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Innovative Technologies for the Protection of Historical Structures against Earthquakes

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Abstract

Cultural heritage buildings are special structures and must be protected from natural disasters preserving at the same time their authenticity. In the seismic areas, one of the building classes that is consistently exposed to seismic risk is the one constituting the architectural heritage of the region. To minimize further destruction under future seismic activity it is necessary to reinforce the existing structures that are more vulnerable. As a consequence, new technological systems are needed, able to provide solution not only to specific structural or architectural problems, but also aiming at improving the global performance of the construction. Similarly, great attention is paid not only to reliability and durability of intervention methods, but also to the possibility to be easily monitored and removed if required, according to the widely shared policy, aiming at the safeguard of existing buildings, in particular in case of historical and monumental works, from inappropriate restoration operations.

Keywords: *historical structures, preservation, innovative method, reversibility*

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This study aims to represent innovative technologies and strategies to preserve the cultural heritage structures against earthquake effect. In particular, the application of fibre reinforced polymers and structural control systems are explained. Suitability of the strategies to architectural, historical and structural features and reversibility aspects are evaluated. As a case study the application of these strategies to a historical building in Istanbul is discussed.

INTRODUCTION

With its permanent occupancy over 8000 years Anatolia is the cradle of civilization. Since Hittites, different tribes, resulting with the establishment of many countries and empires, have occupied the region. Roman, Byzantine, Seljuk and Ottoman empires are the most significant civilizations in the history that had brought Anatolia to its historical structure stock. There are many churches, bridges, school, mosques, cisterns, public baths, palaces and pavilions, defying the centuries with their magnificence. Istanbul, as the capital of Byzantine and Ottoman empires has an important and special place among the other cities in Turkey with respect to cultural heritage.

As well known, Turkey is greatly exposed to seismic hazard, which causes its large and valuable buildings to be strongly at risk of severe damage or even destruction due to earthquake. This problem mostly stands for historical and monumental constructions, due to the fact that most of them frequently lack basic anti-seismic features. In one of the latest seismic event, 1999 earthquakes, 36 historical monumental structures including Fatih mosque have been damaged in Istanbul. Only this situation is enough to underline the necessity of special care for the preservation of the cultural heritage structures (Aras 2013).

Heritage structures should be passed on to future generations in its authentic state and in all its variety as an essential part of the memory of the human race. Otherwise, part of man's awareness of his own continuity will be destroyed (Amsterdam Charter, 1975). For the protection of the historical structures the best available protection strategy must be aimed. For this reason the problem must be analyzed well and the solution should be effective to provide desired safety with minimum intervention. In that respect the technological and innovative solutions should always be used, bearing the authenticity of the structure in mind. This study aims to represent innovative technologies and strategies to preserve the cultural heritage structures against earthquake effect. Recently two main applications for the preservation of the heritage structure are the strengthening and rehabilitation of dynamic properties of the systems. For the strengthening of the systems use of Fibre Reinforced Polymers became very popular strategy for the historical structures and Base Isolation technique is seen as an effective and applicable.

Great attention is paid not only to reliability and durability of intervention methods, but also to the possibility to be easily monitored and removed if required. Aiming to safeguard the existing historical structures from inappropriate restoration operations, the key parameter is named as reversible technologies. The use reversible technologies in the protection of the historical heritage buildings are also assessed briefly in this study.

EARTHQUAKES AND HISTORICAL BUILDINGS IN TURKEY

Over the course of history Anatolia has been the site of numerous destructive earthquakes. At least 70% of the region is under-risk of earthquake. Between 1902 and 2005, 128 earthquakes hit the region causing more than 80.000 deaths. The recent Van and Erciş earthquakes also confirm the destructive effects of the seismic activities in Turkey. Most of the historical documentation is related to damages suffered in Istanbul. The earthquake history of the city reveals that; it experiences with a medium earthquake (I_0 = VII – VIII) in every 50 years and with a strong earthquake (I_0 = VIII - IX) in every 300 years. Moreover recent extensive geophysical studies have clearly delineated the presence of a single major tectonic entity crossing the Marmara Sea. The probability of having an MW 7 + earthquake is in the vicinity of 70% in the next 30 years (Erdik et al 2004).

Historical structures in Turkey can be classified based on the construction material as masonry and timber structures. Masonry structures are brittle and heavy, and their substantial masses impose significant seismic loads on the walls. The typical damage in a masonry structure is in the form of a crack on load bearing structures. The depth the extent of the crack determines the severity, and failure is brittle. On the other hand, well-designed wooden structures, with timber frames and floor systems, have generally performed well in earthquakes because of the ductile nature of the wood. Failures are often due to insufficient foundation anchorage or unbraced cripple walls and soft stories. Figure 1 shows damaged masonry and timber structures under earthquake loads in Turkey (Prohitech, 2014).

Figure 1.

Figure 1.
Earthaquake damage for masonry and timber structures (*Prohitech, 2004*)

INNOVATIVE TECHNOLOGIES FOR CULTURAL HERITAGE

Any strategy, used for the rehabilitation of historical structures should have some superiority over a common one such as the efficiency of the strategy should clearly be set, the application must not disturb the cultural value of the structure and it should be reversible. Meeting these requirements needs to use the best available techniques, materials and strategies. As a result, technological developments introduce innovative products for the protection of historical buildings. An extensive literature survey has resulted with identification of different contemporary materials and method such as use of shape memory alloys, active and passive control techniques, use of fibre reinforced polymers, health monitoring techniques, use of damper braces or use of tuned mass dampers for the protection works. Apart from the others, this study aims to presents the technical details about the use of fibre reinforced polymers and base isolation techniques since they are applied to the historical buildings efficiently.

Fiber Reinforced Polymer Overlays (FRP): Structural intervention with FRP overlays is one of the most widely used strategies to upgrade the performance of masonry structures. The application increases the strength and ductility of the masonry. They can be regarded as innovative because the FRP material is new in seismic retrofitting, because it's very good mechanical characteristics and because it offers a wide range of attractive technical solutions (Calado et al. 2006; Beg et al. 2006).

There are two basic approaches to FRP strengthening of the masonry walls. The first one is the application of FRP overlays on the surface of the wall (for normal masonry walls). The second one is the application of FRP overlays on both surfaces and connecting the overlays with metallic tie rods to induce larger confinement action. FRPs are composite materials constituted by two core materials, namely fibre material with high mechanic properties and matrix acting as a binder. The role of the fibre is to resist the external loads, while the matrix has both the function of guarantying the adhesion to the support and transfer the stress: the result is a lightweight material with high strength capacity (Beg et al. 2006). A wide range of mechanical properties can be covered by selecting different types of fibre and matrix (i.e.: Young modulus and strength capacity). Commonly, fibres used for the realization of composite materials are glass, carbon and aramid fibres (Figure 2).

Figure 2.
FRP applications and stress-strain relationships (*Beg et al. 2006*)

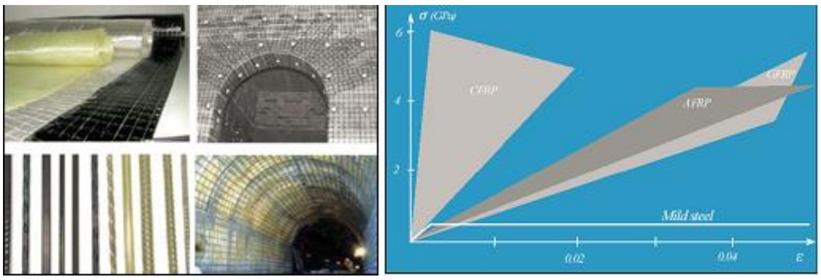

Figure 2.

In order to prove the useful effect of FRP applications many experimental studies have been carried. 1/6 scaled model of Mustafa Pasha Mosque has been tested on tri-dimensional shake table with its original and strengthened forms with FRP and the strengthened model by FRP has shown very good performance (Prohitech 2004). Figure 3 shows another experimental study to prove the application of vertical and horizontal FRP strengthening for Un-reinforced Masonry (UM) walls. Increase of strength and especially ductility is evident (Stoian et al 2003).

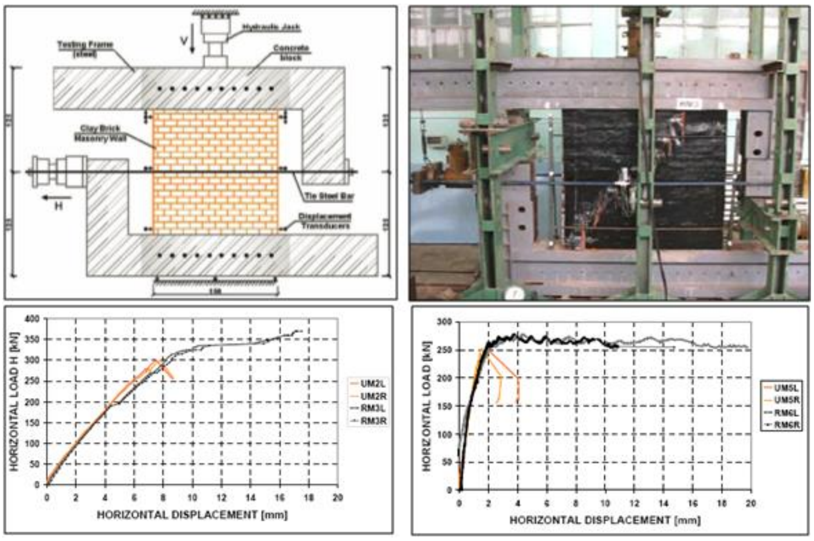

Figure 3.

Figure 3.
Experimental study of FRP strengthening (*Stoian et al 2003*).

Base Isolation: For in-plane and out of plane loading masonry walls are very stiff and brittle. Typical inter-storey drifts at the initiation of cracking are in the range of few millimeters (2-3mm). Secondly small periods in the dynamic behaviour may cause the structure to be affected from ground motion severely. For this reason, base isolation technique is one of the most effective strategies to upgrade the performance since it restrict the relative displacements of the within the wall and lengthen the period.

Isolation devices can be classified as Elastomeric Devices, High Damping Rubber Bearings (HDRB), Lead Rubber Bearings (LRB), Added Damping Rubber Bearings (ADRB), Friction Pendulum System (FPS), Sliding Devices, Flat Slider Bearings, Curved Slider Bearings, Elasto-plastic Bearings and Wire-Rope Bearings (Figure 4).

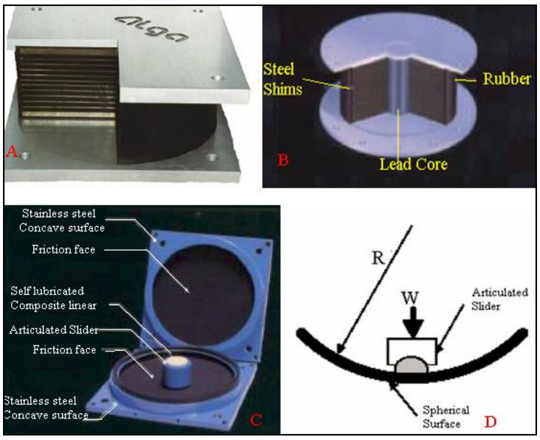

Figure 4.

Figure 4.
Base isolation devices (A : HDRB, B:LRB, C, D : FPS)

Basically, the effect of such devices is to shift the fundamental vibration period of the building upward, so as to reduce the value of the maximum spectral acceleration. For this reason seismic isolation is very appropriate for structures with short periods and low damping like masonry buildings. The devices themselves can dissipate a given amount of input energy, when these devices possess special dissipative features, or can be absorbed by additional damping devices.

The first historic structure seismically retrofitted with base isolation, the Salt Lake City and County Building, drew attention to the use of isolation for sensitive existing buildings. Later on, seismic isolation was applied to many vulnerable masonry buildings of historic significance, including the Ninth Circuit U.S. Court of Appeals building in San Francisco, Due to the possibility of efficiently improving the seismic capacity with minimal disruption to its architectural features, base isolation system has been recently suggested as an innovative retrofitting strategy (Aras and Altay 2015).

REVERSIBILITY

As a consequence, new technological systems are needed, able to provide solution not only to specific structural or architectural problems, but also aiming at improving the global performance of the construction. Similarly, great attention is paid not only to reliability and durability of intervention methods, but also to the possibility to be easily monitored and removed if required, according to the widely shared policy, aiming at the safeguard of existing buildings.

Reversible Technologies are based on the integration of structural members of different materials and/or construction methods into a single construction. The basic feature of them is that their application should be always completely recoverable, that is reversible, if required. This is considered as an essential design requirement in order to prevent historical and monumental buildings from unsuitable rehabilitation operations (Prohitech 2004).

CASE STUDY - BEYLERBEYI PALACE

As a case study earthquake performance and rehabilitation of Beylerbeyi Palace is briefly discussed in this study. Detailed information can also be found in the recompleted journal papers (Aras et al 2011; Aras and Altay, 2015).

Architectural and structural system of Beylerbeyi Palace: Beylerbeyi Palace is the largest and most elegant Ottoman palace in Asia. Great importance was given to this palace and its decorations. Figure 5 illustrates the palace with exterior appearance and interior spaces.

Figure 5.

Figure 5.
Beylerbeyi Palace (A: Exterior appearance, B, C, D: Interior spaces)

The palace consists of two main floors and a basement containing kitchens and storage rooms. In the basement floor storey heights vary between 1.5 and 2.2 m whereas in regular floors, they vary between 6 – 9 m. The building has a 72 m length along the shore and 48 m in the perpendicular direction. The total height of the structure, excluding the timber roof, can be approximated to 20.60 m. The load bearing system is mainly made of masonry walls and timber slabs. The basement floor of the palace enables to identify the masonry, which is composed of lime mortar, brick and stones. These walls are also forming the foundation system of the palace. The thickness of the walls in the basement floor is generally 1.4 meters whereas it is 80 cm in the first floor and 60 cm in the second floor of the palace. Timber slab systems constituted by oak and fir have been used. Figure 6 shows the structural masonry walls and timber slab system in the foundation of the palace.

Figure 6.

Figure 6.
Masonry walls and timber slab system in Beylerbeyi Palace

Beylerbeyi palace is used as a museum now. A damage survey, carried out in the palace has shown that, the palace is presenting the sign of earthquake-oriented damages. For this reason, the palace is investigated within the PROHITECH project.

Analyses of the Palace: Dynamic properties of Beylerbeyi Palace are identified with ambient vibration survey (AVS) and the results are used to calibrate the finite element model of the palace constructed in SAP2000-V10. Presented in another publication (Aras et al. 2011) in detail, the tuning process has resulted in three different moduli of elasticity for brick masonry in the palace (Figure 7). To determine the earthquake hazard level for Beylerbeyi Palace, the hazard maps obtained by Erdik et al. (2004) have been used. Maximum Considered Earthquake (MCE), which has 2% probability of exceedence in 50 years and approximately 2500 years of return period, has been used to check the safety of the palace. The constructed response spectrums for 2%, 5%, 10% and 20% damping ratios are illustrated in Figure 8. AVS has indicated the damping ratios are between 1 % and 2.7 % for the first eight modes of the structure.

Response spectrum analyses have been performed for both transversal and longitudinal directions. The safeties of the masonry walls, which are the main structural elements, were concerned. Figure 9 shows the horizontal stresses (S11), vertical stresses (S22) and shears stresses (S12) under Maximum Considered Earthquake for 2% damped structure. The high stress concentration regions (in yellow and green colours) are clearly seen. For horizontal stresses the upper portion of the structure is under risk. These stresses reach to 7 MPa. Obviously these S11 stress stem from the out of plane movement of the walls. The magnitudes of the vertical stresses are less than those of horizontal stresses and high stress concentrations are gathered on the lower levels as expected. Additionally wall segments between two openings are under high stress. S22 stresses are beyond 3.5 MPa. The magnitudes of shear stresses are less than that of vertical stresses. Generally its maximum value is about 1.5 MPa and on the corners of the opening shear stress concentration is observed.

Figure 7.
Numerical model of Beylerbeyi Palace before and after the modal tuning

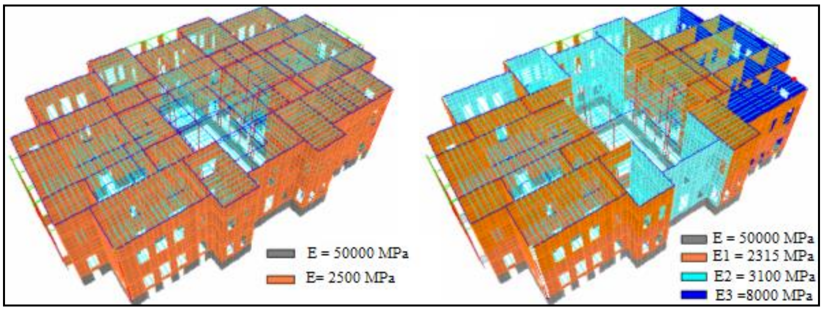

Figure 7.

Figure 8.
Response spectrum of MCE for different damping ratios

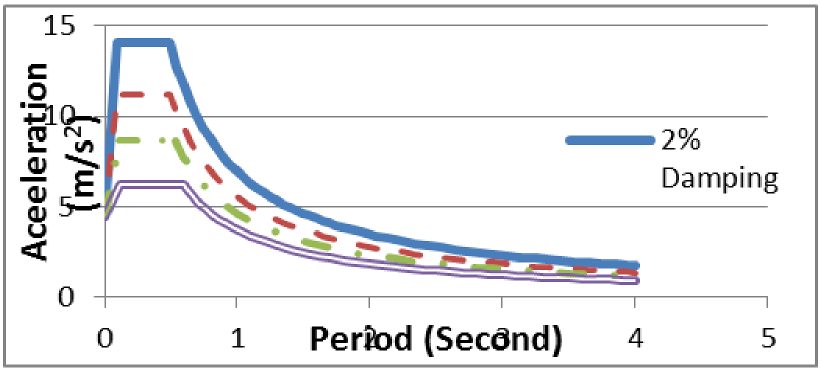

Figure 8.

The experiments over the wall and mortar specimens made in the laboratory have given the strength properties for the masonry walls in the palace as 10 MPa for compressive strength and 0.85 MPa for tensile strength. As the result of out of plane action of the walls, S11 stresses are well beyond the tension strength of the masonry. Secondly the compression stresses (S22) are less than the compressive strength of the masonry. Finally the shear stresses on the masonry walls exceed the tensile strength of the material however the shear strength of the masonry depends on the compression stress on the masonry as stated in Equation 1, where τ_{safety} is the expected lateral shear strength, τ_0 is the masonry cracking shear obtained experimentally, μ is the friction coefficient and σ is the vertical stress on the masonry wall in the system. τ_0 and μ values can be accepted as tensile strength and 0.5 respectively. Evaluation of the stress values showed that, most of the walls in the palace are safe under S12, shear stress but there are many masonry wall segments on which the shear stress exceeds the shear strength of the wall.

$$\tau_{safety} = \tau_0 + \mu \sigma \quad (1)$$

The result of the safety evaluation has shown that, Beylerbeyi Palace is safe under vertical stresses. On the other hand horizontal and shear stresses exceed the strength parameters of the material. It can be concluded that, the structure is not capable to resist the earthquake ground motion, according to MCE.

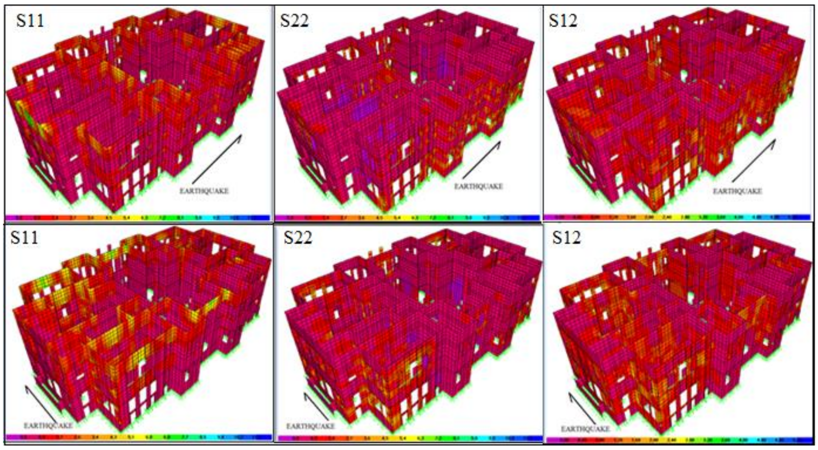

Figure 9.

Figure 9.
S11, S22 and S12 stresses under RSA of MCE for 2% damping

Strengthening of Beylerbeyi Palace with FRP: The FRP application for Beylerbeyi Palace is based on the computed horizontal and vertical tension stresses by Response Spectrum Analysis (RSA). The critical locations of the horizontal and vertical stresses were determined as the regions on which the stresses exceed the tensile strength of the masonry. (Figure 10).

For the strengthening fabrics type of FRP is appropriate because of their simple application. Main fibres of FRP fabrics should be horizontal. Horizontal fibres are effective to carry out of plane stresses on the top part of the structure. The wall between two windows can be treated as a column and it can be fully confined by FRP fabrics. These increase the vertical load capacity and ductility of the wall. MCE requires that, almost every wall should be covered by FRP. In that respect each wall in the first and second storey of the palace should be covered by FRP along with horizontal direction. Here the FRP is applied to the walls from one face. One face application is important with respect to historical and aesthetics appearance aspects of the palace.

The reversibility of composite materials is a very important aspect. These types of materials, in some cases, reach the "complete reversibility". Composite materials using different bare materials and construction technologies can reach three different degree of reversibility (e.g. small, medium and large). The aspect that must be controlled for having a good degree of reversibility is the type of resin used (Beg et al. 2006).

Figure 10.
Critical regions of stress according to MCE

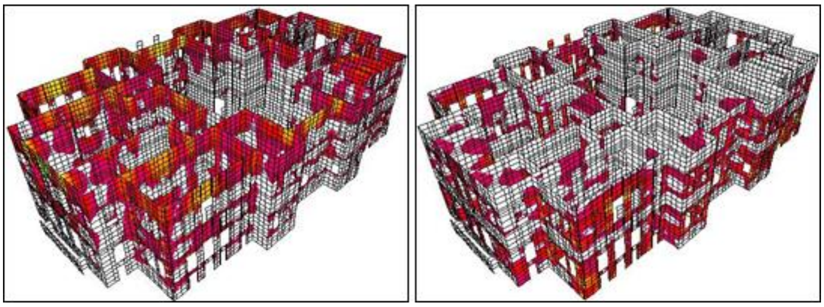

Figure 10.

In case Beylerbeyi Palace, it was noted that the walls are covered from one face. This requirement is very important with respect to aesthetic appearance. For the external walls, FRP can be applied between küfeki stone façade and masonry walls. In that condition all application would be hidden. For the internal walls the stucco plaster is in main concern and application side of the wall depends on this covering. For the timber-covered room FRP can be applied underneath the timber surface. Finally for normal plastered walls there is no problem since plaster can be applied over the FRP application.

Rehabilitation of Beylerbeyi palace with base isolation: Dynamic modes of Beylerbeyi Palace showed that; the first 44 modal frequencies of 60 modes are on the flat plateau of the response spectrum. For this reason shifting the fundamental periods is going to result in significant reduction in spectral acceleration. Secondly the small damping ratio of the existing palace is another source deficiency. In these respects, High Damping Rubber Bearing (HDRB) is preferred to isolate the structure.

The isolation devices are planned to be inserted in basement walls of the palace since the basement walls are also suitable to insert the isolators with respect to safety and historical texture concerns. The isolator should be distributed to the plan of the structure in a way that it does not disturb the load flow and cause torsional behavior. The selected distribution of the devices is shown in Figure 11-A. Total number of bearing is determined as 123. Isolator design for the palace has been done according to the procedure defined in Yang et al. (2002) and FEMA 302 (1997). Details of the procedure have been presented in another study (Aras and Altay, 2015) and designed HDRB device is illustrated in Figure 11-B. The diameter of the circular elastomeric portion of the device was determined as 90 cm and 13 rubber layers of 12 mm thickness were used. The steel plate thickness was determined as 2 mm. Finally, two rectangular steel plates (1 m * 1 m) with a thickness of 3.5 cm have been used on the top and bottom-side of the isolator. Figure 11-C shows the insertion of the devices to the structure.

Response Spectrum Analysis (RSA) has investigated the efficiency of the base isolation. The numerical model was revised to contain the determined device properties. The response spectrum, used for the isolated model, has also been revised according to effective damping of isolator (Figure 8). The application of isolation has altered the overall behaviour of the structure significantly. Mode shapes of the structure turned to simple rigid body motions with a period of 2 second. Figure 12 shows the S11stress values, which was the maximum stresses, for the isolated Beylerbeyi Palace under MCE for two orthogonal directions. The stress values have been reduced significantly under maximum considered earthquake.

Figure 11.
Details of HDRB application in Beylerbeyi Palace

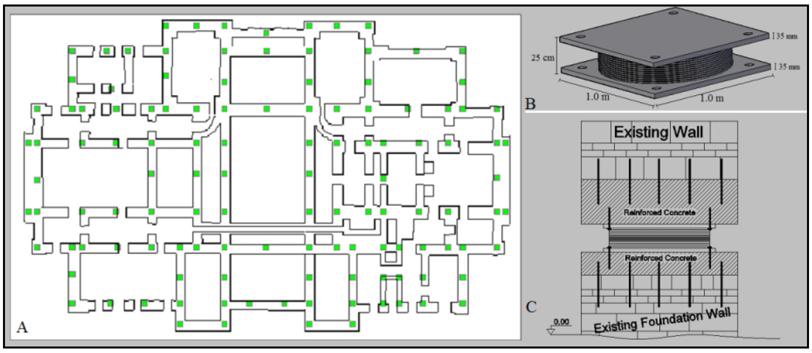

Figure 11.

The proposed base isolation strategy, at the level of foundation, is an irreversible intervention. Reversibility means the ability to undo the change without harming the original structure. Although base isolation intervention is irreversible, it does not touch the historic fabric of the palace and other historical resources.

Figure 12.
S11 stresses under MCE for isolated Beylerbeyi Palace with HDRB

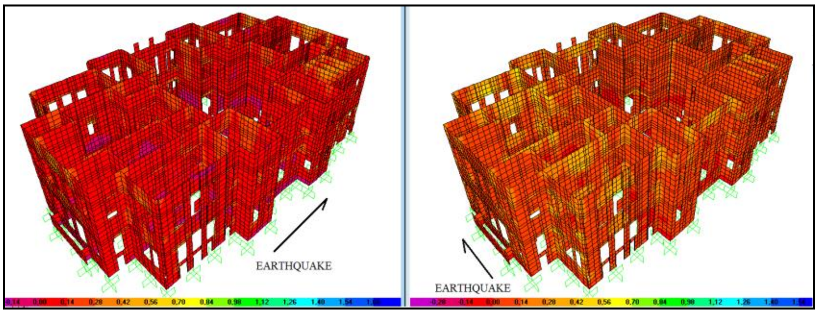

Figure 12.

The proposed intervention is limited to the foundation level of the building. The facade and the interior characteristics, including frescoes, paintings and other architectural elements are fully preserved. Application of base isolation system also requires the separation of the palace by a 25 cm gap from its surrounding to ensure the serviceability after expected earthquakes. Moreover all lifelines, ducts and the other required links must be connected to the palace via flexible connections.

CONCLUSION

Importance of the historical structures and preservation of them from earthquake ground shaking is outlined in this study. For the preservation the use innovative strategies, namely use of fibre reinforced polymers and base isolation techniques investigated in detail. Moreover the reversibility concept and its key role in the preservation are explained.

As a case study, one of the most important structures in Istanbul, Beylerbeyi Palace has been investigated. The earthquake performance of the palace is found inadequate. Strengthening of the palace with FRP and rehabilitation of the dynamic properties by the application of base isolation techniques has been investigated. It is shown that the earthquake safety of the palace can be ensured by the strategies without damaging the palace's historical authenticity.

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