SEISMIC EVALUATION AND RETROFIT OF A 16TH CENTURY HISTORIC BRICK MASONRY DOME IN ISTANBUL USING COMBINED STEEL RINGS AND CFRP SHEETS

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ABSTRACT :

As many unreinforced masonry domed structures have damages on their domes (even under gravity loads), this study mainly focuses on an investigation of effectiveness of placing galvanized steel rings at the dome's support level and CFRP sheets along the tension zone on the inner face to improve the structural behavior. The problem is considered through an example of a real conservation case study of the Yavuz Selim Mosque in Istanbul, dating back to the 16th century. The structure is subjected to gravity and seismically originated forces. FEM analysis is conducted using SAP2000. The behavior of the system before and after retrofitting process is compared. Also, the site observations related to the crack patterns are explained in detail. Numerical results show that external confinement or tightening using steel rings reduces the principal stresses and displacements of the structure significantly and a more distributed stress condition is obtained.

KEYWORDS:

Historic masonry domes, steel rings, CFRP sheets, seismic retrofit.

1.INTRODUCTION

Historic masonry mosques represent an important role of the Turkish cultural heritage and have demonstrated some structural weaknesses during the past Turkey earthquakes [Cili, 2005], [Sesigur et al. 2006]. Although the structural configurations of historic mosques are quite symmetric and they have sufficient lateral rigidity due to larger wall thicknesses provided, this type of buildings may be seismically vulnerable because of many openings on the walls and the poor characteristics of the structural material used.

Carbon fiber reinforced plastic (CFRP) sheets are preferred in seismic applications of deficient reinforced concrete buildings and bridges to improve their structural behavior. The use of these materials in steel and / or wooden members is also promising and increasing. In historic masonry buildings, these high performance materials can be viable alternatives to conventional ones due to their higher resistance to loads, lightweight, ease of application, and resistance to corrosion. Masonry domes supported by huge masonry arches and/or solid walls are assumed as one of the most important structural members in historic mosques. Due to the material used in construction and geometrical properties, they are quite heavy compared to other modern systems and may be vulnerable to large gravity and seismic effects. Also, nonductile behavior is expected under seismic loads. At the support level, masonry domes usually accommodate cast iron rings to resist tangential tension forces by preventing or limiting cracks. These members are much more resistant to corrosion and rusting than steel. However, over the period of time and due to loss of contact between the existing iron ring and the dome, these members become ineffective and some cracks may develop in masonry domes.

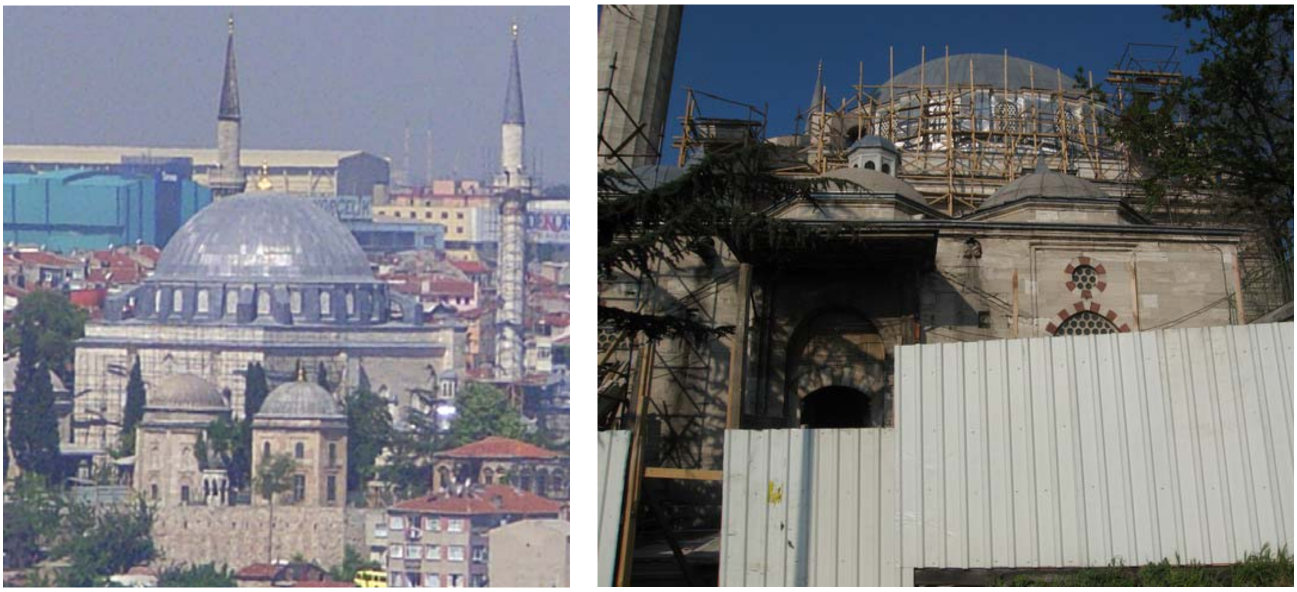
This study numerically investigates such a 25m diameter, brick masonry dome which has the main dome of the Yavuz Selim mosque in Istanbul. The 16th century dome has several crack patterns. To retrofit the dome, combined outer galvanized steel rings and inner CFRP sheets were used as the tension members at appropriate dome levels. Preliminary analyses propose that two rows of slightly prestressed externally placed galvanized steel rings and five rows of CFRP sheets along the tension zone would be selected as the retrofit system.

2. THE YAVUZ SELIM MOSQUE (16th CENTURY)

The Yavuz Selim Mosque is an Ottoman imperial mosque located on top of the 5th Hill of Istanbul, overlooking the Golden Horn, Figures 1a,b. Completed in 1522, the Yavuz Selim Mosque is the second oldest existent imperial mosque in Istanbul. Although the architect is unknown, numerous attempts have been made to associate the structure with the famous imperial architect Mimar Sinan, but there is no supporting documentary evidence. The large courtyard has a colonnaded portico with columns of various types of marble and granite extracted from various quarries around the region. The mosque itself is decorated with very early distinctive examples of Iznik tiles and is flanked by twin minarets. The building is under restoration process and scheduled to be opened in 2009.

2.1. Description of the structural system before retrofitting

The Yavuz Selim mosque has a symmetrical plan shape with dimensions of 29.50mx31.00m, Figure 2. The roof system consists of eighteen hemispherical, small diameter brick masonry domes with a diameter of 4.00m and a main (central) dome with a diameter of 25.00m. The thickness of the main dome is 90cm at the top and the support level. The main dome is also supported by symmetrically located eight small-scale flying buttresses, again made of masonry members. Outer surfaces of all domes are covered with heavy lead layers as roofing to protect the building from natural effects. The masonry walls support loads from the main dome have thicknesses varying from 160cm to 260cm. Material used in the masonry walls consists of shallow solid bricks, limestone, equal thickness crushed tiles and lime mortar for joints.



(a) (b)

Figure 1 The Yavuz Selim Mosque under restoration

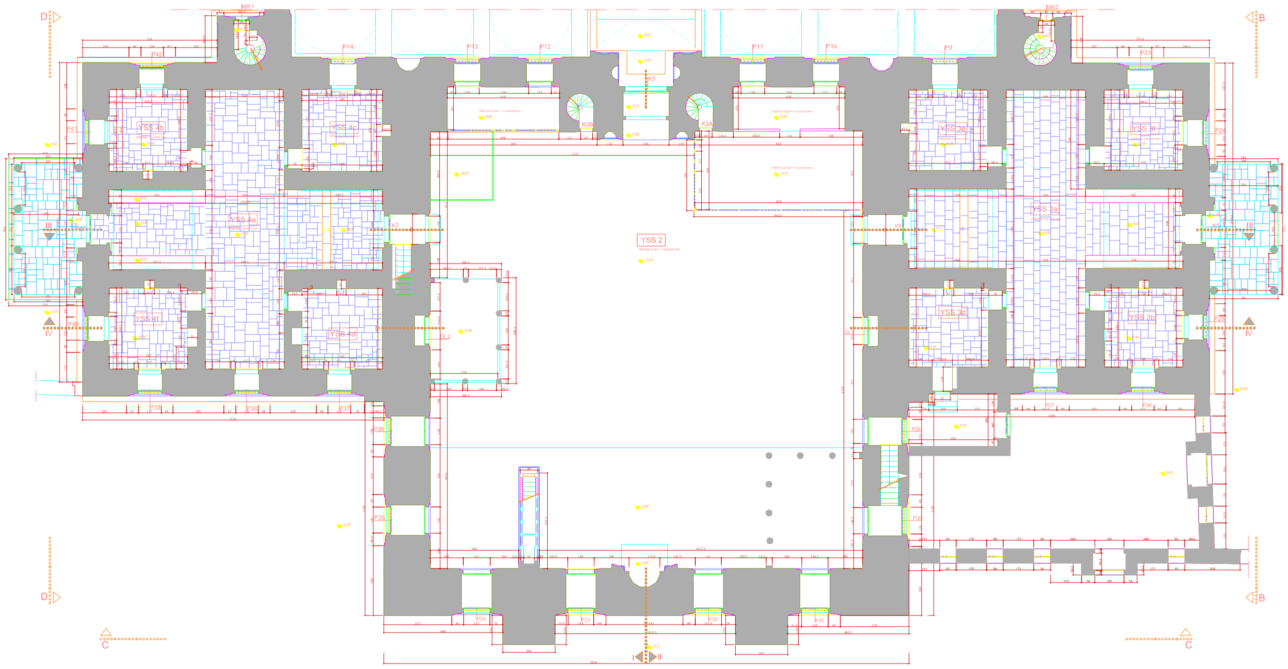


Figure 2 Structural Layout of the Yavuz Selim Mosque

After detailed investigations in the building, it is recognized that the major structural problems of the Yavuz Selim Mosque originated from the tensile stresses (i.e. the masonry material in the system has low tensile strength) which occurred at different points of the building. These structural cracks are mostly concentrated at the lower zone of the main dome. Thus, due to the circumferential tension, meridional cracks occurred, which might be produced by the last decade earthquakes took place in the Marmara region. In fact, the cracks distribution is nonsymmetrical over the dome and could be attributed to a lateral loading. Some of the observed crack patterns on the inner surface of the dome are illustrated in Figure 3.

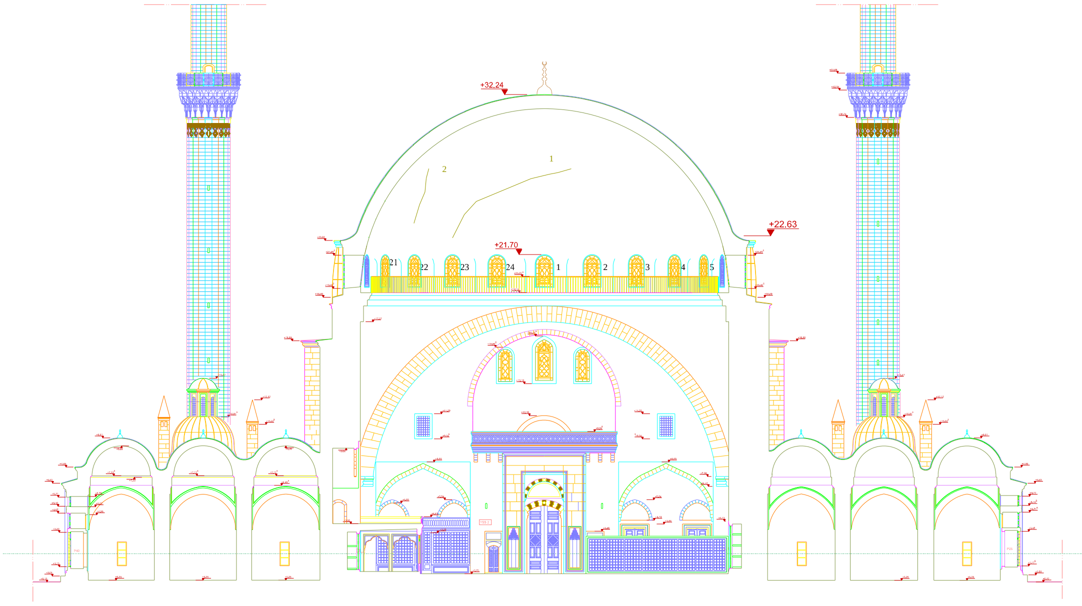


Figure 3 Observed crack patterns (interior view)

Although the soil conditions are weak under the mosque, very high retaining walls are present around complex. This would positively affect the behavior of the mosque.

2.2. Masonry Dome Behavior

To show the effect of the retrofitting technique used in this work, fundamental behavior of a hemi-spherical dome is illustrated in Figure 4. This diagram conceptually gives the variation of the tangential stress along the dome height. Note that, after the addition of tension members (both steel rings and CFRP sheets) around the dome, lower stresses are expected especially at the support level where cracks would initiate under high stress concentrations. Also, the compression zone on the dome can be increased (seen as a downward shift in the diagram) by adding the tension members.

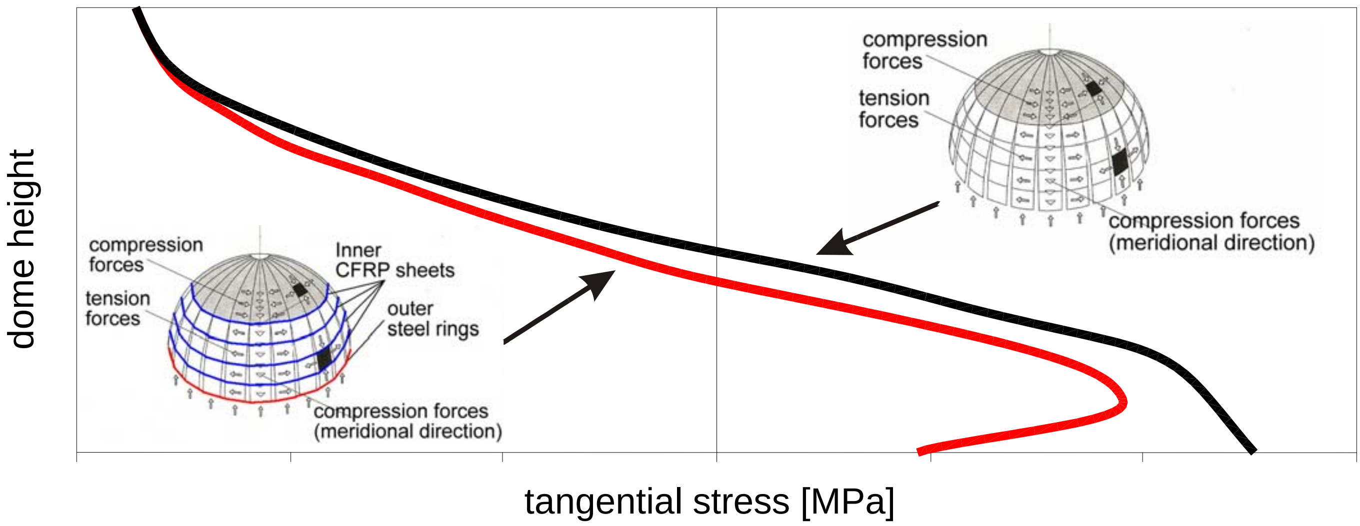


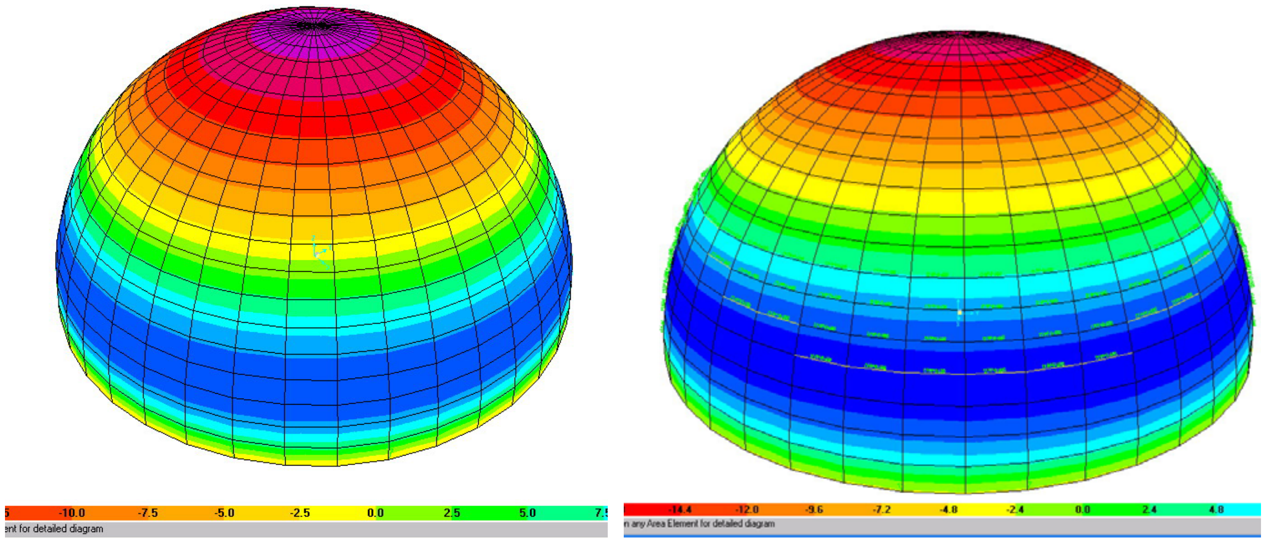
Figure 4 Expected behavior of masonry dome with and without tension members

2.3. Numerical Modeling of the Dome

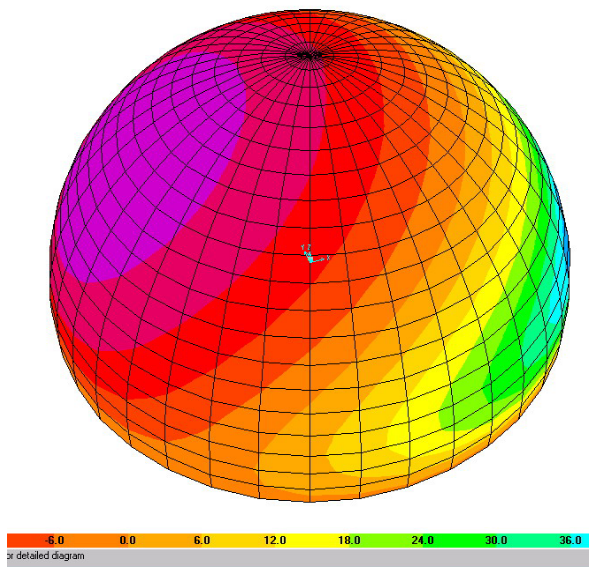
As a preliminary assessment to investigate the crack formation, a linear, 3D model in SAP2000 [CSI, 2004] has been developed, Figure 5. Although a refined analysis would require to model the whole structure including the subgrade soil, only the dome structure is modeled here to focus on the behavioral changes of the bare and retrofitted domes. The analytical dome model was built using curved shell elements. This model consists of 800 shell elements and a total of 4686 and 2283 stiffness and mass degrees of freedom respectively. Based on the experiences on these types of buildings materials, the mechanical properties of the elements are assumed as 20GPa and 0.20 for Young Modulus and Poisson's Ratio respectively. Both dead and earthquake loads are taken into account in the analysis. Other loads such as snow or wind actions have been disregarded because they could be neglected compared to the buildings self weight. Tensile strength of the masonry was neglected in the analyses.

The model has shown that the dome structure weighs approximately 15860kN. Under gravity loads, maximum compressive stress of 0.22 MPa is found at the support level of the structure and 0.13MPa at the level of the keystone ring. Analysis of the principal stresses in the dome shows that sub-vertical direction is mainly under compressive stresses. Stress patterns under gravity loading and earthquake loading before and after retrofitting are shown in Figures 5a,b,c,d.

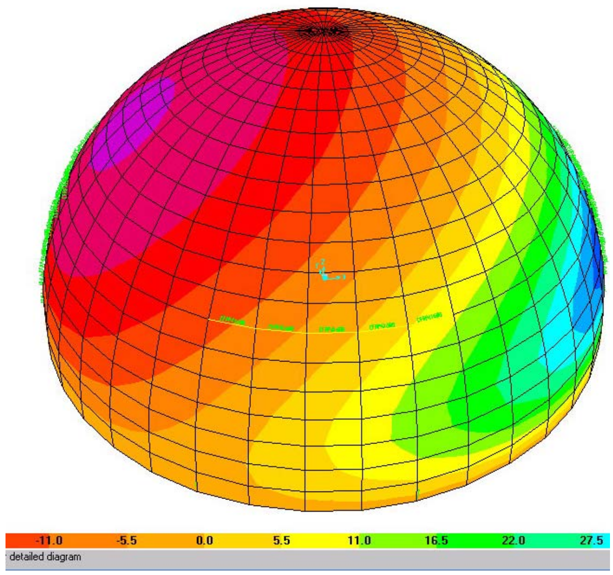
These figures and numerical analyses reveal that, under gravity loading, the highest circumferential tension stresses of 0.31 MPa and 0.15 MPa (52% less) are observed at the base level of the dome before and after retrofitting respectively. Under gravity+earthquake loading, these stresses reach 0.50 and 0.47 MPa leading to a 6% decrease. Effectiveness of the retrofit system under gravity loading is significant. On the other hand, although the effectiveness of the retrofit system seems less in case of earthquake loading, the distribution of stresses over the entire dome is more preferable when compared to the unretrofitted dome.



(a) (b)



(c)

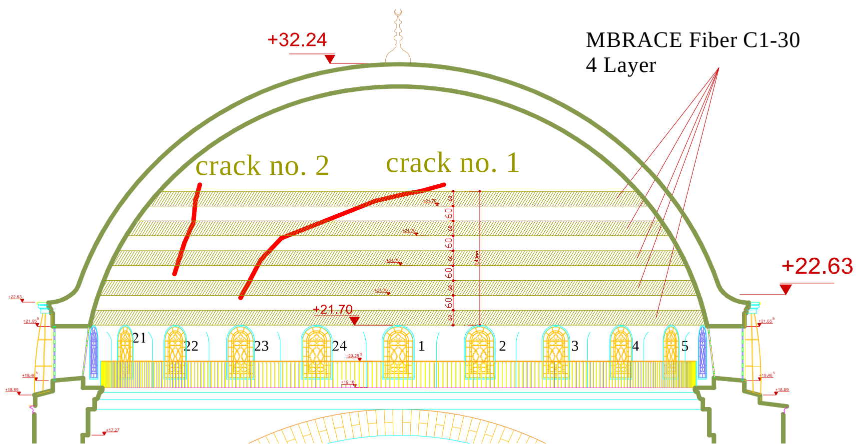


(d)

Figure 5 FEM modeling and principal stress patterns of the main dome (a) Existing dome under gravity loading (b) Retrofitted dome with combined outer steel ring and inner CFRP Sheets under gravity loading (c) Existing dome under earthquake loading (d) Retrofitted dome with combined outer steel ring and inner CFRP Sheets under earthquake loading

2.4. Retrofitting details of the main dome

The state of cracking patterns at the Mosque consists of two different types of cracks (Figures 6a,b): the ones that pass through the masonry dome's entire height of the lower part, which are visible at the intrados; a second type of cracks, which are limited to the surface of the dome. Mortar injection is a typical example of passive type intervention for the second type cracks. Typical crack widths were measured within the range of 0.8cm to 2.0cm. Since the crack pattern was growing to the tension stress zone it was decided to apply additional CFRP sheets to the inner surface of the dome, Figure 6a. The distance between MBRACE CFRP sheets are chosen as 1200mm. Four layers are applied with a quality of C1-30. The mechanical properties of the CFRP sheets include a density of fiber 1820 kg/m^3, an effective thickness of 0.165 mm, a tensile strength of 4000 MPa, and a tensile modulus of elasticity of 230 GPa [BASF, 2007].



(a)

(b)

Figure 6 (a) Application of CFRP sheet layers on the inner surface of the main dome (b) A typical crack on dome

The situation is beneficial to the stability of the dome, as the zones where sub-vertical compressive stresses are highest help to stiffen the entire dome with respect to tensile stresses arranged in the tangential direction. In this respect, two steel plate rings of 20mm thickness and 300mm wide are placed at 20.60m and 22.60m level of the main dome, Figure 6a. The connection and splice details of the rings are shown in Figure 7 and 8. The ring configuration has splices minimum at two locations. The connections use high strength bolts. In addition, the steel plates are galvanised and connected with equal-leg angles by M33 high strength bolts. In order to give some prestressing force to the system via the bolts, a gap of 50mm between angles is provided (Figure 8).

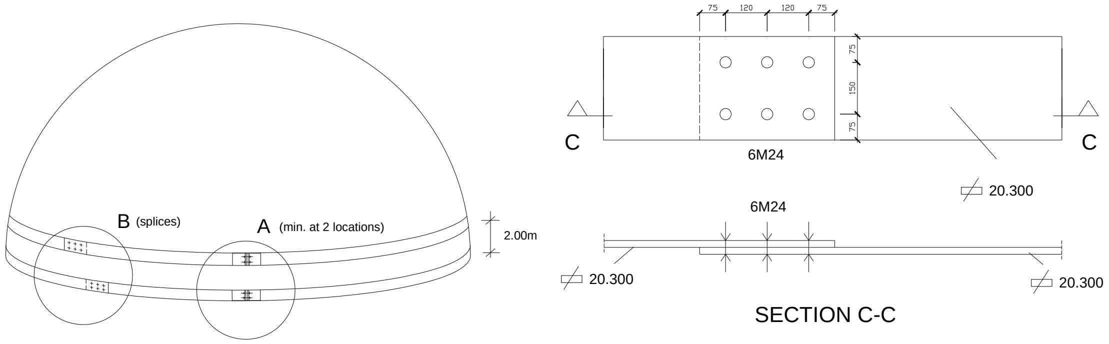


Figure 7 Typical ring configuration and splice detail

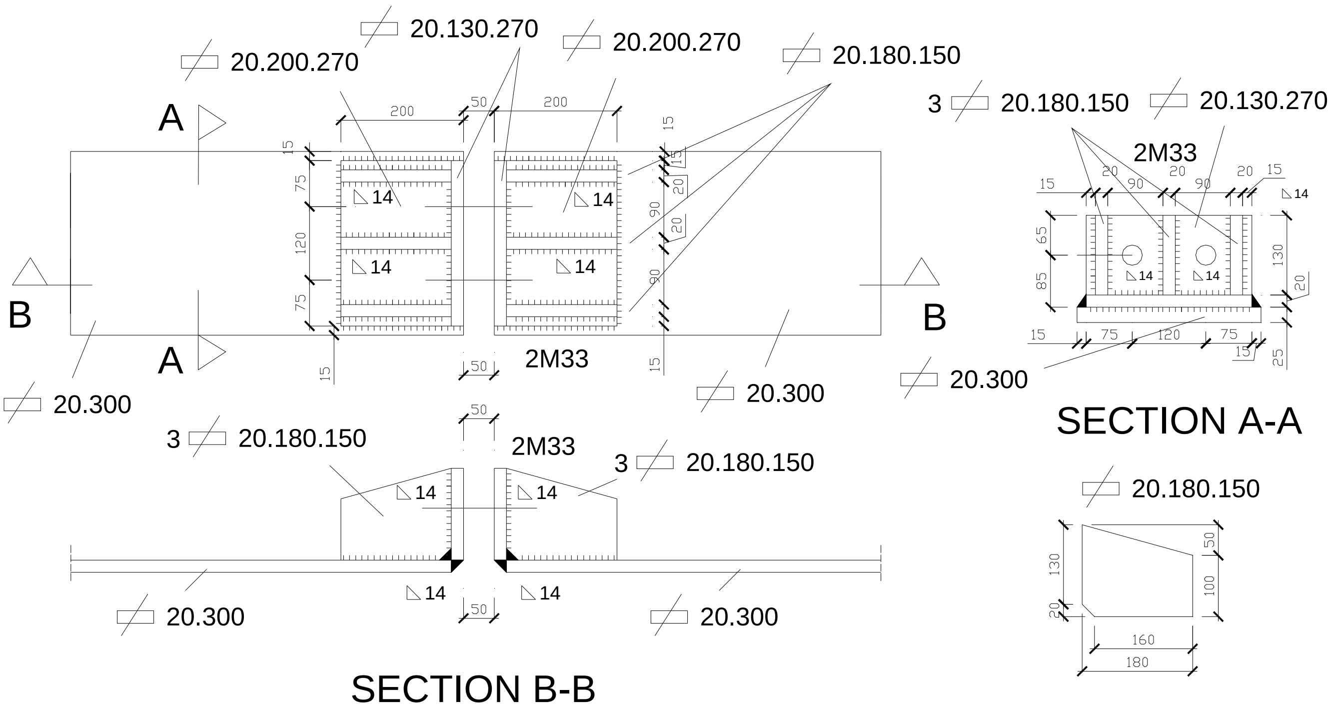


Figure 8 Detail A

2.5. 3D Dynamic Analysis

In order to assess the seismic behavior and effectiveness of external confinement and the CFRP sheets of domed structure, a dynamic analysis for the dome was further carried out with reference to the elastic time history analysis under the 17 August 1999 Kocaeli NS and 12 November 1999 Duzce 41N-29E strong ground motion records, Figure 9.

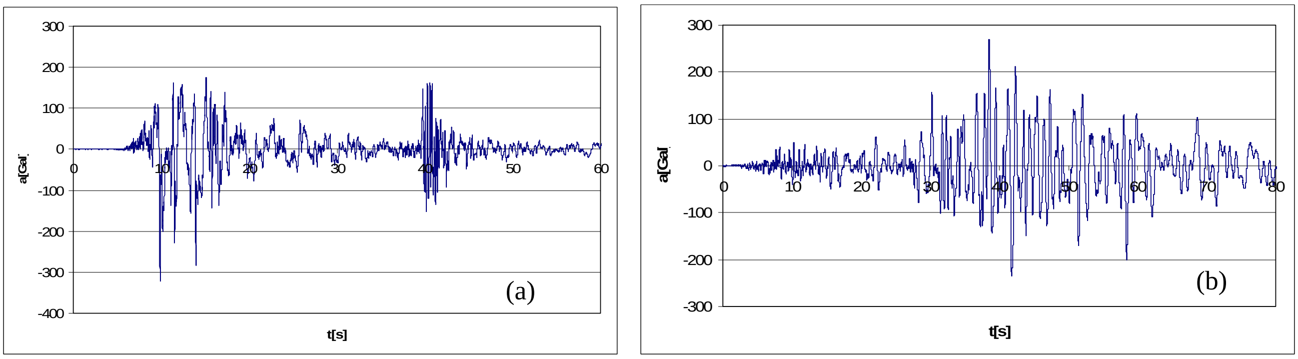


Figure 9 Strong motion records of the (a) 17 August 1999 Izmit Eq. (b) 12 November 1999 Duzce Eq.

For support points of the main dome, principal stress histories before and after retrofitting are given in Figures 10a and 10b. These figures show that stresses are significantly reduced by up to 65%. Furthermore, a more uniform stress distribution over the dome is obtained after retrofitting.

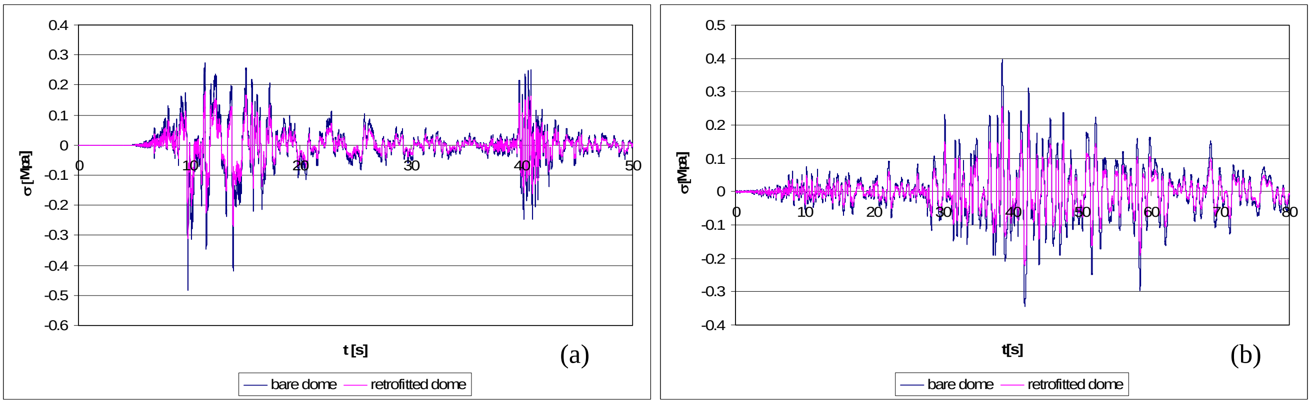


Figure 10. Normal Stress History at the Support Point of the Main Dome Before and After Retrofitting
(a) 17 August 1999 Izmit Eq. (b) 12 November 1999 Duzce Eq.

3. CONCLUSIONS

Seismic retrofitting of a 16th century historic masonry dome using combined external steel rings placed at its support level and CFRP sheets along the tension zone on the inner face is numerically investigated. The problem is considered through examples of a real conservation case in Istanbul, involving the Yavuz Selim mosque's ancient dome of 486 years old. Finite element model with linear elastic shell and frame elements was used to simulate the behavior. When external steel rings and CFRP sheets are used in the dome, numerical analyses reveal that stresses are significantly reduced up to 65%. Effectiveness of the retrofit system under gravity loading is significant. On the other hand, although the effectiveness of the retrofit system seems less in case of earthquake loading, the distribution of stresses over the entire dome is more preferable when compared to the unretrofitted dome.

Furthermore, a more uniform stress distribution over the dome is obtained after retrofitting. The restoration works in the mosque is still under way. Although the retrofit system proposed in this study has been approved by the government, application process has not been initiated.

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