover and mortar and two operations have been carried out: (i) coating of the base of the main dome with injection mixture based on lime mortar and (ii) placement of CFRP wraps on a layer of epoxy glue along the perimeter of the dome base within 2.5m.


Figure 7. Seismic retrofitting of dome and walls, Sultan Mehmet Fatih Mosque

After these operations, the entire domes have externally been coated by lead according to the conservation requirements and design. Retrofitting of the walls started after cleaning all the joints on the outside surface of the walls, (Fig.7); CFRP bars of defined mechanical characteristics (tensile strength of ft = 1800 – 2000 MPa) have been inserted in the horizontal joints and covered with an epoxy mortar layer, connecting them to the vertical joints. Then the joints have been filled with pointing lime mortar. In the entire part of the structure extending above the ground level, all the cracks together with the additional cracks detected after the opening of the external joints, have been injected with lime mortar of defined (increased) mechanical characteristics.

5 CONCLUSIONS

The reinforcing techniques based on the use of CFRP have already been applied on RC structures and masonry walls for cladding. The use of these materials for historic monuments and old masonry structures represents a specific and new method of retrofitting that has big advantages but, at the same time, it requires special attention and caution during construction and design. The relevance of the design of such an important monuments wisely suggested testing the validity of these techniques on a large scale model. The experimental evidence was very helpful in proving the suitability of the design choices and the effectiveness of the applied consolidation system.

The knowledge gained through shaking table testing is unique and incomparable and hence necessary for 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.

The developed and experimentally verified methodology was successfully implemented in the structures of the real historic monuments. The design process, which has been followed as shown in this paper, should emphasize the suitable way to follow when facing the complex problem of protection and conservation of a cultural heritage construction.

ACKNOWLEDGEMENT

The authors wish to express their gratitude to the Turkish Foundations TIKA for their support and financing the projects, to the Ministry of Culture and Tourism of Turkey, the Ministry of Culture of Republic of Macedonia, the National Conservation Centre in Skopje, the Ministry of Culture of Kosovo, the Institute for protections of Monuments in Pristina and Prizren, Kosovo, the Akcayalar Restorations Company from Afion, Turkey as well as to all the participants for successful collaboration during project elaboration and realization.

References

Gavrilovic P., W. S. Ginell and V. Shendova (1991-1995), Seismic Strengthening, Conservation and Restoration of Churches Dating from Byzantine Period in Macedonia. Joint research project, IZIIS - Skopje, GCI -LA; Reports IZIIS 500-76-91, 92-71, 94-68.

Mazzolani F., Krstevska L., Tashkov Lj & Gramatikov K. 2007, Shaking Table Testing of Mustafa Pasha Mosque Model, Final report, EU-FP6 PROHITECH project

Sendova V, Gavrilovic P. & Stojanoski B. 2007, Main Project on Repair and Strengthening of the Mustafa Pasha Mosque in Skopje, IZIIS Report 2007-41, Vol.1- 3, Skopje .

Gavrilovic P. Ceko B. Jekic G. “ Main Project on Structural Consolidation and Seismic Strengthening of Fatih Mosque- Prishtina”, Prishtina 2007