PRELIMINARY STRUCTURAL ASSESSMENT OF KARIYE MONUMENT - NORTHERN ANNEX

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ABSTRACT

In this study, the architectural and structural features of Kariye Monument are outlined, with particular emphasis on the evaluation of structural behavior of Northern Annex. The evaluation study included extensive on-site observations, preparation of in-situ drawings of the existing structural system, damage assessment, and two and three dimensional structural analysis of the Northern Annex, as well as examination of existing documents on Kariye Monument. The observed damages in the Northern Annex are found to be consistent with the structural analysis results, which included the effects of foundation settlement and rotation as well as vertical loads.

1. INTRODUCTION

Kariye Monument, which is among few remaining examples of Byzantine period, is briefly described in various books and articles on Byzantine architecture [3], [5]. These documents represent Kariye Monument as a unique example of the 14th century Byzantine art. The building was studied in depth for the first time during the restoration works of American Byzantine Institute (1947-58). Except for some architectural/structural interventions especially in the eastern parts of the monument, the works undertaken during these years focused mainly on the mosaic and fresco restoration. However, the excavations, photographs, plans, sections, elevation drawings and the observations of this period are of great value and constitute the foundations of the later studies. The summary reports of the Kariye excavations were published in 1960 [6]. Three volumes published by P.A.Underwood in 1966 were also based on the findings of the same period; however, except the introduction of the first volume, Underwood also focused on the mosaic and fresco art of Kariye monument [10]. Almost two decades later, R. G. Ousterhout published in 1987 the only detailed and in depth study that deals with the architectural and structural features of the monument. His study included valuable insights into the structural weaknesses of the monument [8].

In this study, after an outline of the history and architectural characteristics of Kariye Monument as well as some construction features, the observed damages and structural analysis results are presented for the Northern Annex of the Monument. The two dimensional and three dimensional analyses were in good agreement with each other, as well as the observed damages of the vaults of the Northern Annex.

2. HISTORY OF KARIYE MONUMENT

Kariye monument, located in Edirnekapı, Istanbul, is very close to Theodosian Walls that constitute the border of Historic Peninsula today and the border of Byzantine Constantinople. Although the history of the monument dates back to 6^{th} century, no reliable information exists for the period until 11^{th} century. In 11^{th} and 12^{th} centuries, extensive rebuilding and enlargements were carried out. At this period, the monument was transformed into a church or small monastic complex. During and after French and Italian invasions and occupations in the first half of the 13^{th} century, Constantinople was plundered and burned down, and many churches were destroyed and robbed until 1261. Michael Palaeologos during his reign (1261-82) encouraged the reconstruction and repopulation of the capital [9]. When Kariye was rebuilt in the second decade of the 14^{th} (1315-21) century, large churches were not being built anymore due to smaller religious community and economic situation. The attitude of the donors and builders during the Palaeologan Dynasty was to repair and enlarge the existing churches and monasteries rather than building new ones [3]. The donor and very probably the designer of the 14^{th} century Kariye Church was Theodore Metochites, who had very close relationship with the Palaeologan family. He was also the person, who ordered the rich mosaic and frescoes in the monument. After the conquest of Constantinople by the Ottomans in 1453, the church was converted into a mosque (1511) [7]. The bell tower was immediately replaced with a minaret, mosaics were plastered. Some repairs were also made later, mainly to improve the building structurally or to keep the water away from the interior.

There is no information about the damages caused by 1509 and 1754 earthquakes. In 1766 earthquake the main dome of the monument collapsed. It was replaced by a wooden dome during the restoration undertaken in the same year [5]. Half of the minaret fell down in the earthquake of 1894.

The monument was turned into a museum in 1945. The monument and its mosaics and frescoes were restored by the American Byzantine Institute during the Republican years between 1947 and 1958. Kariye Monument is famous for its mosaics and frescoes that are the unique examples of Byzantine Art.

3. ARCITECTURAL CHARACTERISTICS AND CONSTRUCTION

The building settles on an area of 27.5×27 meters. The main dome, which is carried by 12^{th} century arches and piers measures 7.45 meters in diameter. Four arches that transfer the load of the dome to four corner piers rise approximately 10.35 meters above the floor level. Over the cornice, which ends at 11.52 meters, comes the dome that rises another 6.40 meters [8]. The dome is rebuilt from wood and plaster (bagdadi technique) in the Ottoman period in 1766, possibly after the earthquake in the same year [8]. Both prothesis and diaconicon that constitute the pastophoria are rectangular in plan. Those were turned to squares with the help of vaulting. The parecclesion, which functioned as a funerary chapel and sheltered the tombs of Theodore Metochites and other members of the aristocracy, was entirely constructed in the 14th century, including two long barrel-vaulted cisterns beneath the ground level. The second largest dome, which measures 4.70 meters in diameter, was situated in parecclesion. The irregularity of the rooms between naos and parecclesion show clearly the difficulty of adding new space to the existing naos. The northern annex, which was used as Metochites' library, has two floors. Lower floor is rectangular in plan measuring internally 10.14×2.99 m and is covered with barrel vault. Upper floor measures internally 2.97×9.79 m and is covered with barrel vault that rises 3.50 m above the floor.

The oldest foundations of Kariye date back to the 6th century (Figure: 1, phase 1) [8]. Two brick arches, which were part of an arcaded wall survived in the eastern part of the building. Ousterhout claimed that those were used as a funeral crypt, but the function of the building they belong is not known [8]. Those arches were blocked (strengthened) in the 9th century and were used as a terrace wall supporting the next building (Figure: 1, phase 2). The 11th century brick construction survived in the lower naos walls (Figure: 1, phase 3). In 1120, the church was rebuilt and the central space, dome and apse were enlarged. Except for the dome, which was rebuilt in the Ottoman period, the piers, walls, arches of the naos and bema, which survive today, were built in that time (Figure: 1, phase 4). The crusade armies' occupation (1204-1261), the earthquake of 1296 and the rioting of Catalan Company (1302) may have caused serious damages to the 12th century Kariye Monument. The church was repaired and enlarged by Theodore Metochites in the 14th (1315-1321) century; pastophoria, northern annex, parecclesion, two narthexes, the flying buttress (that supports the apse) and bell tower were constructed (Figure: 1).

The three layered walls of 11th and 12th centuries Kariye (naos and main apse) were built with the recessed brick technique [8]. This is common in almost all of the buildings in Constantinople constructed in the same period. Recessing every second course of brick roughened the inner surface and bonded firmly the rubble core of the wall (Figure: 2). The use of rubble core walls was common in Constantinople, because bricks were no longer available in the Middle Byzantine Period as they were in the earlier centuries [3]. The construction of the 14th century Kariye is almost entirely solid masonry with little or no rubble fill; this could be traced through the wall pattern, which is the same in the interior and exterior [8]. In Kariye Monument, the bricks are used alternating with stone with the pattern of four courses of brick to four of stone. This pattern changes only in prothesis and north annex, where three courses of brick alternating with four of stone (Figure: 3). Byzantine mortar includes lime, sand and crushed brick. The ratio between thickness of brick and mortar joint, which changes throughout centuries, is approximately 1:1.5 in 11th and 12th century walls, and 1:2 in 14th century walls of Kariye.

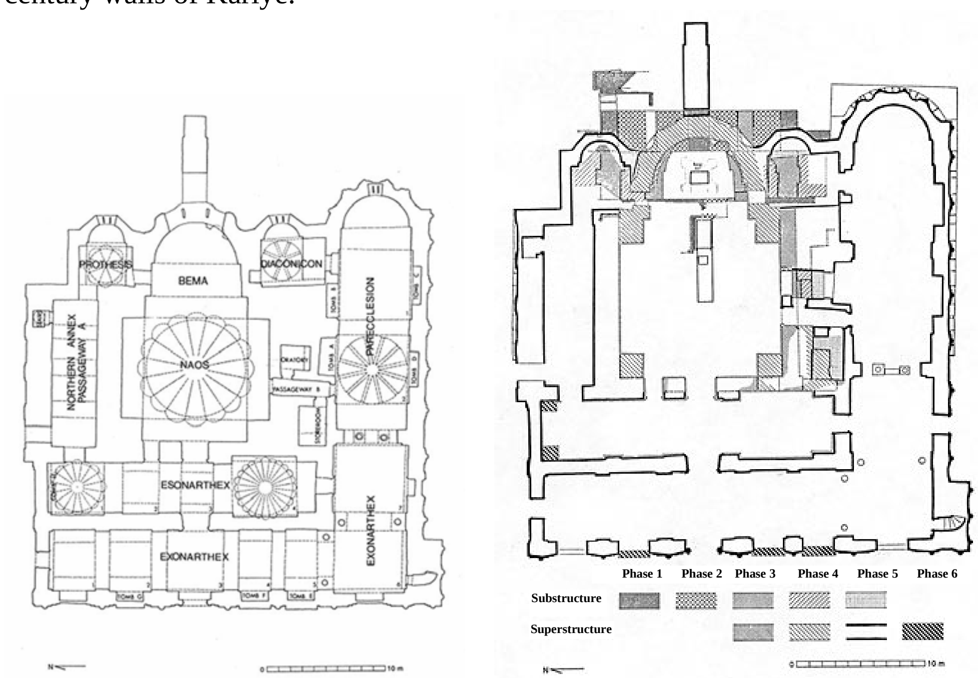

Figure 1 [8]

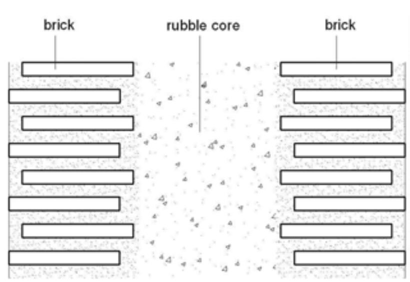

Figure 2

Figure 3

4. DAMAGES

The terrain of Kariye monument has been shifting downhill. This phenomena caused cracks in the Eastern part of the building. A 8 cm wide crack, which occurred in the eastern bay of parecclesion, was repaired using cement mortar during 1950s (Figure: 4). The shifting of the terrain was also the reason for the construction of a flying buttress in the 14th century to support the eastern wall of the apse and later the collapse of buttress's central flyer, which was restored in 1950s (Figure: 5).

Figure 4 [8]

Figure 5 [8]

During the Ottoman restoration of the monument in 1875-76 to level the roof, a considerable amount of rubble was placed. This intervention not only changed the appearance of the monument, but also brought extra load to the structure. The appearances of the monument before 1875-76 restoration and today are presented in Figure: 6. The architectural additions made to the 12th century naos and bema had to be adapted to the older elements and meet certain functional requirements of the period, resulting in a structural irregularity, which is pointed out to be the major factor of the monument's structural weakness [3], [8]. According to Ousterhout, lack of vertical coordination of windows in the eastern wall of the north annex is the reason of the wall crack there [8]. The vertical non-alignment could be observed also in the western wall of the north annex, where the vent window is not aligned with the entrance door (Figure: 7).

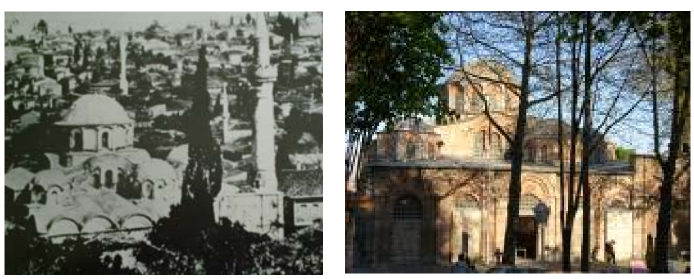

Figure 6

Figure 7

Figure 8

Moreover the south wall of the north annex, built as a facing of the 11-12th century naos rests on the preexisting foundations, while the outer north wall rests on the 14th century foundations. The settling of northern foundation seems as one of the reasons for the cracking of the vault covering the lower chamber of northern annex (Figure: 8). The vault was strengthened by the Ottomans who added three pointed arches of brick and stone.

5. STRUCTURAL ANALYSIS OF THE NORTHERN ANNEX

In order to explain the causes of large cracks on the vault covering the lower chamber of the Northern Annex, a number of finite element analyses were performed on a portion of the structure. Two and three dimensional analyses were carried out using commercial finite element programs SAP2000 v.9.03 and ABAQUS v6.6-1, respectively [2], [1]. For the sake of simplicity and reduced run time, linear elastic and isotropic constitutive laws were utilized for material characteristics of the masonry components. The material characterizing the alternating brick-stone masonry walls and the brick vaults covering the lower and upper chambers of the Northern Annex were assumed to have an elastic modulus of 1000 MPa, poisson ratio of 0.15 and density of 2000 kg/m^3. These values are compatible with the values given for this type of structures [4]. The two dimensional simplified model was created using equivalent frame members, while 261716 four-noded C3D4 type tetrahedral elements with an average element size of 200 mm were used for three dimensional sophisticated analysis. The view of the Northern Annex and the finite element model are shown in Figure: 9.

The initial three dimensional finite element analysis was performed for the vertical loads, which were determined as the self-weight of the structure. Apart from the load bearing structural components, the weight of the infill material used for leveling of the upper chamber was also included in the analysis. Under the effect of self-weight, maximum compressive stress in the main walls of the lower parts of the structure was around 0.18 MPa, which is well below the compressive strength of brick and stone masonry. An average compressive stress of 0.10 MPa, and tensile stress of 0.10 MPa were obtained for the upper and lower faces of the mid-span of the lower story vault, respectively. From these values, it can be concluded that the intensity of the stresses induced by the self-weight of the structure is not sufficient alone to explain the damage pattern shown in Figure: 8. The deformed shape of the structure and the close-up view of the maximum principal stress distribution at the vault cross-section are given in Figure: 10.

Following the statements done by Ousterhout [8] and the in-situ observations, it was decided to investigate the effect of settlement of the ground. After a number of trials on the type and the amount of a probable ground settlement, it was seen that a differential settlement causing around of more than 6 mm difference between the opposite sides of the northern façade wall may cause the damage pattern shown in Figure: 8. The deformed shape of the structure and the close-up view of the maximum principal stress distribution at the vault cross-section obtained only for the differential settlement are given in Figure: 11. As seen in this figure, the maximum principal tensile stresses at the lower face of the mid-span and the upper portion of the vault-main wall connections are higher than the assumed 0.2 MPa tensile strength of the masonry. As seen in Figure: 11, the locations of tensile stresses higher than the tensile capacity of the vault correspond to the actual crack locations observed on-site.

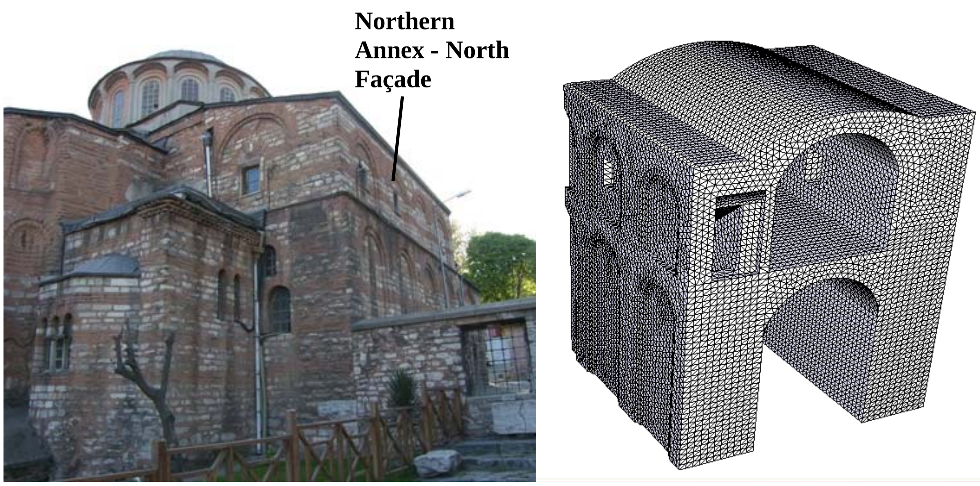

Figure 9

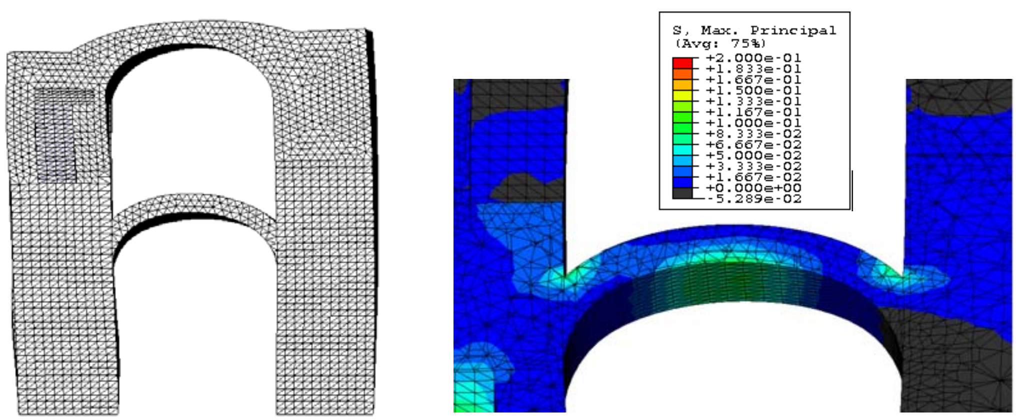

Figure 10

The maximum principal tensile stresses formed due to combination of self-weight and differential ground settlement explained above are very close to stresses formed due to ground settlement only. This indicates the significant contribution of differential settlement to the overall behavior.

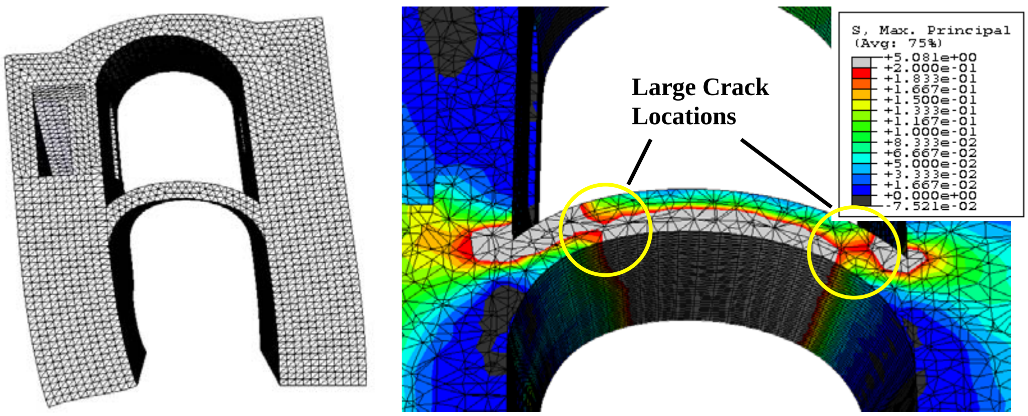

Figure 11

6. CONCLUSIONS

According to structural analyses carried out using finite element methods and on-site damage observations, it is concluded that the damages in the vaults of the Northern Annex are not formed due to the self weight of the structure, but formed as the result of differential settlement of the foundation of the north wall of the Northern Annex, which is thought to settle on relatively shallow 14th century foundations.

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