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Structural Evaluation and Strengthening of Zeynelbey Tomb in Hasankeyf, Turkey

TURER Ahmet[1,a]

[1]Department of Civil Engineering, Middle East Technical University, Ankara, Turkey

[a]aturer@metu.edu.tr

Abstract Hasankeyf historic settlement area is one the most important sites in southeastern Anatolia which dates back to the 15th century. Zeynelbey Tomb is a distinct cylindrical structure has a height of 9.6 m and with double domes extending to an overall height of 16.5m; however, the outer dome suffers from multiple and large vertical tension cracks threatening the overall structural stability and safety of the structure. A preliminary visual inspection and structural evaluation using analytical modeling was carried out. The tension zones developing at the outer dome was determined using analytical simulations and causes of vertical tension cracks were elaborated. A general remedy of strengthening was developed to surround the dome using vertical ribs and horizontal post tensioning strands that are placed in three vertical layers. The deterministic analytical simulations using the horizontal post-tensioning have allowed finding the necessary amount of tension force in each horizontal strand to diminish the tensile stresses inside the dome and put the structure in a stable compression state. This paper describes the steps carried out for the assessment, evaluation, and retrofit studies, which might set an example to similar historic structures with comparable structural problems in the dome.

Keywords: Dome, evaluation, strengthening

Introduction

Hasankeyf historic settlement area is located at city of Batman in the southeast part of Turkey (Fig.1). The Zeynelbey Tomb is a distinct structure that has significant importance in the Hasankeyf historic area and has been studied since 2006 by METU (Turer 2009) as a consultancy to KABA (KABA Conservation of Historic Buildings and Architecture Ltd. 2010). The tomb is located at the entrance of Hasankeyf, near Tigris (Dicle) river and is a part of general complex of buildings (Külliye) which normally consists of mosque, kitchen to feed poor people and students, school, library, hospital, and bath. The two schools and bath are from Artuklu era (13th century), tomb and kitchen is from Akkoyunlu era (15th century), others are from Ottoman times (16th to 18th centuries). According to the writings on the tomb, the tomb was constructed in about 1475 for Zeynel bey who is the son of Uzun Hasan, the sovereign of Akkoyunlu state (The information sign in front of Zeynelbey Tomb, Hasankeyf 2007). Being the only example of such architecture and fine brick tile art in Anatolia, the structure has a special importance. The tiles form Arabic inscriptions that are “Allah” on the first belt, “Ahmet” and “Muhammed” in the second and third belts, and “Ali” at the lower belt (Hasankeyf website 2010).

More than four centuries old Zeynelbey tomb has a cylindrical main body from exterior, octagonal shape from the interior, and supports a double dome structure (Fig. 2). The main body of the tomb has a cylindrical structure with a height of 9.6 m and the overall height extends to 16.5m; however, the outer dome suffers from multiple and large vertical tension cracks threatening the overall structural stability and safety of the structure. A preliminary visual inspection and structural evaluation using analytical modeling was carried out (Fig. 2). The tension zones developing at the outer dome was determined using analytical simulations and causes of vertical tension cracks were elaborated. Section loss at the base level and major cracks on the dome are spotted to be the two main structural problems of the structure. It was learned that illegal fish poaching in the nearby Tigris River using dynamites might also possibly be a factor in the accumulated structural damage on Zeynelbey tomb. This paper

discusses the causes and developed remedies to stabilize the crack opening and possible instability based failure of the outer dome.

Figure 1: Turkey map and location of Hasankeyf

Figure 2: General view of Zeynelbey Tomb

Visual Inspection and Structural Evaluation

The external view of the historic building manifests various problems mostly due to aging process and improper maintenance. The initial observation is the loss of section at the first 2 meter height of the building (Fig. 2). The section loss is significant at the base of the building which might possibly be

due to change of the river elevation and the first few meters of the structure being flooded by the river. It might also be possible that the lower part of the tomb was supported by large stone blocks in the form of stairs and has been taken by the locals as free construction material. It is also known that there have been interventions to support the lower parts of the tomb in the last decade using Portland cement which might have harmed the chemical composition of building material due to salt intrusion. The intervention using cement was later on understood to be unsatisfactory and removed away.

The dome of the tomb seems to have a slightly expanded (onion like) view. Existence of vertical cracks around the dome could be clearly seen from distance. Previous repairs by inserting bricks in the vertical orientation can also be identified on earlier cracks. Some vegetation growth at the top of the dome is also clearly seen from distance, which is an indication of material degradation (turning into soil) as well as root growth into the cracks of the dome. However, the exterior view of the bulging dome and vertical cracks is nowhere near as frightening as the view that was observed from the inside of the dome (Fig. 3). The cracks are much more pronounced and large in the vertical direction. The observation indicates that the tension stresses developing due to self weight of the dome and in the transverse direction causes the vertical cracks to form. The dome walls have a tendency to open in the peripheral axis as the cracks expand. The dome is now divided into about 8 vertical slices that are expanding outwards. The top portion of the dome is behaving differently since the close-to-flat top portion of the dome is more stable within itself due to better confinement and its self weight is pushing the sides outwards. As the sides of the dome are expanding, the circular region between the relatively vertical and relatively flat parts is cracking as well (Fig 3). When the bottom of the dome where the inner and outer domes come together is also severely cracked. The vertical crack opening between the two domes have a larger with at the top compared to the bottom of the crack indicating an outwards rotation of the outer dome's support. Furthermore, two holes at the top of the dome were determined. The larger hole is expected to generate a cause for instability by itself since it disturbs the stress flow in the dome structure. The edges of the hole can easily be eroded by the precipitation in the area.

The main behavior of the dome is identified to be peripheral expansion of the vertical walls of the dome. Overall degradation of the material in centuries and poor maintenance adds up to the vulnerability of the dome. The top portion, which might be called as 'hat', has the danger of collapsing downwards over the inner dome if the outer dome continues to expand. The expansion would leave the 'hat' being unsupported. The roots of the vegetation at the dome's top surface might also have adverse effect by their roots moving into the cracks and further expanding them.

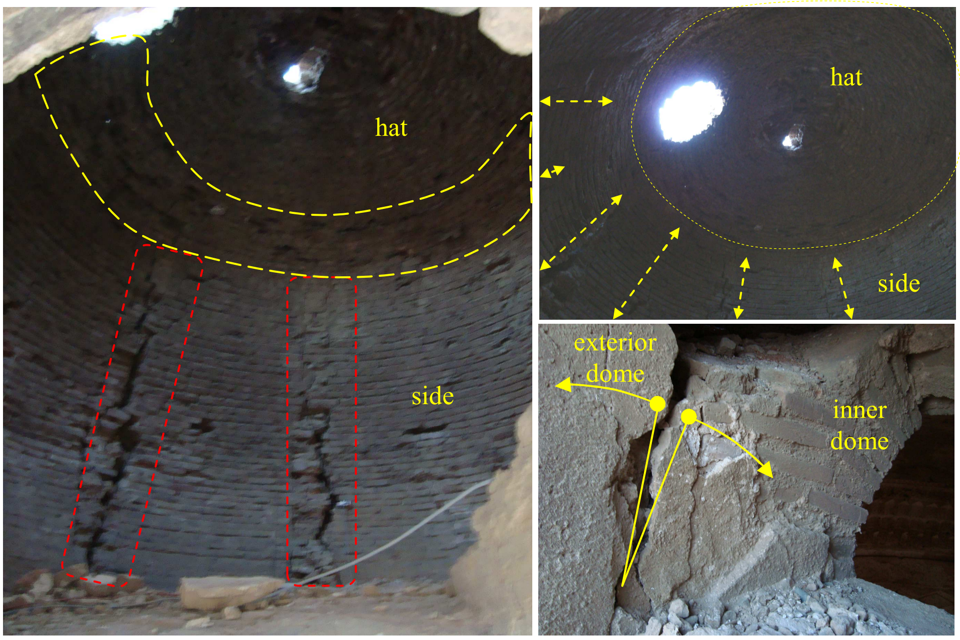

Figure 3: Inside view of the dome

Proposed Structural Strengthening Methodology

The major and urgent structural problem of Zeynelbey Tomb is considered to be the expanding outer dome structure. Due to the expanding behavior, the top portion (hat) of the dome is under the risk of falling down over the inner dome. If the hat falls inside the dome, it would push the side and vertically cracked dome segments outwards; when crashes on the inner dome (Fig. 2, Fig. 3) it would also cause the inner dome to receive substantial damage or collapse. The secondary major problem is considered to be the lower part of the cylindrical main body, which has major section loss and material damage.

The strengthening strategy proposed for the exterior dome structure was peripheral post-tensioning (Fig. 4). As an example, barrels have wooden ribs that are placed side by side in vertical orientation. The post tensioning rings around the ribs apply peripheral pressure on the wood, which causes a stable structure even though the wooden ribs are not interconnected at their vertical joints. The cracks on the Zeynelbey Tomb's exterior dome are similar to those joints that exist in a barrel. If a peripheral post tensioning could be applied, that would prevent further expansion of the exterior roof providing a stable structure. If the dome cannot expand in the horizontal direction, the top (hat) portion is expected to stay in its current position as well. A light weight internal supporting structure is also suggested to for the hat portion to guarantee its stability.

The suggested external post tensioning is thought to consist of cables passing through eight vertical ribs which will press on the dome. The exterior surface of the dome is not smooth enough for a continuous post tensioning ring. Furthermore, it was not desirable to have full contact with the dome exterior surface. Most importantly, a possible peripheral ring could have slipped upwards not providing its post-tensioning duty. Placement of a horizontal ring would be suitable for post-tensioning application, which needs to be monitored continuously and fully adjustable over time as needed. Therefore, vertical ribs were planned at 8 locations around the dome with 45º intervals. The post-tensioning cables would pass through holes on the vertical ribs and can be easily tensioned to the desired force. The holes on the ribs were elevated to a distance of 0.0824×(r) as shown in Equation 1, so that the post-tensioning cable would not touch the dome and can be tensioned. The ribs were planned to have rubber surface to distribute the force evenly and without causing stress concentrations on the rough and uneven surface of the dome. Nevertheless, a cushion level of mortar is planned to be applied on the large voids on the dome at the location of the ribs. Such mortar application will not be placed on the brick tile motifs but at locations of heavy damage and large voids. The vertical rib structure is planned to have four pieces that are interconnected using three one-dimensional hinges (Fig. 5). The post-tensioning cables need to be tensioned in incremental steps. The force in the cables will be measured and changes over time will be monitored using a series of load-cells that will be connected to the cables in series. The crack widths will also be monitored during the strengthening process as well as in the future years to come.

$$(a-r) = (1-\cos(22.5))\times(a) = 0.0761\times(a) = 0.0824\times(r) \quad (1)$$

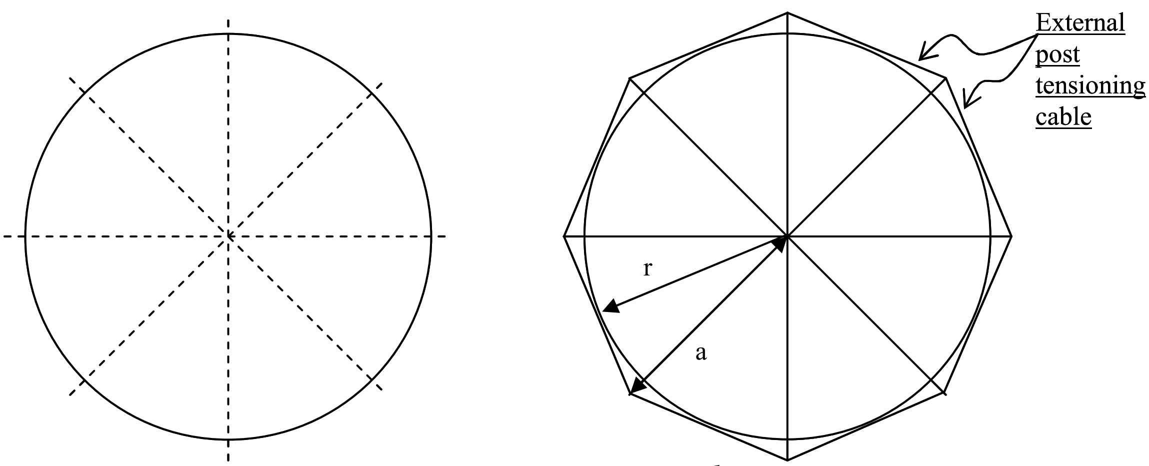

Figure 4: Put your caption here

Figure 5: Put your caption here

The second major problem is considered to be the section loss at the lower 2m height of the cylindrical shaped main body (Fig. 6). If the missing parts of the wall are completed without any reinforcement, the completed segments are expected to fall out in time due to inclined surface and pushing action of the main wall (Fig. 6c). Peripheral reinforcement was initially planned to be placed at the outermost layer of the newly placed triangular portion keep those new addition parts of the wall in place by applying a confinement effect. However, the peripheral reinforcement has to be continuous and the door openings might be a problem. Furthermore, the rebar sizes were found to be quite large for using in a historical structure. Alternatively, short and perpendicularly placed rebars were planned to be used for keeping the new triangular shaped additional wall segment in place (Fig. 6b, c). The rebars were planned to be 8mm in thickness; therefore, a minimum length of 40φ diameter should be supplied to maintain proper development length. The bars' length need to be a minimum of 0.32m, thus the length of rebar that will be inserted to the old and new wall segments planned to be 0.2m long for a total length of 0.4m. The rebar dimensions will be the same everywhere, except their application density will be different as a function of the slope of the additional wall.

The slope calculation plays an important role on the shear and tension forces developing on the surface of the triangular shaped additional wall. Assuming that the pressure from the upper structure ($P_{vertical}$) will be approximately in the order of 300 kPa (15m×20kN/m^2); the pressure acting perpendicular and parallel to the surfaces can be calculated using Equation 2, which is derived using equilibrium of forces.

$$(P_{tension}) = (P_{vertical}) \times (\sin(\alpha))^2, \quad (P_{shear}) = (P_{vertical}) \times \sin(\alpha) \times \cos(\alpha) \qquad (2)$$

The calculations indicate that the density of rebars that will be placed inside the wall, perpendicular to the surface between the old and new wall segments will get higher as the inclination of the wall approaches to 45 degrees. The most critical value for tension is found to be equal to the pressure coming from the above. Considering 300 kPa of vertical compression, and 141 MPa allowable stress for the rebars, about 42 bars is needed for each 1 m^2 area. If the rebars will be placed evenly, each rebar needs to cover an area of 241 cm^2 or a square with each side of 0.155m. Therefore, each rebar having a total length of 0.40m is planned to be planted on a grid of 0.15m×0.15m. The 8mm diameter rebars will be placed inside 0.20m deep drilled holes with proper mortar and other 0.20m long piece will remain inside the new wall to be constructed to fill the lost triangular shaped gaps (Fig. 6b, c).

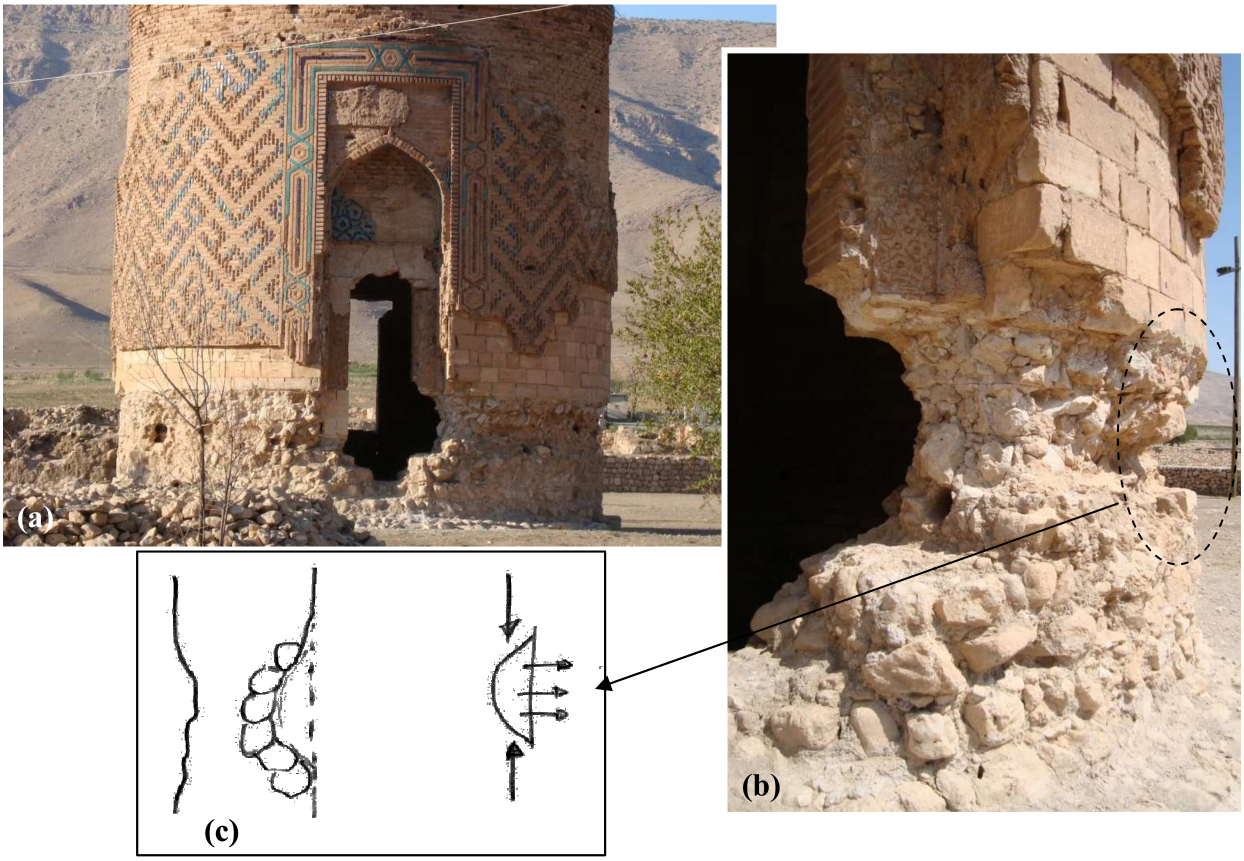

Figure 6: Put your caption here

Conclusions

The two major structural problems of Zeynelbey Tomb were identified to be the vertical tension cracks on the exterior dome and the section loss at the base walls. The post-tensioning and internal support of the exterior dome is absolutely necessary to prevent possible collapse of the exterior and consequently the interior domes. The remedies developed to stabilize and improve the current structural condition were planned to be minimum intervention and respecting the authenticity of the structure, while applying compatible or reversible materials and techniques.

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