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Preliminary Observations on the Structural Condition of a Byzantine Monument in Historic Peninsula of Istanbul: Pantokrator Church

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Abstract The Church of Pantokrator (Zeyrek Mosque) is a Byzantine located in the Zeyrek district of Istanbul which was included in the World Heritage List in 1985 by UNESCO. The church suffered from earthquakes, fires and alterations in its history. In this paper, a brief history of the church, description of the northern structure with its damages and a preliminary analysis of the structure including an intervention proposal is presented. The reason to choose the northern part of the complex was due to its fragile condition in comparison with the other parts of the monument. This part has severe cracks on its structural elements and consequently during a possible repair and conservation work, it has priority.

Keywords: The Church of Pantokrator, Zeyrek Mosque, historic masonry, structural analysis, numerical simulation

Introduction

The Church of Pantokrator (Fig. 1) is one of the most important Byzantine monuments in the Historic Peninsula of Istanbul, dated to the 12th century (Müller-Wiener 2001). The monument is composed of three churches which were built in rapid succession between 1118 and 1136 (Fig. 2).

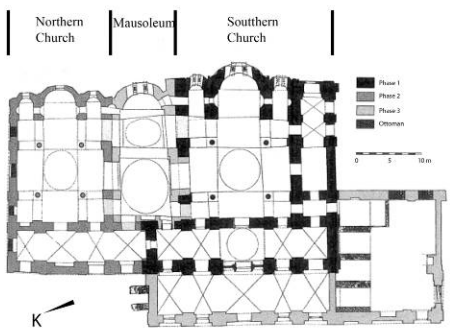

Figure 1: Plan of the church (Ousterhout, Ahunbay, 2000)

Figure 2: Eastern façade of the church

The southern church is the first structure erected by Queen Irene in 1118. The northern church was built in the second phase and finally the middle part, the imperial mausoleum was added after the death of the Queen in 1134 (Ousterhout and Ahunbay 2000). Today the south church functions as a mosque while the mausoleum and the north church are not used. In 2008, the repair and conservation work of the monument was given to a private company by the General Directorate of Pious Foundations.

Description of the North Church

The church is an example of cross in square type with a dome supported by four columns (Fig. 3). A cross vaulted narthex with a gallery is attached to the main structure. The plan of the naos, excluding the bema and apses is laid out as a square 13.50 meters on a side. Inscribed in this is a cross with arms 6 meters in width, projecting in the four cardinal directions. The structure has barrel vaults on the cross arms and a dome with a 5.50 meters diameter surmounting the cross at its intersection (Fig. 4). The dome is raised on a cylindrical drum and pierced by eight windows. Transition elements are pendentives and domical vaults are used to cover the four subsidiary bays, those flanking the bema and the two corner bays to the west.

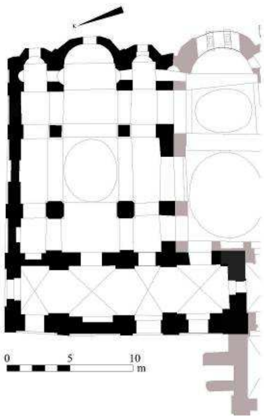

Figure 3: Plan of the north church

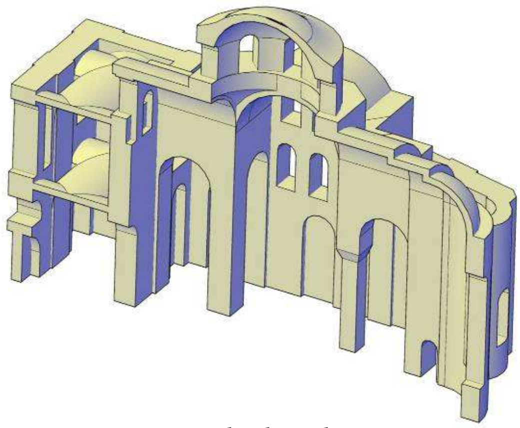

Figure 4: North church

Structural Damages and Preliminary Analysis of the Structure

The monument has suffered from earthquakes, fires, repairs and alterations in its long history (Ahunbay and Ahunbay 2005). During the site inspections all visible cracks were documented and indicated on the 1/50 scaled drawings. The main damages are listed below;

Southeast Pier The southeast pier and its capital are severely damaged. There are a lot of wide vertical cracks that begin from the capital and continue down over the ashlar pier until the floor (Fig. 5).

Figure 5: Southeast pier of the structure

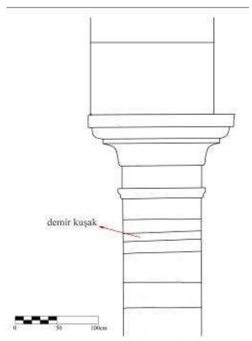

Figure 6: Western face of the southeast pier

The vertical cracks on the southeast pier result from the combination of two damage mechanisms. The first mechanism is due to the asymmetrical and irregular distribution of stresses within the pier. Originally the dome was supported by columns (Gurlitt 1999). During the conversion of columns into piers, which probably took place after the 1766 earthquake, the southeast pier was not placed precisely under the arch but displaced a little, causing eccentricity (Fig. 6). The second mechanism is due to the construction of the pier itself. There are voids behind the stone facing and some stones are detached from the core. In addition to these facts, during the construction of the pier, vertical joints of the stones were not placed properly.

North Cross Arm of the Structure A crack which ran parallel to the north wall was detected on the north cross arm of the during the conservation works on the roof in 1997 (Ahunbay and Ahunbay 2001). The vault was plastered from the interior so the crack could not be seen from the interior of the building. Before covering the vault with lead sheets, the crack was cleaned and then stitched in order to reintegrate the divergent parts of the vaulting. The damage mechanism should be related to out of plane behavior of north wall due to earthquake excitations.

Narthex and Gallery There are many wide cracks over the brick surfaces of the groin vaults covering the gallery. A lot of interventions took place in this area between 1950-1970. The groin vaults and the west wall were restored (Çuhadaroğlu 1974). The interventions made by using cement based mortar and bricks are detached from the original brickwork in most of areas. Original timber ties, which connected the transversal walls of the narthex, are missing; so there are no tie rods which can prevent the displacements related to the out of plane behavior of the west wall during earthquakes. The damage mechanism can be related to this phenomenon.

Walls: From earlier repairs and alterations, there are random fills in the masonry walls. The loss of bonding mortar at the joints of the original brickwork affects the load bearing capacity of the structural elements.

Timber Network To provide monolithic behavior and to avoid the out of plane collapse mechanisms, the walls and columns of historic masonry structures were connected by using timber or iron elements. Tie rods have been used for many centuries securing masonry structures against lateral excitations. But timber elements deteriorate and decompose during the long history of the buildings and therefore masonry structures become more vulnerable to tremors. The Church of Pantokrator was affected from this phenomenon. Original timber reinforcements within the walls were deteriorated, thus provoking further damage to the vulnerable masonry. There are voids in the place of decomposed timber beams those incapable of providing the reinforcement that were originally designed for.

Finite Element Analysis of the Structure

In order to get further information about the behavior of the structure under its self weight and seismic excitations, some numerical models were prepared using finite elements. Masonry was modeled as a homogeneous material which behaved within the elastic range under compressive and tensile stresses. The parameters of the linear elastic material such as density (1800 kg\m^3), modulus of elasticity (1,5E+9 Pa) and Poisson's ratio (0,20) were defined according to information related to other Byzantine structures. Finite element discretization of the structure was made by using sufficient number of elements (solid 45) with max edge dimension of 30 cm (Ansys 2003). The foundation of the building was assumed to be rigidly fixed to the ground for all types of analyses.

At the beginning, a series of elastic linear static analyses of the structure under its self weight by using different geometrical characteristics were conducted in order to understand not only the structural behavior but also the contribution of its structural parts. The building of the geometrical model started with the core of the structure namely the barrel vaults, pendentives, drum and cupola and continued by adding the other parts of the structure (Fig. 7).

Figure 7: Geometrical models of the structure

The stress distribution of the structure under its own weight indicated that the maximum compressive stresses appeared at the southeast pier which has vertical cracks (Fig. 8). As expected, the values of tensile stresses which dominate the barrel vaults and the arches that connect the piers to the perimeter walls were not big enough to provoke damages that would lead the structure in to a vulnerable condition. One of the important results obtained from the analyses was the displacements on the transversal direction corresponding to the eastern piers (Fig. 9). As the structure lacks tie beams between the piers and walls, there is no effective system that could prevent the displacements and secure the monolithic behavior the structure.

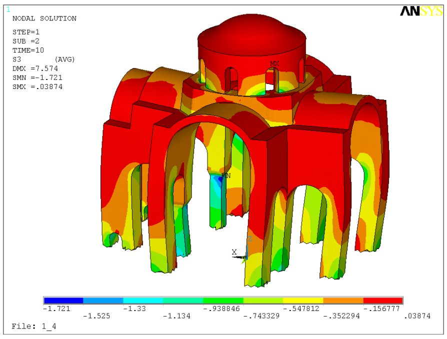

Figure 8: Max compressive stresses on southeast pier

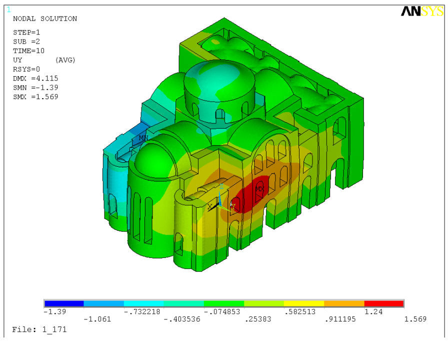

Figure 9: Displacements on transversal direction

Modal analyses were conducted to figure out the vibration characteristics (natural frequencies and mode shapes) of the structure. The first mode shape of the structure was influenced by transversal movement, the second by longitudinal and the third by torsion. The data obtained from these analyses served as a starting point for a spectrum analysis (Ansys 2003). The behavior of the structure under earthquake excitations was obtained through spectrum analysis in which a predetermined acceleration spectrum graph was used. The response spectrum was defined according to Turkish Earthquake Resistant Design Code[1] and internal forces were obtained by using SRSS rule. The analyses were carried out in longitudinal and transversal directions. The effective mass of the considered modes were greater than 90% of the overall mass of the structure.

Earthquake loading computed in the longitudinal direction (EW) indicated that due to the out of plane mechanism of the west wall, the tensile stress distribution between cross vaults and west wall could possibly cause a crack pattern that runs through the vaults parallel to the west wall (Fig. 10). This mechanism matches the crack pattern of the gallery vaults which were repaired during the conservation works between 2001 and 2005 (Fig. 11). The results of the analysis indicated also relatively high shear stresses on northern and southern walls but the damages should be expected on the secondary load bearing elements such as tympanums.

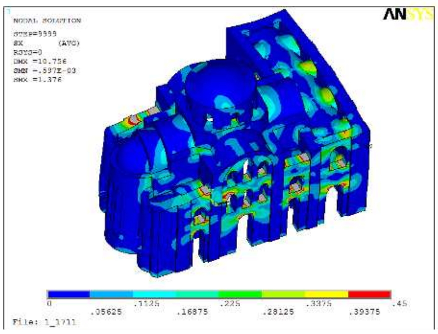

Figure 10: Tensile stresses between west wall and cross vaults of the gallery

Figure 11: Cracks on the cross vaults of gallery, 2001

Shear stress distribution of earthquake loading computed in the transversal direction (NS) demonstrated that the eastern wall was subjected to high values of stresses in comparison with other parts of the structure (Fig. 12). During the earthquake excitations, pastophorion walls probably would be affected by a crack formation that begins from the ground and reaches to the upper parts of the wall running through the openings. This result also verifies the damaged condition of the eastern wall which was repaired during the conservation works, carried out by professors Metin and Zeynep Ahunbay in 2005 (Fig. 13).

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[1] The Ministry of Public Works and Settlement of Turkish Republic, "Turkish Earthquake Resistant Design Code", 2007

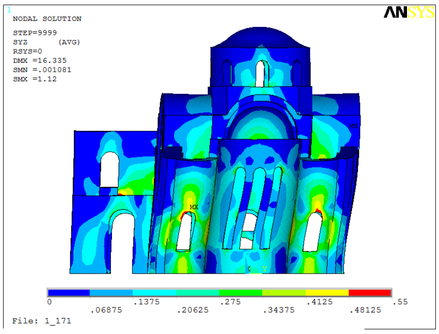

Figure 12: Eastern façade of the building

Figure 13: Eastern façade of north pastophorion before the repair works, 2004

Proposals for Repair Works

In order to keep the character of the structure in the present state and to prevent further damages from the possible earthquake excitations, preliminary proposals were prepared having in mind the minimum intervention-maximum efficiency principle. Naturally these interventions aim primarily to prevent out of plane mechanisms and to restore the mechanical properties of the structural elements. The materials for the repair works should be compatible with the original ones. The proposals that should be detailed by further studies are listed below;
*To connect the opposite walls and the vaults by applying a network of ties.
*To substitute the role of now missing timber reinforcements and also to connect the longitudinal walls of the structure by using tie rods in their place. In order to make this intervention effective, cohesion and cooperation of the ties should be ensured.
* To replace surface timber ties with new timber beams where it is possible.
*To embrace the eastern pier with stainless steel frame and to connect all the piers to the walls by rods.
*To restore the load bearing capacity of all structural elements by grouting the masonry, stitching major cracks, reintegrating-rebuilding of disorganized and missing parts.
*To clean, repoint and replaster vaults, domes and walls.

Conclusion

The Church of Pantokrator is one of the important Byzantine monuments in Istanbul. It is a unique structure not only because of its high historic and aesthetic values, but also as a resource of information on construction techniques and details of medieval period. Therefore, there is a need to combine the efforts to increase its earthquake resistance while preserving its authenticity.

As a part of the structural analyses, the response of the church under its own weight and lateral excitations were examined by using finite elements. The results of the analysis were compared with visible damages of the structure and the probabilities of different damage scenarios were considered. The areas, at which the tensile stresses exceeded the corresponding strength of the masonry, were determined and compared to the existing crack pattern. But further research is needed to understand more precisely the behavior of the structure against earthquake excitations and to validate the models based on comparison with the results of in-situ experiments.

Acknowledgements

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