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STRUCTURAL EVALUATION OF KILITBAHIR CASTLE IN CANAKKALE, TURKEY

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Abstract. *Kilitbahir castle was constructed by Fatih Sultan Mehmet in 1452 – 1463 at European side of Canakkale city to control passage in the strait from the Aegean Sea to the Sea of Mar-mara. The castle has a very interesting shape in the form of a clover leaf surrounding a tri-angle shaped central tower. Additional exterior rampart walls protect the castle from the land side. The castle is recently going through a restoration work, while the earlier major restoration works were carried out in 1541 and 1870. This paper consists of visual struc-tural evaluation of the castle and highlights on various structural issues to guide some of the restoration work. The castle suffers from material degradation on the masonry walls due to water leakage from the roof level. All of the floor beams holding the walls together were lost. Various cracks on the castle walls and surrounding rampart walls show indica-tions of structural deficiencies and possible damage due to temperature shifts or soil set-tlement. The conclusions of this paper try to set a path for structural interventions during restoration work which may also be suitable for similar castles.*

1 INTRODUCTION

1.1 Brief history

Kilitbahir castle was constructed by Fatih Sultan Mehmet in 1452 – 1463 at European side of Canakkale city to control passage in the strait from the Aegean Sea to the Sea of Marmara (Fig. 1). The castle has a very interesting shape in the form of a clover leaf surrounding a triangle shaped central tower (Fig. 2). Additional exterior rampart walls protect the castle from the land side. First restoration was made by Kanuni Sultan Suleyman's order in 1541. Second restoration took place in 1870 by Sultan Abdulaziz and a reconstruction of the northern wall was ordered by II. Abdülhamit between 1893-1894 [1, 2]. Current restoration work has been supported by a structural evaluation and visual evaluation of the castle summarized in this paper.

Figure 1: Location and satellite image of Kilitbahir Castle (ref. Google).

Figure 2: General view of the Kilitbahir Castle from the sea and air.

1.2 Current work carried out on the castle and objective of this paper

The structural evaluation in this study includes a detailed visual inspection of the castle tower walls as well as the surrounding defense walls [3]. Degradation in material level and then structural member losses were documented. Possible sources of weakness were out-lined and restoration studies were steered in those directions. The major issues can be grouped under a) loss of wooden floor beams in the tower to tie opposing walls together, b) degradation in the double leaf walls at the lower parts of the castle, c) water seepage at the dome level to cause decay in the wooden wall lintels as well as weakening and loss of mortar layers, d) structural cracks forming at the surrounding exterior rampart walls, e) earthquake vulnerability and other issues.

2 MAJOR STRUCTURAL PROBLEMS AND POSSIBLE REMEDIES

2.1 The castle tower

One of the major problems with the tower is the loss of wooden floor beams which structurally used to form a platform in the past. The castle walls reach unsupported height of 25 meters above ground (Fig. 3) over a water cistern which is more than 3 meters deep. The out-of-plane bending stability of the walls is improved by the presence of such horizontal beams connecting opposing walls in alternating directions. Logs found in the tower that has original nails on them also is an indication of thick wooden floor covering over beams which might in a way form diaphragm action as well. The floor should be reconstructed to structurally connect the opposing walls and at the same time for non-structural purpose of providing walking platforms for visitors.

Figure 3: Interior view of the Kilitbahir Castle tower (looking up) and damaged floor beams.

Almost all of the openings in the walls, which includes tunnels and window openings, have structural cracks clearly visible on the upper parts (Fig. 4). The cracks on the floor are possibly covered and filled with dust and earth. Similar cracks were also traced from the outside.

The crack formation on the walls indicate that the 3m to 4m thick tower walls have suffered dismantling by forming vertical cracks in planes that have horizontal normal vectors perpendicular and parallel to the wall surface. Majority of the wooden members horizontally placed inside the walls during the construction in parallel and perpendicular to the wall surface were lost over time due to dampness and possible biological activity (Fig. 5). The loss of wooden members, which are responsible for holding the wall's building blocks together in horizontal planes (parallel and out-of-plane directions), caused walls to crack possibly during a past moderate seismic activity.

Figure 4: General view of the structural cracks on the tower wall sections.

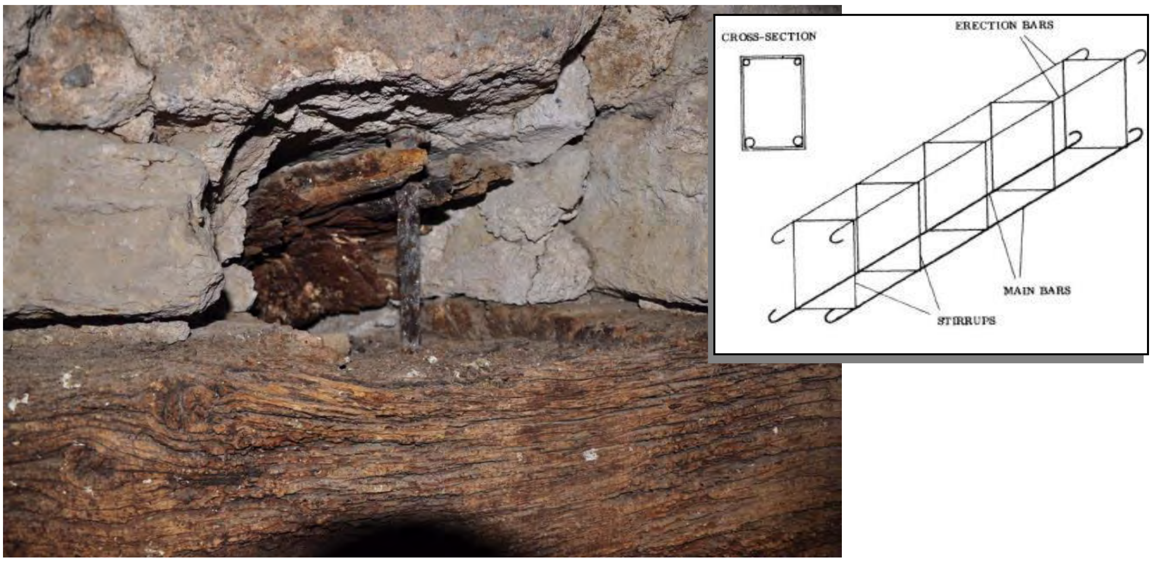

Figure 5: One of the remaining wooden wall members.

The cracks that are heavily visible from the inner side and window openings and trace-able from the outer surface are critical because they form weakness layers for shear stresses developing during a possible horizontal in-plane loading such as earthquakes. Similarly, out-of-plane bending of the castle walls during a possible earthquake is also quite vulnerable, since the bending capacity of the walls are depreciated due to surface cracks as well as missing floor beams cannot contribute to the transfer of out-of-plane forces to other walls that are oriented in their stronger axis of in-plane shear due to triangular shape of the castle. On top of that, the cracks are forming weakness against vertical dead load stresses and additional vertical forces that may form during earthquakes due to Poisson's effect: vertical forces cause tensile stresses in the horizontal directions which are in the in-plane and out-of-plane directions. Possible double-leaf architecture of the walls loses much of its strength as the wooden beams are missing across the thickness of the walls.

It is not possible to place wooden members inside the walls as their original size. Either smaller sized but stronger material wooden members can be placed in voids with mortar injection or *stainless steel* bars can be placed in those void spaces with proper infill mortar. The wooden members may create better adhesion with the existing walls since they have larger surface area. Similarly, smaller diameter but larger number rebars may be used instead of missing wooden members to increase the adhesion surface area. Development length of rebars is a function of the bar diameter and if smaller diameter bars are used the forces can be transferred on rebars at shorter distances increasing the efficiency of application. The smaller diameter rebars at larger numbers (e.g. 4 to 8 bars) placed inside the void spaces left from wooden members can also be connected to each other using stirrups which would add shear resisting capacity to the application as well (Fig. 5). In this way, a modern and compatible intervention to the historic castle using smaller and large number of stainless steel bars with stirrups can mimic the performance of wooden members and practically lasts for the rest of structure's life.

2.2 The surrounding rampart walls.

The surrounding walls of the Kilitbahir castle's tower are two folds: there is an interior wall series that has the combination of three circular walls where the connection points of the circles are nicely aligned with the corners of triangularly shaped tower at the center (Fig. 2). The height of the interior walls is about 18m and more than 7 meters thick. The exterior walls are smaller, 8 to 10 meters high, about 2 meters thick and spans the western side of the castle on the land side as an additional line of defense for attacks coming from the land. The exterior walls have 9 observation/watch towers built that would also strengthen the walls against out-of-plane collapse creating a buttress-like structural effect.

The circular shape of the interior walls is a good choice for structural stability as well as 18m height versus 7m thickness is a good ratio of about 2.5:1 for out-of-plane bending stability. Nevertheless, thick masonry walled towers are known to collapse without prior warning in the past such as 900 year old Pavia Civic Tower collapse [4] that took place in 1989. The stress levels in walls reaching at heights of close to 20m, which are obviously unconfined in the out-of-plane direction, can easily build up to 400 kPa levels. Unconfined masonry, which has been badly treated by Portland cement in the past and possibly has weak infill material between outer leaves, can have lower strength than expected in the level of 0.5 to 1 MPa. Creep of masonry wall material is an important phenomenon, which can lead to sudden collapse even under self-weight of a structure. The wooden members placed in the out-of-plane direction is again an important structural element which would tie the outer surfaces of a thick wall together, in a way providing passive confinement effect; however, majority of wooden elements are lost over time with void spaces left behind.

The outer walls are 8 to 10 meters high but relatively thinner, having only 2m thickness with about 5:1 ratio. Vertical cracks on the exterior walls from inside and outside (Fig. 6) were observed indicating a) possible support settlement, b) temperature related expansion joint formation, and c) out-of-plane bending. Out of these three possibilities, temperature loading and out-of-plane bending are thought to be more effective since the cracks mostly have vertical patterns. A differential settlement would be expected to generate diagonal cracks except if two sides of a section settle down at the same time causing a negative bending forming a vertical crack starting at the top of the wall.

Figure 6: Vertical cracks observed on the exterior walls.

2.3 Possible investigations and interventions

The simplest way of intervention during a restoration study is to fill the cracks with injection and complete the mission sections of walls using similar stones or bricks and most of the restoration companies like to follow this path. However, towers and castles are special structures and usually more demanding than ordinary small to medium size historic masonry houses. The massive size

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Nondestructive or semi-destructive tests may need to be conducted to investigate the strength of building material as well as the existing stress levels. Radar imaging, baroscopic investigations, ultrasonic pulse velocity measurement, flat-jack testing, material sampling, core sampling, and similar techniques can be used to evaluate the existing state of the historic structure.

Analytical modeling and loading simulations is a must for structural evaluation of an extraordinary large masonry structure. Canakkale city, where Kilitbahir castle is located, is a highly seismic area with major active fault lines (Fig. 7). The massive structure of the castle is good against invasion armies; however, the earthquake forces are linearly proportional with the mass of a structure and as a castle is more massive it will attract more force during an earthquake. Structural simulation of earthquakes can be better made if the resonant mode shapes and vibration frequencies of the structure is known since spectral acceleration during an earthquake and coupling with the existing modes of a structure plays an important role on the earthquake induced dynamic forces on a structure. The structural evaluation can be improved if a nondestructive dynamic testing is conducted on the existing castle. The analytical computer model should be calibrated using material test results as well as dynamic testing. A calibrated analytical model would better simulate the existing structural properties of a many centuries old historic structure and can have more accurate simulation results.

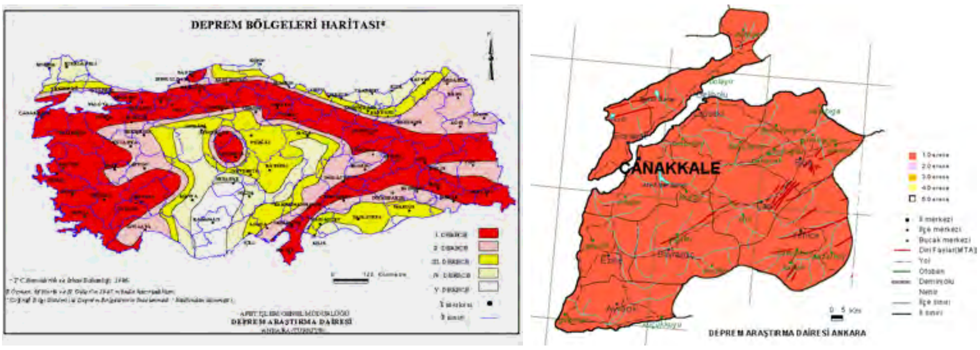

Figure 7: Earthquake map of Turkey, red areas (1st degree) indicating the largest earthquake activity zones.

Missing wooden members is a major problem since these members can resist tensile stresses developing in the masonry walls as well as shear forces to certain extend. Replacement of wooden members may not be possible since the exact shape and dimensions cannot be found or placed inside the existing irregularly shaped hole. Instead, a rebar cage with multiple small diameter stainless steel rebars with stirrups can be place in those void spaces left behind by decayed wood members providing short development length, high tensile strength, certain shear capacity as well as durability that would last longer than wooden members.

Existing cracks should be carefully investigated since mortar injection to the cracks is not always a good idea. Expansion joints used in modern civil engineering structures carry the responsibility to compensate relative movement between segments of a large structure, which may be caused as a result of differential settlement or thermal effects. Structures that are subjected to temperature shifts between summer and winter must expand or con-tract based on environmental temperature. Structures with relatively long lengths, such as the exterior walls of the castle, experience the temperature induced stresses more than other shorter members. That is why large shopping malls or long sidewalks on the streets have horizontal joints to separate shorter length segments in a controlled manner to prevent development of large internal forces. If differential settlement exists or thermal expansion joints are not provided, the structure may have to develop its own expansion joints in the form of cracks, in a similar pattern that was observed in Kilitbahir Castle.

The existing cracks can be monitored using crackmeters as a part of structural health monitoring study, which would reveal if the cracks are of cyclic nature as in Equation 1, where t is time in years, φ is shift in time axis to adjust the starting point, and A is the amplitude of annual crack width change cycles which is approximately equal to the maxi-mum minus minimum crack width in a year. If the crack widths are not returning to their starting value on a yearly basis, then the cracks are progressive in nature and crack opening over time can be characterized as in Equation 2, where B is the permanent change of crack width per year and C is a constant to adjust starting point.

The next example is a multi-line equation:

$$w_{crack} = A.\sin(\frac{t}{365.25}.2\pi + \varphi) \tag{1}$$

$$w_{crack} = A.\sin(\frac{t}{365.25}.2\pi + \varphi) + \frac{B.t}{365.25} + C \tag{2}$$

Measurement of crack width changes over time is important since filling the cracks can cause internal stresses to develop and generate crushing zones if ‘A’ value in Equation 1 is large. The threshold of A is a function of annual temperature differences and spacing of the cracks along the wall. Filling the cracks can also be unsatisfactory if ‘B’ value is a large positive number since the wall will try to open the same crack or another one in close proximity since the wall is progressively opening possibly due to some ongoing support settlement. If both ‘A’ and ‘B’ value are smaller than a certain limit, it means the cracks were formed during a past earthquake or a settlement due to soil or structural loss that took place and stopped; in this case, repairing the crack with infill and injection is expected to yield the best results.

Monitoring a crack over time provides additional advantages other than understanding if the crack is stationary or progressive; some of these are a) how fast is the crack opening (B) in terms of mm/year, b) how many millimeters does it move on a yearly basis (A), and c) what is the month of a year when the crack width reaches its minimum value. Knowing the crack movement in a quantitative way helps restoration experts to decide on the strengthening method to improve the behavior of the cracked wall while knowing the minimum crack width date of the year would be useful to plan a crack injection schedule. Filling a crack during its most closed state is better than filling it when it is opened to a larger width since the crack will try to close again after injection which would generate trapped internal forces and stresses.

3 CONCLUSIONS

The Kilitbahir Castle composed of an interesting triangular shape for the tower and tri-circular inner and exterior walls is a 550 years old beautiful historic structure. The structural evaluation of the castle is carried out by visual inspection and various suggestions for testing and instrumented are suggested [5].

As a summary, the structure suffers from losing its wooden members originally placed inside the walls against tensile forces as well as at the floor levels of the tower to connect opposing walls together. Numerous large cracks were observed on the tower walls indicating the thick walls are separating “in-plane” and “out-of-plane” directions most likely due to loss of wooden members under its own weight and possibly shaking during a past earthquake since the castle is located in the highest earthquake prone zone in Turkey and possibly suffered small and large earthquakes during its 550 years of lifespan. The void spaces left from biologically degraded wooden members was thought to be filled using re-bars that are larger in number and smaller in diameter to improve the development length while using stirrups to add shear resisting capabilities. The floor beams inside the tower and thick timber floor covering must be restored to their original condition since these members are not only responsible to form a walking platform but also holds the walls together in the horizontal direction even generating diaphragm action to a certain level. Some of the damage to walls and wooden members is caused or aggravated by water leak-age from the dome level and proper water proofing is absolutely necessary.

Structural condition of tower walls (t>3m), inner (t>7m), and exterior (t>2m) rampart walls cannot be fully understood by visual inspection only since the quality of the inner parts of the walls is far more important than what can be visually seen from the outside. There might be void spaces or weak infill earth or poor mortar quality can make walls vulnerable to even its own weight and mass during an earthquake. Therefore, material sampling and baroscopic investigation is highly recommended.

Ambient dynamic vibration testing was recommended for the tower to investigate dynamic characteristics since natural vibration modes and frequencies would interact with earthquake spectrum. The dynamic characteristics can also be checked against and used for model updating (calibration) of an analytical model, which is absolutely necessary for structural evaluation studies.

The soil conditions cannot be separated from the structural behavior and footings as well as underlying ground characteristics should be investigated using enough number of boring exploration. Small observation excavations such as 1m x 1m can be opened to find the footing location and shape or nondestructive georadar or electric resistivity investigation can be carried out.

Instrumented structural health monitoring is recommended to investigate the movement characteristics of structural cracks on the tower and surrounding walls of the castle. Structural intervention planning must be based on the monitoring and modeling results.

The restoration study of such a historic tower must be something more than just injecting the cracks, repairing 50mm exterior part of the mortar between stones, and putting back some missing stones. A thorough investigation, design, and planning must be done prior to starting a restoration work. The restoration work contract taken by the contractor would almost never include a budget for these studies and usually quite lowered during the bidding process. Additional budget may sometimes be found by Ministry of Culture executive or control personnel but greatly depends on the economic conditions and extra fund availability. Ideally, the scope of pre-restoration study at project development stage should include these investigation studies including long term monitoring for at least 2 years.

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