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Seismic Assessment of Monastery of Stoudios (Imrahor Mosque) in Istanbul

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Abstract: Monastery of Stoudios, dated back to the reign of Eastern Roman Empire, is known to be the oldest surviving –albeit partially- religious building in Istanbul. During sixteen centuries, the building has been exposed to several earthquakes, fires and other minor disasters which have caused considerable damages and partial destruction in some of its sections. As a part of a general master plan for the structural condition assessment of historical buildings and monuments of Istanbul, this study aims to evaluate the seismic resistance of the monastery against future excitations. The expected failures and corresponding preventive/controlling repairs and strengthening measures will also be discussed in the article.

Keywords: Seismic resistance, historical construction, masonry, structural modeling and analysis

Introduction

Historical masonry constructions constitute significant part of the architectural heritage which acts as a link between the past and the present where the concept of identity is generally attributed. The conservation of the present condition or rehabilitation of the deficiencies in the monuments gains importance as the reflection of this common sense of identity. Time, destructive effects of the nature and man-made factors are the main sources of damage affecting the structures in different aspects for which some conservation measures might be necessary. Among these, seismic action is one of the most devastating actions that seriously threaten the integrity of historical masonry constructions. It has been known from the history that many monuments, structures and even complete cities destroyed by earthquakes (Agrawal 2005).

Anatolia, located in the intersection of Eurasian and African plates, has known to be seismically active area since antiquity and has witnessed devastating earthquakes which has been one of the serious challenges for the masons and constructors on this land. Although most of the survived structures of the past are overdesigned, depending on the structural factors and the earthquake properties, the extent of damage varies greatly. Moreover, the survival of the structure to the past earthquakes does not necessarily guarantee its survival. Within this context, the assessment studies of the seismic resistance aims to understand the behavior of the structure under lateral action, which, in the later stages, will base the any intervention to improve its performance during the expected earthquakes. This paper provides a relevant case study to demonstrate the use of numerical analysis methods to assess a partially collapsed structure.

Structural Behavior of Masonry under Seismic Action

Masonry is a heterogeneous material that is composed of masonry units and binding mortar, which makes the generalization on the features of the masonry impossible since material properties and behavior greatly changes among different masonry types covering a wide range of materials from mud to natural stone. Of all, the weakness in tension and the high compressive strength are the identifying characteristics of the masonry that dominate the behavior of masonry structures under different actions (Kucukdogan 2008).

Seismic excitation is considered under the dynamic actions that induce external acceleration and movement in the structure changing the stress balance, in turn, which most of the time reflected as damage. Basically, earthquakes occur by the sudden release of the accumulated energy of the crust in the form of a rupture and this energy propagates as radiating waves reaching up to surface. Regardless of their type, the waves do create both horizontal and vertical forces on the structure. However, most damages and collapses are generated by the horizontal components of movements for which historical constructions are not designed to resist like the contemporary ones (Sevgili et al. 2005, Croci 1998).

Seismic performance of historical masonry buildings is affected from a variety of factors that are related with structural features of building, characteristics of earthquake, source to site distance and soil conditions. The mass, stiffness, period of vibration, damping capacity, structural continuities and distribution of mass and stiffness are among the structural features that determine the resistance to seismic excitation. Ductility, the ability of the building to deform plastically without collapse, is another characteristic that is of prime importance regarding the dissipation of energy however historical masonry constructions are generally rigid and structural connections are not designed to exhibit ductile behavior (Unay 2002, Feilden 1989). Damage during an earthquake is produced progressively that with every single shock the building becomes more damaged, disconnected which, in a way, result in the decrease in stiffness and increase in natural period (Croci 1998). Although the decrease in stiffness seem to reduce the amount of force induced, due to the weakening of the global behavior due to disintegration, cracking or partial collapses, this decrease does not help the structure at all. On the other hand, cracking and other damages may increase or decrease with the change in natural period interacting with the frequency of ground shaking (like dynamic resonance) (Feilden 1989).

However, with the damage the structure loses its initial structural properties thus its original behavior. Depending on the extent of damage, the structural mechanism can alter such that it may not be feasible to intervene greatly to get the initial state and the reconstruction, most of time, is not compatible with the articles of the Venice Charter that underline the importance of authenticity and the minimum intervention. The general approach for the heritage structures -damaged or partially collapsed -is to preserve the current state and improve its behavior in the sense that with upcoming actions the structure does not damage further. This, in a way, may seem as a decrease in the extent of intervention but it necessitates a comprehensive understanding of the actual behavior of the structure in the damaged state in which the behavior might be completely different. This can be obtained through a series of activities that is called condition assessment. Following the data acquisition, laboratory and in situ testing step comes aiming to get the reliable material properties of the structure. Within the light of acquired data, a realistic structural model of the structure under concern is developed to observe the behavior under certain actions. In the case of seismic resistance, the model is analyzed under a response spectrum which is likely to be valid for the region that the structure is located and the critical locations are determined. Diagnosis stage consists of both qualitative and quantitative investigations and aims to define the causes and their probable results at critical circumstances. The accuracy of diagnosis directly affects the safety and evaluation stage and consequently the preventive intervention. With today’s knowledge it seems not possible to get the 100% accurate results due to the inherit complexity of material characteristics, structural features and uncertain past histories of changes and damages in a historical structure but the results is certainly helpful and can reveal the parts accurately that need strengthening (Kucukdogan 2008).

Description of the Structure and the Observed Damage

The monastery of Stoudios was founded in 462 in the north west of the historic peninsula of Istanbul (Byzantine Constantinople). The monastery is considered important in the sense that it is one of the first examples of the religious architecture of Eastern Roman Empire and accepted as the oldest remaining religious building in Istanbul. It was assumed to be composed of several complexes for religious activity but today the only part remained is the church of St. John. The monastery was destroyed by the Crusades in 1294 and was damaged by the severe earthquakes in 542, 1296 and 1509. It was converted into a mosque in the early 15th century and reconstructed after the 1784 fire and 18-19th century earthquakes. The remaining part used as a mosque was completely abandoned after the fire in 1920 (Byzantium 1200 2008, Löffler 2007). Fig. 2 shows the 3D reconstructed image of the monastery as well as today's inside and outside view.

Figure 2 3D image and actual view of the Monastery of Stoudios (Byzantium 1200 2008, http://www.anlayalim.com/ wp-content /uploads/2010/01/imrahor_cami.jpg)

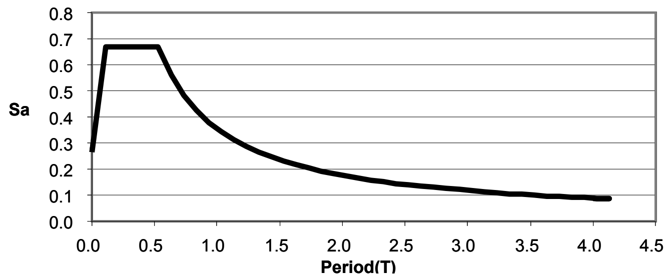
The monastery was made with the technique called byzantine opus mixtum which is composed of the alternating layers of brick and stone. The openings for windows and doors, in some parts, filled with brick assumingly during the modifications through time. The only remained parts from the whole monastery are the walls on four sides. The walls with a thickness of 1m are 42m-long with a varying height of 10 m to 12 m in the east-west direction while 25m with 6 m to 15m high in the north-south direction. The remained structure is more like a box with openings and has two wings that were once connected. Inside the structure, there is a pair of walls relatively shorter connected to main wall with arches (Fig. 3a). The minaret is located on one of the sides of the apses and more likely a free standing structure. The colonnades inside the main walls are mostly monolithic stones and are standing in only one side with a metal propping. Similarly, the rectangular windows that are not filled are supported with iron lintels. In few corners, there observed cracks due to relative movement of the walls resulting in separation. However, the separation is relatively small compared with the size of the walls. Similarly, diagonal cracks on the column like supporting substructures of the east-west walls are visible probably caused by the earthquake action and do not seem to occur recently (Fig. 3b). Minor cracking is seen throughout the structure but does not seem alarming. Material deterioration in some parts is clear but due to the very local concentration of the deterioration it is neglected. Although being nonstructural elements, the columns inside the courtyard pose the threat of overturning due to the lack of lateral connections in both sides. The architraves are mostly multi-piece and seem highly vulnerable to disintegration (Fig. 3c)

(a) (b) (c)

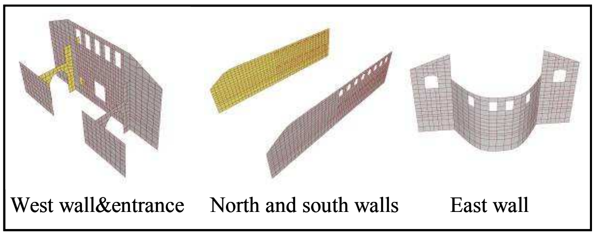
Figure 3 : The monastery in 3D (a); Cracks-main wall and supporting column (b); the collonade and the architraves (c)

Modeling and the Analysis of the Structure

Finite element model of the structure was developed with SAP 2000 using 3255 nodes and 3043 shell elements. The material properties of the structure are obtained through the literature works on Byzantine masonry and the suggested values for masonry in the Turkish Earthquake Code since no tests or material sampling was possible for the material characterization due to the legal status of the structure. The masonry units and the mortar are assumed as one homogeneous material with a constant modulus of elasticity and unit weight as 450 MPa and 24.5 kN/m^3, respectively. Linear elastic finite element dynamic analyses are carried out according to the inelastic spectrum obtained through the site dependent spectra derivation methods of Boore et al (1997) and Kalkan&Gulkan (2004) for M_w=7.2, 15km- closest distance to the fault and 5% damping (Fig. 4a). For the easiness in the evaluation of the results, the spectrum is applied to the structure in two different directions as EQ_x and EQ_y and the load combinations are made accordingly. Besides, allowable compressive stress values provided by the current Turkish Earthquake Design Code for stone masonry (f_c=0.3 MPa) is increased by 3 instead of decreasing the forces imposed by the excitation (i.e. R=1) in order to compare the results with the capacity. The allowable tension is assumed as 15% of the compressive strength, as 0.135 MPa. The allowable shear stress of the wall is calculated through the formula $\tau_m = \tau_o + \mu\sigma$ where τ_o, allowable stress for cracking (0.3 MPa), μ, the coefficient of friction (0.5) and σ vertical stress (0.45 MPa), thus, obtained the value 0.53 MPa for the allowable shear stress of the stone. Beside the analysis of the whole structure, local analyses are conducted for the walls to observe the behavior in detail, the 3D mesh of which is given in Fig. 4b.



(a)



(b)

Figure 4 : Inelastic spectrum used in the analyses(a); Seperated walls for local analyses (b)

Discussion of the Results

Modal analyses reflected the expected out of plane behavior in the north and south walls in the first two mode while in the third mode free motion of the wings are observed (Fig. 5).

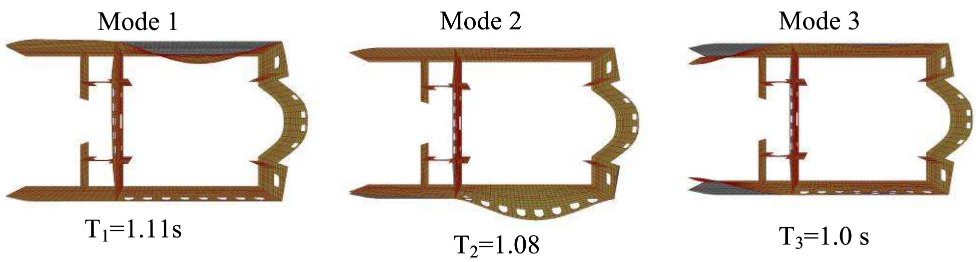
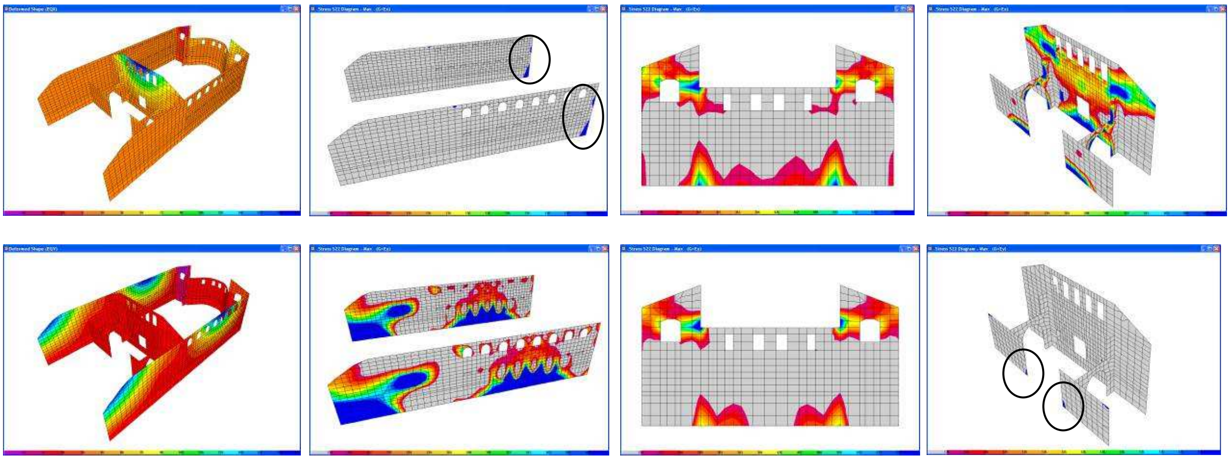


Figure 5 : Modal shapes

The analyses conducted using the spectrum in Fig. 4a has shown that the maximum displacement in both directions are observed in the places where the free cantilever behavior is dominant and the values are 197 mm in x-dir and 192 mm in y-direction, respectively (Fig. 6a). During this relative displacement, depending on the construction material and the quality of the bonding between the units, cracking or partial collapses can be expected. At this point the evaluation of the tensile stress distribution of the structure can help to determine the locations of probable cracking/separation. In Figs. 6b-d, the stress concentrations are given on the walls highlighting the stresses greater than 0.405 MPa where first row is for the excitation in x-dir, while the second is for the one in y-dir. For the north and south walls, the high tension in the intersection plane explain the tendency for the further separation of the walls under the excitation parallel to the walls while the tensile stresses are highly concentrated on the free wings and the mid section of the walls. For the east wall that has the curvilinear apses part the stresses increase around the bigger openings on the sides and on the bottom part of the apses under the effect of motion in both directions. The majority of the west wall is under tension and the high values are mostly observed around the openings under the excitation perpendicular to the wall and the damage seems inevitable in this part. The allowable shear stress is not surpassed in any part of the structure in any direction accept for the arches in the entrance part of west wall. Similarly, damage is not expected due to excessive compressive stress on the structure under this spectrum since the values are well below the allowable limit.



(a) (b) (c) (d)

Figure 6 : Max displacements under Eq_x and Eq_y loadings(a); Maximum tensile stresses: on the north and south walls (b), on the east wall (c), and on the west wall (d)

The analyses reveal that the structure is not under a serious stability threat, however, it should be remembered that in the study the effects of current damages, probable material deteriorations, and the probable foundation failures are not taken into account. Moreover, the material properties used are the common values and might greatly change in the actual case. Within this context, the structure seems to need some precautions to prevent any further damage. As stated previously, any intervention on historical masonry has to be based on an elaborate investigation and careful evaluation processes. Hereby, the aim is not to propose the strengthening applications in detail upon the preliminary analyses which is, in fact, highly prone to be far from the actual remedial measure that the structure needs. However, suggestions may give an idea on how to control further damaging.

The primary problem of this structure under excitation seems to be the out of plane behavior of the walls. The prevention of out of plane failure mechanisms of the walls can be achieved by buttressing, strutting, enlargement of the section, reinforcing and confining with steel systems and FRPs. Buttressing and enlargement of the section is considered to be highly invasive to the historic fabric and the appearance since they necessitate the construction of new sections and supporting elements. However, external reinforcing may give the flexibility to provide same safety level with less intrusion to the appearance and the fabric (Kucukdogan 2008). Use of steel ties connecting the structure to the ground symmetrically on both sides is one of the optimum solutions with minimum intervention and maximum efficiency (Jurina 2003). Corners are to be well connected to prevent the further separation which will also improve the global behavior since the stiffness increases with the box behavior. Openings in masonry walls are the zones of weaknesses where cracking and crushing are observed nearby as demonstrated in Figs. 6b-d. Under dynamic loading depending on their shape, regularity and pattern of openings they may affect the structural behavior considerably and may necessitate additional strengthening. The upper windows of the east wall and the window at the bottom of the west wall are examples of this situation. Architraves can be reinforced by steel beams, injection to mortar joints and tie-bars and steel plates stabilized by anchored tie-bars. Repointing and grouting the masonry arches in the west wall can strengthen the form greatly against shear failure. External reinforcement and tying of the springings of arches are commonly used applications to overcome the lateral thrust action in these elements.

Concluding Remarks

This paper presents the preliminary seismic assessment of a byzantine monastery within the general master plan on the evaluation of the historical constructions in Istanbul. The plan aims to classify those structures according to their vulnerability and thus aims to give the priority to highly vulnerables. Within this context, the monastery of Stoudios is analyzed under a site dependent spectrum obtained using the ground motion records of Turkey. The results revealed that the walls are prone to damage due to excessive tensile stresses that may lead cracking or partial collapses. Since the structure is known to be suffered from several severe earthquakes and already in a damaged state, strengthening of the walls is thought to be essential for the preservation of the current condition of the structure. However, with the present numerical analysis it was not possible to define and design the remedial measures in detail since the assessment is done without elaborate investigation stages just as a preliminary study for the further studies.

References

[1] (2008) The Byzantium 1200 website. [online] Available: http://www.arkeo3d.com/byzantium 1200/studion.html

[2] Agrawal, S K (2005). "Seismic rehabilitation of heritage buildings in India- Problems and prospects," in *Proc. SAHC :Possibilities of numerical and experimental techniques*, Modena, Lourenço & Roca (eds), 3-14.

[3] Boore, D M, Joyner, W B, and Fumal, T E (1997). "Equations for Estimating Horizontal Response Spectra and Peak Acceleration from Western North American Earthquakes: A Summary of Recent Work." *Seismological Research Letters*, 68(1),128-153.

[4] Croci, G (1998). "*The Conservation and Structural restoration of architectural heritage*," Computational Mechanics Publications, Southampton.

[5] Feilden, B M (1989). "*Conservation of Historic Buildings*." Butterworth & Co. Ltd, England

[6] Jurina, L(2003)."Il consolidamento delle strutture fortificate" [online]. Available : http://www.jurina.it/ pubblicazioni/Consolid_strutt_fortific_Como_2002.pdf

[7] Kalkan, E, and Gülkan P (2004). "Site-Dependent Spectra Derived from Ground Motion Records in Turkey." *Earthquake Spectra*, 20(4),1111-1138.

[8] Kucukdogan, B (2008). "Inventory study of strengthening and repair methods for historical masonry constructions." M.S Dissertation. Advanced Structural Analysis of Historical Constructions, Erasmus Mundus SAHC, University of Minho, Czech Technical University in Prague.

[9] Löffler, K (2007). Catholic Encyclopedia [Online]. Available: http://en.wikisource.org/ wiki/Catholic_Encyclopedia_(1913)/Studion/

[10] Sevgili,G, Kucukdogan, B, and Karaesmen, E (2005). "Old Masonry in Seismic Zones," in *Proc. Earthquake Engineering: Essentials and Applications*, Earthquake Engineering Research Center, METU, July 18-20.

[11] Unay, A I (2002). "*Seismic resistance of historical constructions*." METU Faculty of Architecture Press , Ankara, Turkey (in Turkish)