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PROPOSAL OF BASE ISOLATION FOR THE EARTHQUAKE SAFETY OF A HISTORICAL MASONRY PALACE

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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 Mediterranean basin, one of the building classes that are 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, but this action always causes some perturbation to the authenticity of these structures as far as the historical evolution of their design is concerned. At this point base isolation technique is drew considerable attention to rehabilitate the earthquake behaviour of historical structures with limited intervention. Moreover, due to the possibility of efficiently improving the seismic capacity of a building with minimal disruption to its architectural features, base isolation system has been recently suggested as an innovative retrofitting strategy, and has been adopted for the seismic upgrading of some major monumental buildings in the USA.

In this study, base isolation retrofit strategy has been evaluated for the historical Beylerbeyi Palace (1865). In this respect, structural behaviour and the earthquake performance of the palace have been investigated. It is seen that the inherent dynamic properties of the palace make it vulnerable to earthquake ground shaking. In order to reduce the effect of ground shaking, the use of a base isolation system, containing high damping rubber bearings (HDRB) is investigated. The structure is modelled with the proposed system and analysed under maximum considered earthquake (MCE). The effects of the base isolation are discussed in detail.

1 INTRODUCTION

Beylerbeyi palace was built between 1861 and 1865 on the Asian shore of the Bosporus. In the Mediterranean basin, one of the more consistent building class exposed to seismic risk is the one constituting the architectural heritage of the region (D’Ayala and Ansal 2012). To minimize further destruction under future seismic activity it is necessary to reinforce the existing structures that are more vulnerable; but this action always causes some perturbation to the authenticity of these structures as far as the historical evolution of their design is concerned. The main purpose of the engineering analysis of these structures is to obtain the best solution that minimizes the intervention and, consequently, to balance between the need for safety and integrity, and the need for preservation of the original structure and tissue (Oliveira CS 2003).

Being aware of the importance of the historical heritage structures and seismic danger of Mediterranean region, 16 institutions from 12 countries, mostly belonging to the South European and Mediterranean area, have participated in a research project, named as “Earthquake Protection of Historical Structures by Reversible Mixed Technologies”, (PROHITECH) (Prohitech 2004). The previous studies (Aras 2010a; Aras 2010b; Aras et al.

2011) and response spectrum analyses have shown that Beylerbeyi Palace has some inherent dynamic properties, making the palace vulnerable to the earthquake ground shaking.

In this study, base isolation retrofit strategy has been evaluated for Beylerbeyi Palace. 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 (Mokha et al. 1996). Due to the possibility of efficiently improving the seismic capacity of a building with minimal disruption to its architectural features, base isolation system has been recently suggested as an innovative retrofitting strategy, and has been adopted for the seismic upgrading of some major monumental buildings in the U.S.A. (De Luca et al. 2001). In that respect, a base isolation system, containing High Damping Rubber Bearings (HDRB) is proposed. The structure is modelled with the proposed system and analyzed under Maximum Considered Earthquake (MCE). The effects of the base isolation are discussed in detail.

2 BEYLERBEYI PALACE

Beylerbeyi Palace is the largest and the most elegant Ottoman palace in Asia. It illustrates the distinct western influence on Ottoman architecture. 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 change between 6 – 9 m. The building has a 72 m length along the shore 48 m in the perpendicular direction.

The load bearing system is mainly made of masonry walls and timber slabs. The masonry walls are composed of lime mortar, brick and stones. 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. It is determined that the slab of the structure is mainly composed of two types of timber cross-sections. 20*20 cm^2 beams (supporting beam from oak) and 8*40 cm^2 beams (slab beam from fir) Figure 1 shows the palace and its masonry walls.

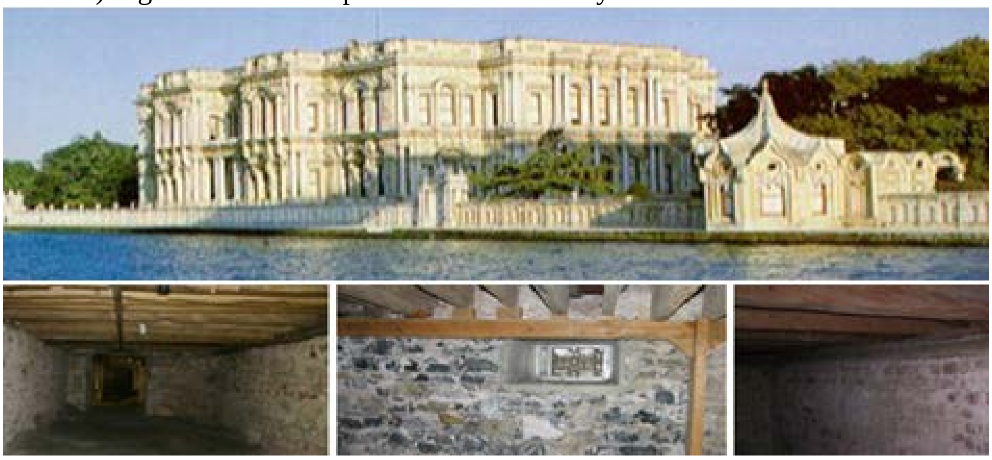

Figure 1. Beylerbeyi Palace and its masonry walls

Beylerbeyi palace is under the protection of Regional Directorate of National Palaces and it 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 (Aras 2010c). For this reason, the palace is investigated within the Prohitech project (2004).

3 DYNAMIC BEHAVIOUR OF BEYLERBEYI PALACE

Dynamic properties of Beylerbeyi Palace were identified with AVS (Krstevska and Taskov 2006) and the results are used to calibrate the finite element model of the palace. This process is presented in a previous paper in detail (Aras et al. 2011). In summary, the obtained mode shapes are showing complex vibration of the structure, although it has a regular and symmetric shape in plan. The complex mode shapes are caused by the lack rigid floor diaphragms and non-uniform material properties of the walls. The damping ratios for the modes vary between 2 and 3%.

The tuning procedure has been resulted with three different moduli of elasticity for brick masonry in the palace (Figure 2). This model is the most appropriate mathematical model representing the dynamic behaviour of the real structure (Aras et al. 2011). Earthquake performance of the palace and the effect of retrofit strategies can be examined with this model accurately. Table 1 shows the dynamic properties of the tuned numerical model.

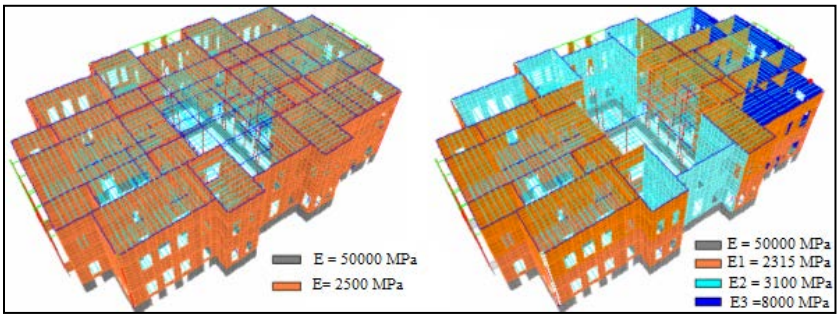

Figure 2 Numerical model of Beylerbeyi Palace before and after the modal tuning

Table 1 Dynamic parameters of the tuned numerical model

MODE	Period (second)	Mass Participation Ratio in LD	Mass Participation Ratio in TD	Total Mass Participation Ratio in LD	Total Mass Participation Ratio in TD
1	0.371	0.000	0.120	0.000	0.120
2	0.289	0.007	0.000	0.007	0.120
3	0.282	0.120	0.001	0.127	0.121
4	0.271	0.180	0.004	0.307	0.125
5	0.260	0.002	0.083	0.309	0.208
-	-	-	-	-	-
59	0.009	0.180	0.025	0.894	0.742
60	0.009	0.025	0.180	0.919	0.922

4 EARTHQUAKE HAZARD IN MARMARA REGION

Based on recent findings, a fault segmentation model for the Marmara Sea region is developed by Erdik et al (2004). By taking NEHRP (IBC 2000) B/C boundary as the reference ground, hazard maps were obtained. (Erdik et al. 2004). A detailed soil investigation directed by Regional Directorate of National Palaces has identified soil type that the Beylerbeyi Palace sits on exactly B/C boundary of NEHRP specification (Eren et al. 2005). Under these conditions, to determine the earthquake hazard level for Beylerbeyi Palace, the hazard maps obtained by Erdik et al. (2004) have been used to specify the Maximum Considered Earthquake (MCE) which has 2% probability of exceedence in 50 years (Fema 356 2000). The response spectrum of MCE is illustrated in Figure 3.

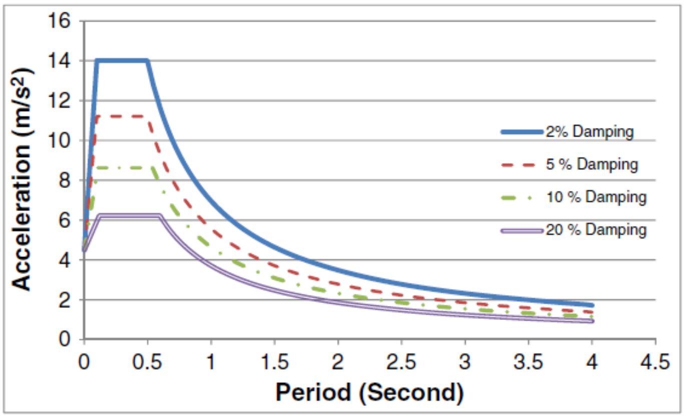

Figure 3. Response spectrum of MCE for different dampings

5 EARTHQUAKE SAFETY OF BEYLERBEYI PALACE

The earthquake safety of Beylerbeyi Palace is assessed by Response Spectrum Analysis (RSA) with the tuned numerical model under characterized MCE for 2% damping. The safety of the masonry walls, which are the main structural elements were concerned. Figures 4 shows the horizontal stresses (S11), vertical stresses (S22) and shears (S12) under Maximum Considered Earthquake performed in the longitudinal and transversal directions respectively. The high stress concentration regions are clearly seen. For horizontal stresses the upper portion of the structure is under risk. In these regions S11 stresses reach to 7 MPa. 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.

Although a detailed performance evaluation methods, defined in different codes and documents (Fema356, 2000; TEC, 2007) can be used, basic comparison between developed stresses under given action and material strength parameters can give consistent results related safety of the structures. The experiments over the laboratory made wall and mortar specimens 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 (Aras, 2007). As the result of out of plane action of the walls, S11 stresses are well beyond the tension strength of the masonry. This proves that, out of plane failure occurs on the higher portion of the walls. 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 2, where τ_{safety} is the expected lateral shear strength of the masonry wall in the system, 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. Evaluation of the stress values showed that most of the walls in the palace are safe under S12.

$$\tau_{em} = \tau_0 + \mu\,\sigma \qquad (1)$$

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.

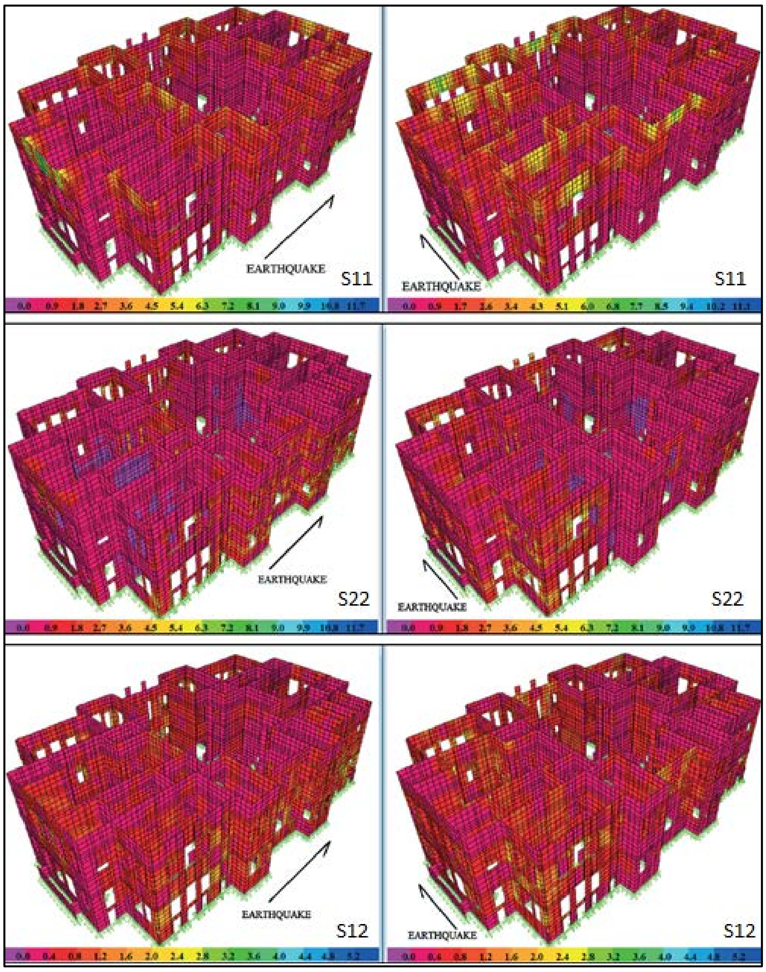

Figure 4. Obtained stresses under MCE for Beylerbeyi Palace

6 BASE ISOLATION DESIGN FOR BEYLERBEYI PALACE

Retrofit of a historical monument is an important task and should consider architectural, historical and structural consideration carefully. The isolation approach is based on the response control concept, aiming at controlling and limiting the dynamic effects on the structural elements by means of special devices (Beg at al. 2006). 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. HDRB devices are composed of rubber and steel layers.

The installation requires cutting the walls and placing two layered reinforced concrete foundation systems and locating devices between them. The upper layer reinforced concrete system is designed to transmit the structural loads to the isolator uniformly. The role of the bottom layer is to connect the existing foundation and the isolators in order to transfer the effects of the ground shaking to the isolators. In this respect the isolator should be distributed to the plan of the structure in a way that not to disturb the load flow and cause torsional behaviour.

The selected distribution of the devices is shown in Figure 5. Total number of bearing is determined as 123.

For the base isolation project, initial point is the determination of the target period of the isolated structure. This is directly related to the amount of decrease in the maximum stress levels. In order to reduce the maximum stress values to acceptable values, the period of the isolated structure should be shifted around 2.5 second. With an additional decrease of damping effect the stress values on the structure would be acceptable. For the design of the system the procedure specified by Yang et al (2002) is followed (Aras et al., 2015).

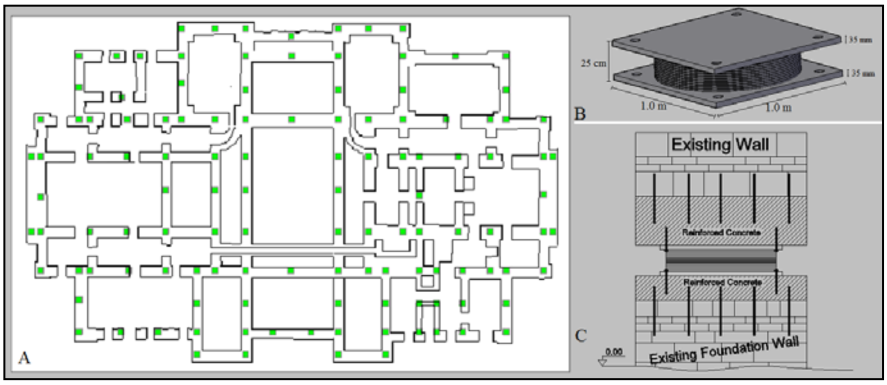

Figure 5 HDRB application in Beylerbeyi Palace (A: Distribution of the devices, B: HDRB designed for the structure, C: Application of the devices on the foundation walls)

7 EARTHQUAKE RESPONSE OF THE ISOLATED BEYLERBEYI PALACE

The efficiency of the base isolation has been investigated by Response Spectrum Analysis (RSA). The numerical model was revised to contain the determined device properties. The HDRB were modelled by beam elements having 25 cm height, geometrical and material properties of devices. Effect of the high damping was reflected to the response spectrum as specified in IBC (2000).

The application of isolation has altered overall behaviour of the structure significantly. Mode shapes of the structure turned to simple rigid body motions in transversal and longitudinal directions. The period of the effective modes are beyond 2 second, indicating a great amount of reduction in spectral acceleration. Table 2 represents the dynamic characteristics of isolated Beylerbeyi Palace.

Table 2 Dynamic properties of isolated Beylerbeyi Palace

MODE	**Period** (Sec)	**Mass Participation Ratio in X**	**Mass Participation Ratio in Y**	**Total Mass Participation Ratio in X**	**Total Mass Participation Ratio in Y**
1	2.08	0.04	0.49	0.04	0.49
2	2.05	0.92	0.08	0.96	0.57
3	2.03	0.04	0.43	1	1

Figure 6 show the S11, S22 and S12 stress values for the isolated Beylerbeyi Palace under MCE for two orthogonal directions. The stress values have been reduced significantly. It is clear that, the isolated structure is safe under maximum earthquake.

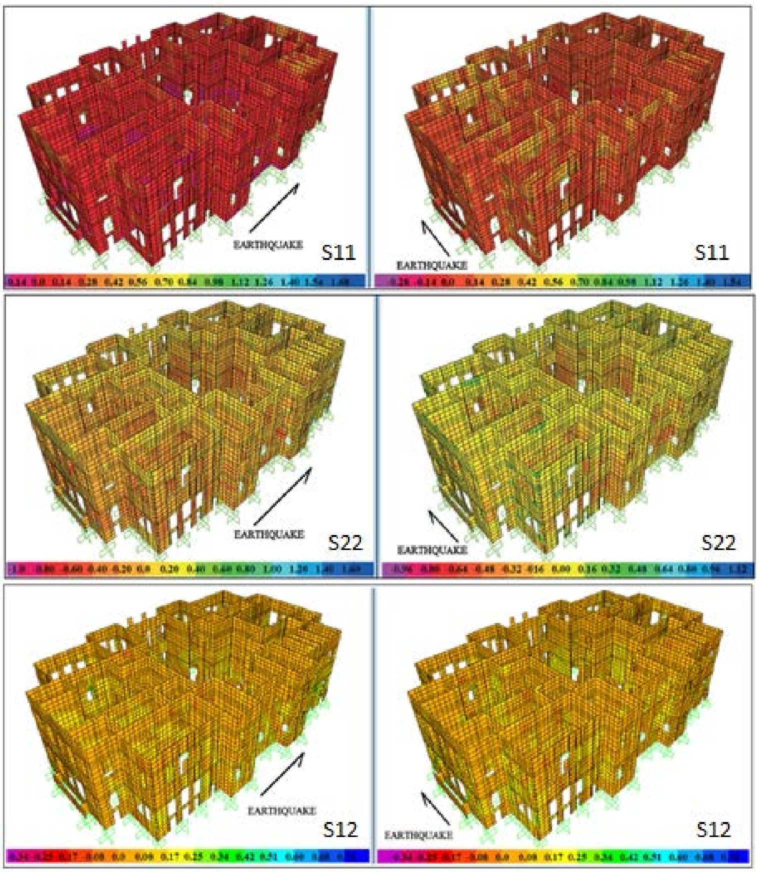

Figure 6. Obtained stresses under MCE for isolated Beylerbeyi Palace.

8 ARCHITECTURAL AND HISTORICAL ASPECTS OF THE STRATEGY

Base isolation intervention is limited to the foundation level of the building. In this way the facade and the interior features including frescoes, paintings and other architectural elements are fully preserved. In this respect, seismic isolation is very convenient for aesthetic appearance and architectural features, reflecting the historical importance of the palace.

However, at the level of foundation, an irreversible intervention by adding rigid foundation beams is necessary. Reversibility means the ability to undo the change without harming the original structure. It is clear that the base isolation intervention is irreversible.

Secondly the intervention technique should also be suitable for the environment of the palace. Since the proposed base isolation intervention changes the overall dynamic behaviour of the palace a gap should be formed between the palace and adjoining facilities. 25 cm continues gap around the palace needs to be arranged and all lifelines, ducts and the other required links must be connected to the palace via flexible connections.

9 CONCLUSIONS

Performed study has been resulted with the following findings;

- The analyses of the palace under MCE have proven the vulnerability of the structure. Especially the horizontal stresses (S11) are seen as the source of weakness.

- In order to heal the dynamic behaviour of the structure and reduce the stress values to the acceptable ranges, base isolation technique with HDRB devices is detailed.
- The analyses of the isolated palace by RSA have shown that, the isolated structure is capable to withstand MCE as the result of changed dynamic behaviour and increased damping ratio.
- Lastly the architectural, aesthetic and historical aspects of the base isolation strategy have evaluated as acceptable for the palace. However the application of the strategy requires a vertical separation line between the palace and connecting facilities.

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