Repair and Retrofit of a 17th Century Library Structure in Istanbul

Sesigur, H. & Cili, F.
Istanbul Technical University, Turkey

SUMMARY:
In the present study a heavily damaged 17th century library structure which is located in the hearth of historical area in Istanbul is investigated. The structure has a cross shaped plan and made of masonry. In order to evaluate the seismic capacity of the structure and to select the appropriate retrofitting technique, the structure is analyzed by means of limit analysis and finite element method. For this purpose the structure subjected to gravity and seismically originated forces and nonlinear analysis with FEM is conducted using DIANA code. Moreover kinematic limit analysis approach applied to the structure to evaluate the seismic individual response of the considered mechanisms. Several numerical simulations are performed starting with linear elastic model comprehending the global structure. Results of the limit analysis approach, allowing the definition of rigid plastic capacity curves for the considered mechanisms are finally compared with the results of the non linear numerical models.

Keywords: Retrofit, Masonry, Historical Structure, Nonlinear Analysis

1. INTRODUCTION

In the last two decades many historical masonry structures have renovated in Turkey. Some traditional and novel techniques have used for repair and strengthening of these structures. Earthquake reconnaissance investigations revealed that masonry arches and domes with tension members showed satisfactory behaviour under earthquake loading. However, due to some reasons like time dependent material flaws (e.g. corrosion), damaged members (fractured or buckled tie bars during a powerful earthquake or differential foundation settlements for example), sectional losses at various levels etc., tension members loose their functions and need to be repaired or replaced by new members. The structure is one of the important library building which is located in Istanbul. It was built in 1742 by Sultan Mahmut I. It is a cross shaped building near the Fatih Mosque, Fig. 1.1.

Figure 1.1. View of the Library Building from the North-East Façade

Its structural system consists of unreinforced masonry walls. The roof system consists of cross masonry vaults and a main dome which are supported by both unreinforced masonry walls and buttresses. Buttresses are connected to each other by timber ties at basement floor and by wrought iron ties at the ground floor. Material used in the masonry walls and buttresses consists of shallow solid bricks, stone and lime mortar for joints, representing the construction technique used in that century.

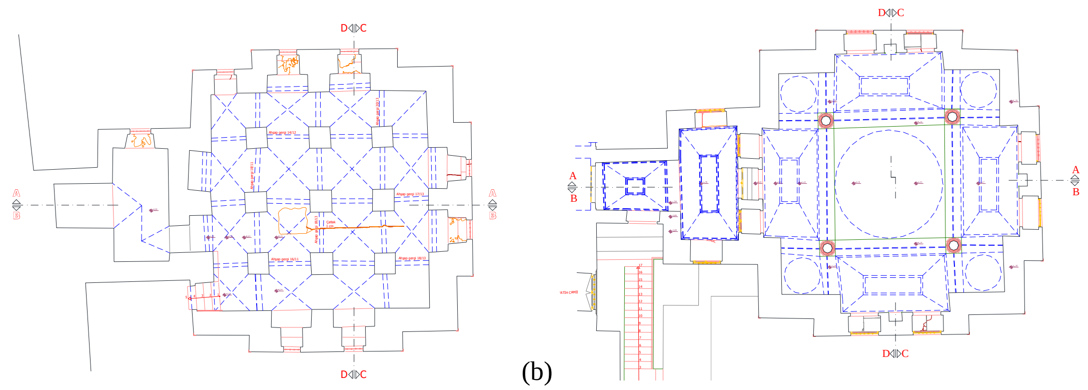
During the structural and architectural site investigations of the Library Building within the scope of a restoration according to the Turkish Cultural and Natural Heritage Protection Act 2863 some structural weaknesses such as material flaws, cracking and inappropriate interventions have been observed. In following structural issues encountered in current repair and retrofit works of the structure are presented.

2. STRUCTURAL SYSTEM OF THE LIBRARY BUILDING

2.1. Description of the structural system before strengthening

The Library Structure has a symmetrical cross shaped plan with dimensions of 24.54mx16.90m, Fig.2.1. It has two stories and the story heights are 3.60m and 7.60~11.00m for basement and ground floor respectively. The roof system consists of four vaults, four hemispherical, small diameter domes with a diameter of 2.00m and a main (central) dome with a diameter of 5.00m. The thickness of the main dome is 35cm at the top and 35cm at the support level. At the basement floor vertical load bearing members at the inner section of the building are aligned to a regular grid system, which consists of 3 gridlines parallel to the outer walls facing east and west and 3 gridlines which are parallel to the outer walls facing south and north. Grid spacing for both directions are of 2.50~2.60m. The buttresses are rectangular shaped elements with a 1.00m x 1.00m dimensions and they are connected to each other by timber ties having 10cm x 12cm cross sectional dimensions. At the ground floor, vaults and domes are supported by arches which are restrained by pillars inside the structure. The main arches have 5.20m span and 2.55m height while the pillars having 40cm diameter of circular cross sectional dimensions. The perimeter wall thicknesses vary from 80cm to 120cm. Material used in the masonry walls consists of shallow solid bricks, equal thickness crushed tiles and lime mortar for joints.

Within the scope of the restoration of the Library Building, detailed structural and architectural site investigations were performed. During these investigations following structural issues was encountered: At the ground floor, the cracks having up to 2cm wide were observed on the cross vaults, while at the roof level, up to 4cm wide were observed on the vaults. The observed crack patterns are shown in Fig. 2.2. Major structural problems of the Library Building originate from the tensile stresses (i.e. the masonry material in the system has low tensile strength) which occurred at different points of the building and are mostly concentrated at the vaults, domes and walls, which might be produced by ground settlements and earthquake forces.



(a) (b)

Figure 2.1. Plans of the building a) Basement Plan b) Ground Floor Plan

Both on the internal and external surfaces of the side walls of the cistern intense pollution and vegetation were observed. There was also a surface degradation of the outer surfaces of the side walls due to loss of some of the stones. In some parts of the side walls holes of different sizes were formed probably to use the cistern unauthorized. In the region of the northeast side walls a noticeable distortion of the cross vaults forming the roof upholstery was observed. The irregular infill over the cross vaults with heights ranging from 0.80 to 2.80 m is clearly a sign of excessive roof loads (Figure 2.3). Although there was not a significant deterioration of the columns, the wooden tension members connecting the columns to each other and to the side walls were completely missing.

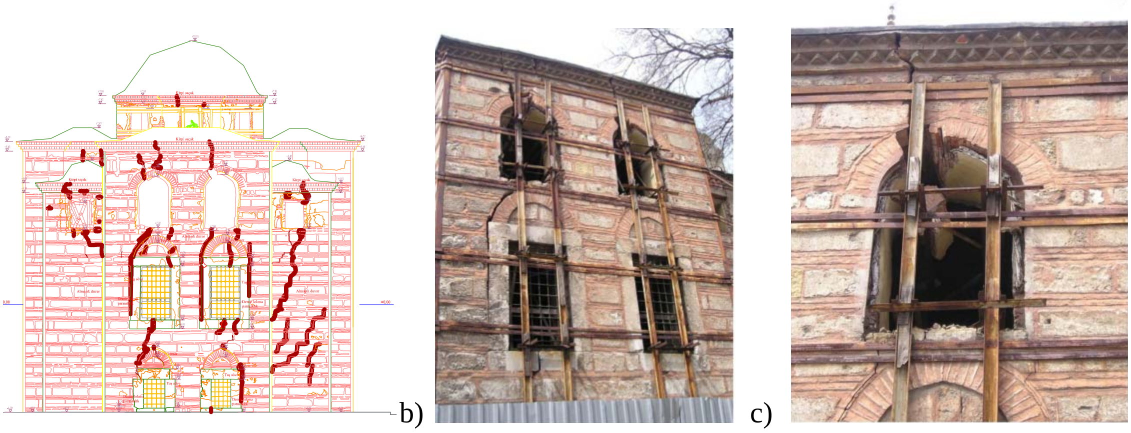


Figure 2.2. Damage patterns are seen at the a,b) South-East Façade c) Detail of a window

2.2. Numerical modelling of the structure

Besides the 2D rectangular curved shell quadratic elements (CQ40) it was also used triangular elements (CT30S). Tie-beams were included in the model by using Class-II fully numerically integrated beam elements, implementing an elastic-perfectly plastic constitutive law. The model comprises 19352 elements with 19107 nodes, resulting approximately 57000 DOF. A non linear behaviour was adopted for all elements, with the exception of the vaults' infill, that was assumed linear elastic throughout the analyses, however with a negligible stiffness compared to those of the structural materials.

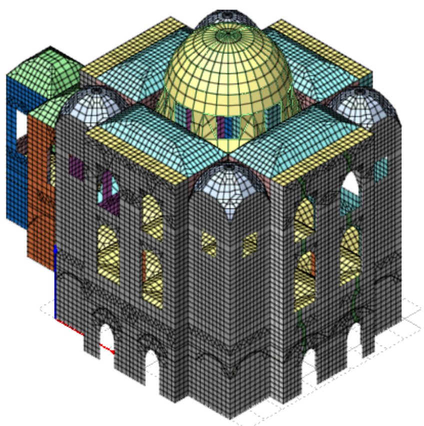


Figure 2.3. FEM model implemented in DIANA™, TNO, Delft

The properties of the materials implemented are summarized in Table 2.1. The structural material mass density adopted, in absence of available data, derives from the suggested value in the Turkish Earthquake Code (2007) representing the average density of the clay brickwork masonry with lime mortar (18 kN/m^3). In absence of experimental determination design tensile strength of 0.1MPa is adopted in all of the numerical models implemented. The model considered both material elasto-plastic constitutive law (in tension) in a first phase and then a law implementing linear softening in tension with a Mode I type fracture energy value of Gf^{I}=100 J/m^2. Loads considered in the analyses are the self weight and the seismic action, introduced by the application of a set of equivalent horizontal mass proportional, triangular and first mode proportional loads. The nonlinear analyses are carried out with indirect displacement control (arc-length method) with line searches, using a full Newton-Raphson solving technique.

Table 2.1. Models properties

Mass Density- Structural (kg/m^3)	1800
Mass Density- Vaults Filling (kg/m^3)	1500
Young Modulus (MPa)	2000
Poisson's Coefficient	0.2
Tensile Strength (MPa)	0.1
Fracture Energy- G_f^I (J/m^2)	100
Compressive Strength (MPa)	20

2.3. Numerical Analysis

The self weight preventive analysis indicates that the compressive stress at the base of the façade wall is approximately equal to ~0.30 MPa, while at the base of the buttresses, an averaged value of ~0.40 MPa was found (Fig. 2.4).

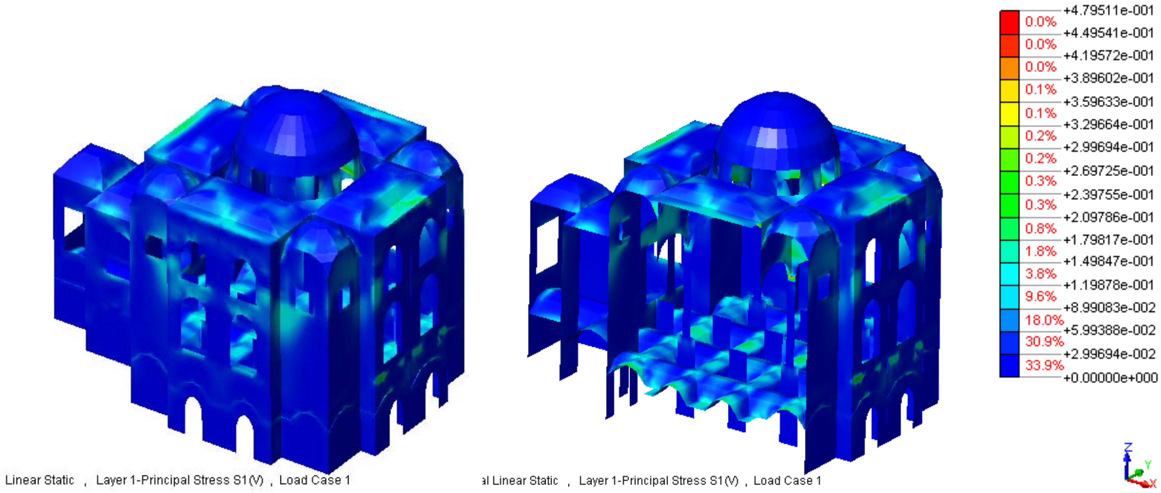


Figure 2.4. Principle stresses due to gravity loads

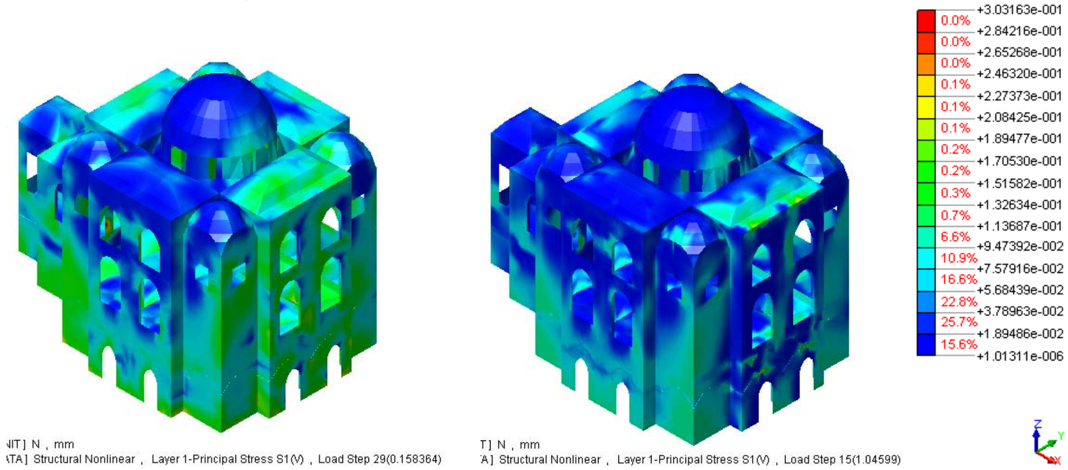


Figure 2.5. Principle stresses due to incremental lateral loads

In order to obtain the capacity of the structure, nonlinear static pushover analysis method is used. For the beginning of the load increment, uniform and triangular load distributions are considered. Due to the damage distribution is widely seen on the south-east façade, pushover analysis is done for y direction of the structure. The relation between the base shear and the displacements for the control point (restraint level of the dome) before strengthening process is presented in Fig. 2.6.

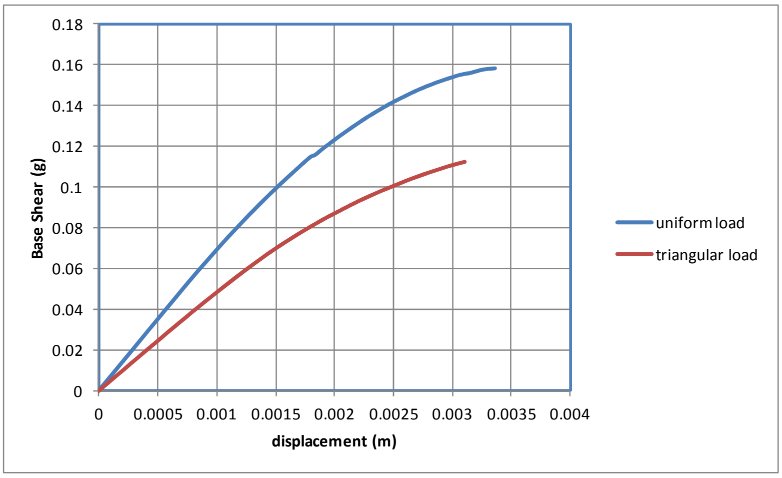


Figure 2.6. Capacity curves of the structure before the strengthening

2.4. Method of the strengthening

The crack patterns are shown that the façade walls have lack of out of plain restraints. In order to prevent the out of plain failure of façade walls it is proposed to conduct high strength steel tie rods for two different levels of the structure, Fig. 2.7.

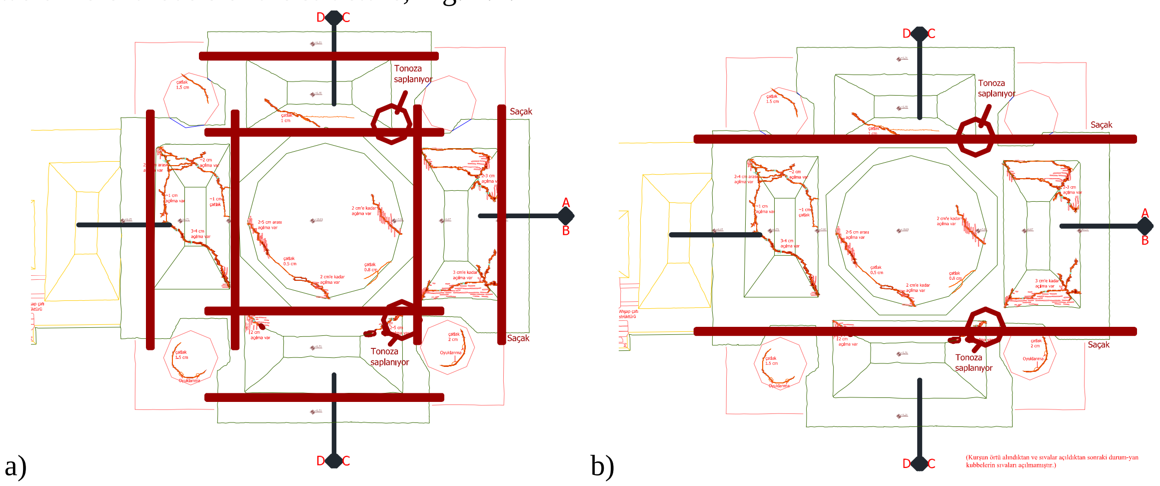


Figure 2.7. Proposed tie rods made with high strength steel for level -2.25m (a) and +5.84m (b)

The anchorage of tie rods at the outer face of the walls is realized by means of bearing plates and for the tie rods 8.8 quality circular steel bars with a diameter of 24mm is chosen (Fig. 1.1). In order to prove the effectiveness of the proposed strengthening system, the capacity of the structure calculated by nonlinear static pushover analysis method. The principal stress patterns and capacity curves before and after strengthening are obtained and shown in Fig. 2.8. and Fig. 2.9.

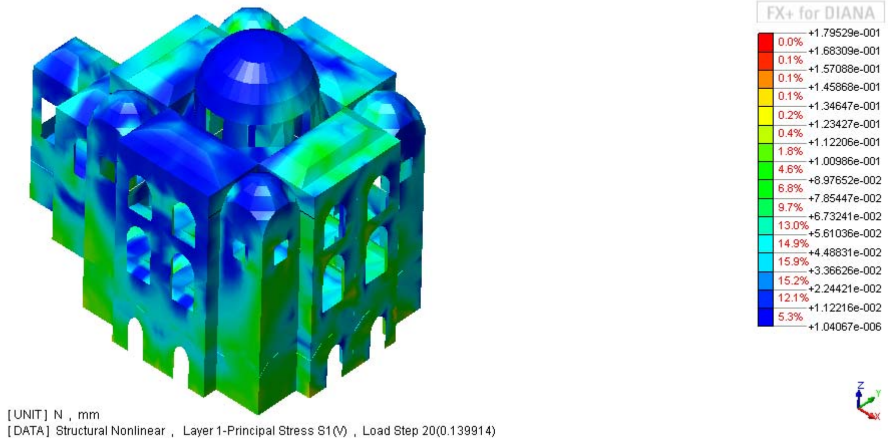


Figure 2.8. Principle stresses due to incremental lateral loads after strengthening

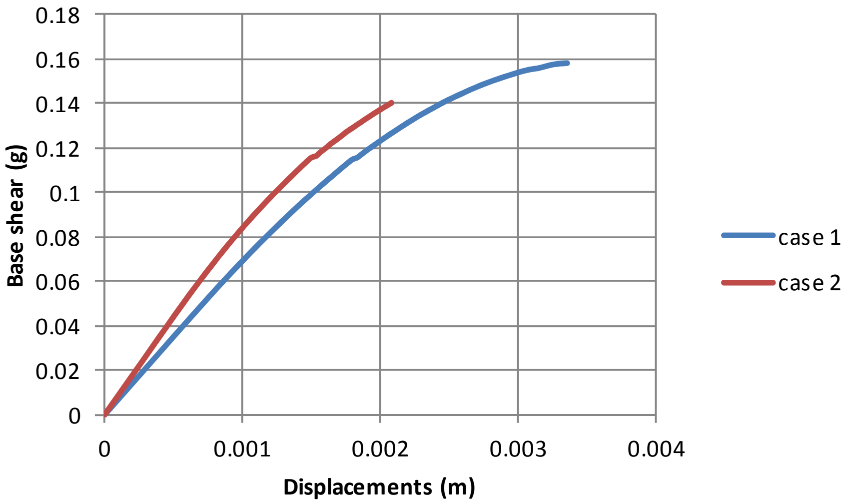


Figure 2.9. Capacity curves of the structure before (case 1) and after (case 2) the strengthening

3. CONCLUSIONS

In this study the 16th century single domed library structure has been numerically investigated under gravity and seismic loads before and after strengthening. In order to select proper strengthening system, a nonlinear static pushover analysis is performed. During the site investigations crack patterns on the south-east façade is observed and due to preventing the walls out of plain failure it is decided to propose steel tie rods which connects the façade walls each other. The numerical results show that the structure becomes more rigid due to the strengthening system.

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