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SEISMIC ASSESSMENT AND RETROFIT STRATEGIES FOR 16TH-CENTURY HISTORICAL STRUCTURES IN NORTHERN INDIA

Shilp Sharan[1], Mr. Vivek Shukla[2], Dr. Jyoti Yadav[3]

Research Scholar, Department of Civil Engineering, SRK University Bhopal[1]

Assistant Professor, Department of Civil Engineering, SRK University Bhopal[2]

HOD, Department of Civil Engineering, SRK University Bhopal[3]

Abstract:

This study explores the effectiveness of targeted retrofitting measures on the Yavuz Selim Mosque, an Ottoman structure facing significant structural challenges. The mosque's main dome exhibited critical issues such as tensile stresses and cracking, worsened by recent seismic events. The retrofitting strategy, involving the application of CFRP sheets and steel rings, successfully addressed these issues, resulting in up to a 65% reduction in stress levels and improved stress distribution. Dynamic analysis using historical seismic data confirmed the retrofit's efficacy, showing reduced stress concentrations and enhanced stability under both gravity and earthquake loads. These interventions not only resolved immediate structural vulnerabilities but also supported the mosque's long-term preservation. The findings underscore the importance of integrating modern materials with traditional construction techniques for preserving heritage buildings. This case study offers valuable insights for similar projects, emphasizing the need for comprehensive seismic assessments and innovative retrofit strategies to ensure the resilience of 16th-century historical structures in seismically active regions.

Keywords: *Retrofitting, CFRP Sheets, Seismic Assessment, Historical Structures, Stress Reduction.*

1. Introduction

The Yavuz Selim Mosque, an Ottoman architectural gem completed in 1522, is a significant historical monument perched atop Istanbul's 5th Hill. As the second oldest existing imperial mosque in Istanbul, its historical and architectural importance is immense. The mosque's structural system includes a grand central dome and eighteen smaller domes, supported by thick masonry walls and reinforced with flying buttresses. Despite its historical significance, the mosque faced structural challenges due to tensile stresses and cracking, exacerbated by recent seismic activity in the Marmara region. Detailed investigations revealed that the main dome experienced severe stress and cracking, primarily in its lower zones, a consequence of the masonry's low tensile strength and lateral loading effects from earthquakes. To address these issues, targeted retrofitting measures were implemented. The retrofit involved applying CFRP sheets to the inner surface of the dome and installing steel rings at strategic levels. These interventions significantly improved the dome's structural integrity, with stress levels reduced by up to 65% and a more uniform stress distribution achieved. Dynamic analysis based on historical seismic data confirmed the efficacy of these measures, demonstrating reduced stress concentrations and enhanced stability under both gravity and seismic loads.

This case study of the Yavuz Selim Mosque underscores the critical role of integrating modern materials and techniques with traditional architectural elements to preserve historical structures. The success of the retrofit highlights the importance of comprehensive seismic assessments and innovative retrofit strategies in safeguarding the durability and resilience of 16th-century historical monuments. The insights gained from this study are valuable for similar retrofitting projects, especially in seismically active regions, offering a promising approach for maintaining the structural integrity of heritage buildings.

2. The Yavuz Selim Mosque (16th Century)

The Yavuz Selim Mosque, an Ottoman imperial mosque completed in 1522, stands atop the 5th Hill of Istanbul, overlooking the Golden Horn (Figures 1a, b). It is the second oldest existing imperial mosque in Istanbul. Although the architect remains unknown, some have tried to link it to the renowned imperial architect Mimar Sinan, but no documentary evidence supports this claim. The mosque features a large courtyard with a colonnaded portico, boasting columns of marble and granite from various regional quarries. The mosque is adorned with early examples of distinctive Iznik tiles and flanked by twin minarets. Currently, it is undergoing restoration and is scheduled to reopen in 2009. This context of historical architectural significance parallels the study of Seismic Assessment and Retrofit Strategies for 16th-Century Historical Structures in Northern India.

Description of the structural system before retrofitting

The Yavuz Selim Mosque features a symmetrical plan measuring 29.50m by 31.00m (Figure 2). Its roof system includes eighteen small hemispherical brick masonry domes, each 4.00m in diameter, and a central dome with a diameter of 25.00m. The central dome, 90cm thick at both the top and support level, is reinforced by eight symmetrically placed small-scale flying buttresses made of masonry. All domes are covered with heavy lead layers for protection against natural elements. The masonry walls supporting the main dome range from 160cm to 260cm in thickness and are constructed using shallow solid bricks, limestone, equal thickness crushed tiles, and lime mortar for the joints.

Figure 1 The Yavuz Selim Mosque under restoration

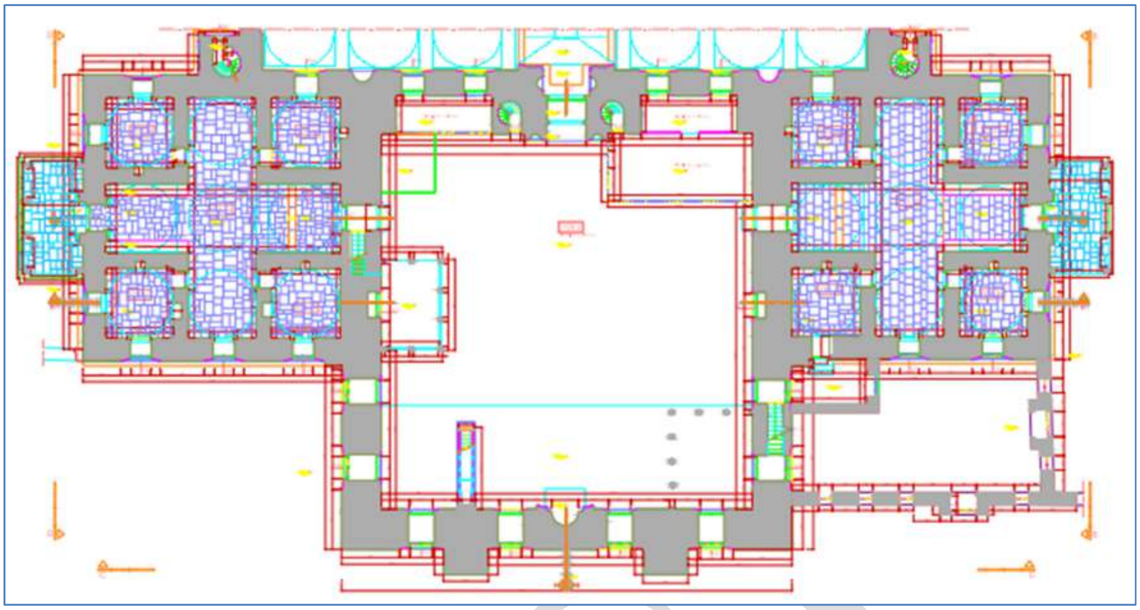

Figure 2 Structural Layout of the Yavuz Selim Mosque

After detailed investigations, it was found that the major structural issues of the Yavuz Selim Mosque stem from tensile stresses due to the low tensile strength of the masonry materials. These stresses have caused structural cracks, primarily concentrated in the lower zone of the main dome. The circumferential tension has led to meridional cracks, likely exacerbated by recent earthquakes in the Marmara region. The asymmetrical distribution of these cracks suggests lateral loading effects. Figure 3 illustrates some of the observed crack patterns on the inner surface of the dome. This analysis is relevant in the context of Seismic Assessment and Retrofit Strategies for 16th-Century Historical Structures in Northern India.

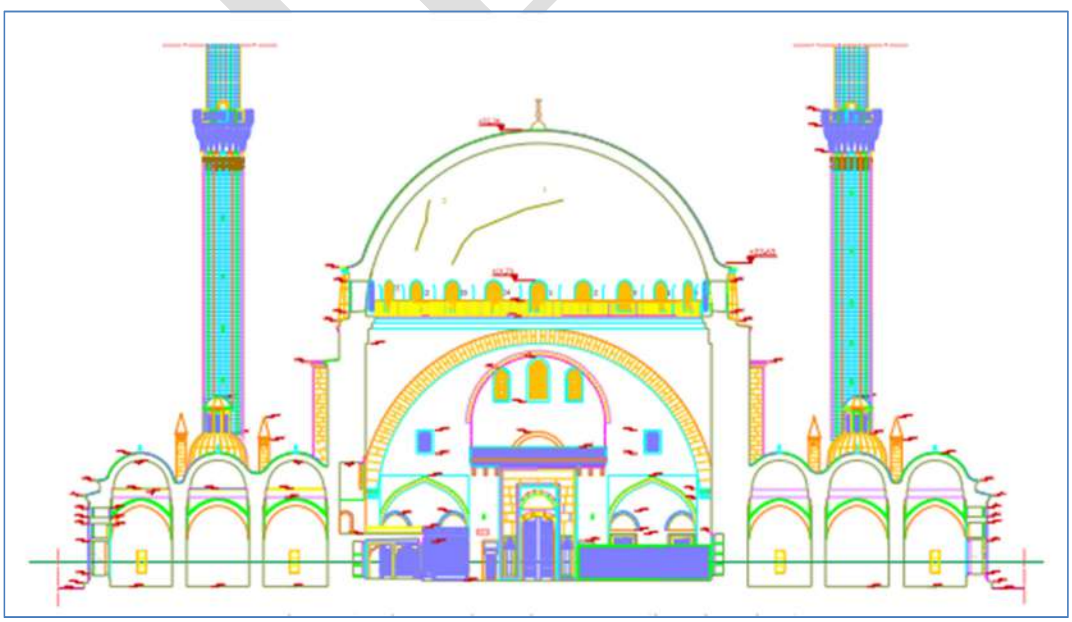

Figure 3 Observed crack patterns (interior view)

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.

Masonry Dome Behavior

To demonstrate the effectiveness of the retrofitting technique used in this study, the fundamental behavior of a hemispherical dome is illustrated in Figure 4. This diagram conceptually shows the variation of tangential stress along the dome height. With the addition of tension members (both steel rings and CFRP sheets) around the dome, lower stresses are expected, particularly at the support level where cracks typically initiate due to high stress concentrations. Additionally, the compression zone on the dome can be increased (represented as a downward shift in the diagram) by incorporating the tension members. This analysis is pertinent to the Seismic Assessment and Retrofit Strategies for 16th-Century Historical Structures in Northern India.

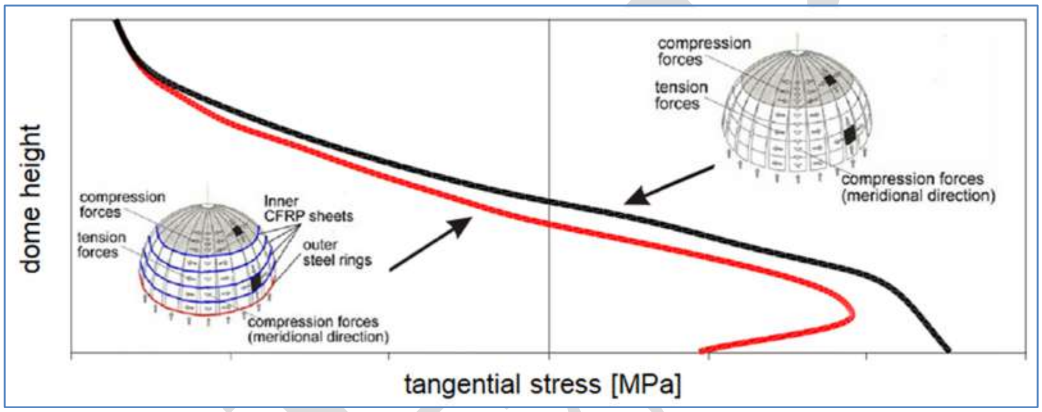

Figure 4 Expected behavior of masonry dome with and without tension members

Numerical Modeling of the Dome

As a preliminary assessment to investigate crack formation, a linear, 3D model was developed in SAP2000 [CSI, 2004] (Figure 5). While a refined analysis would require modeling the entire structure, including the subgrade soil, this study focuses solely on the dome to observe the behavioral changes of both bare and retrofitted domes. The analytical model, built using curved shell elements, consists of 800 shell elements and a total of 4686 stiffness and 2283 mass degrees of freedom. Based on experience with similar buildings, the mechanical properties were assumed to have a Young's Modulus of 20 GPa and a Poisson's Ratio of 0.20. The analysis considered dead and earthquake loads, while snow and wind loads were disregarded due to their negligible impact compared to the building's self-weight. The tensile strength of the masonry was also neglected.

The model indicated that the dome structure weighs approximately 15,860 kN. Under gravity loads, the maximum compressive stress was found to be 0.22 MPa at the support level and 0.13 MPa at the keystone ring. Analysis of the principal stresses showed that the sub-vertical direction is primarily under compressive stresses. Stress patterns under gravity and earthquake loading, both before and after retrofitting, are shown in Figures 5a, b, c, and d. These figures and numerical analyses reveal that, under gravity loading, the highest circumferential tension stresses of 0.31 MPa and 0.15 MPa (a 52% reduction) are observed at the base of the dome before and after retrofitting, respectively. Under combined gravity and earthquake loading, these stresses reach 0.50 MPa and 0.47 MPa, resulting in a 6% decrease. The retrofit system is significantly effective under gravity loading, while its effectiveness under earthquake loading is less pronounced. However, the stress distribution over the entire dome is more favorable in the retrofitted dome compared to the unretrofitted one. This analysis is relevant to the Seismic Assessment and Retrofit Strategies for 16th-Century Historical Structures in Northern India.

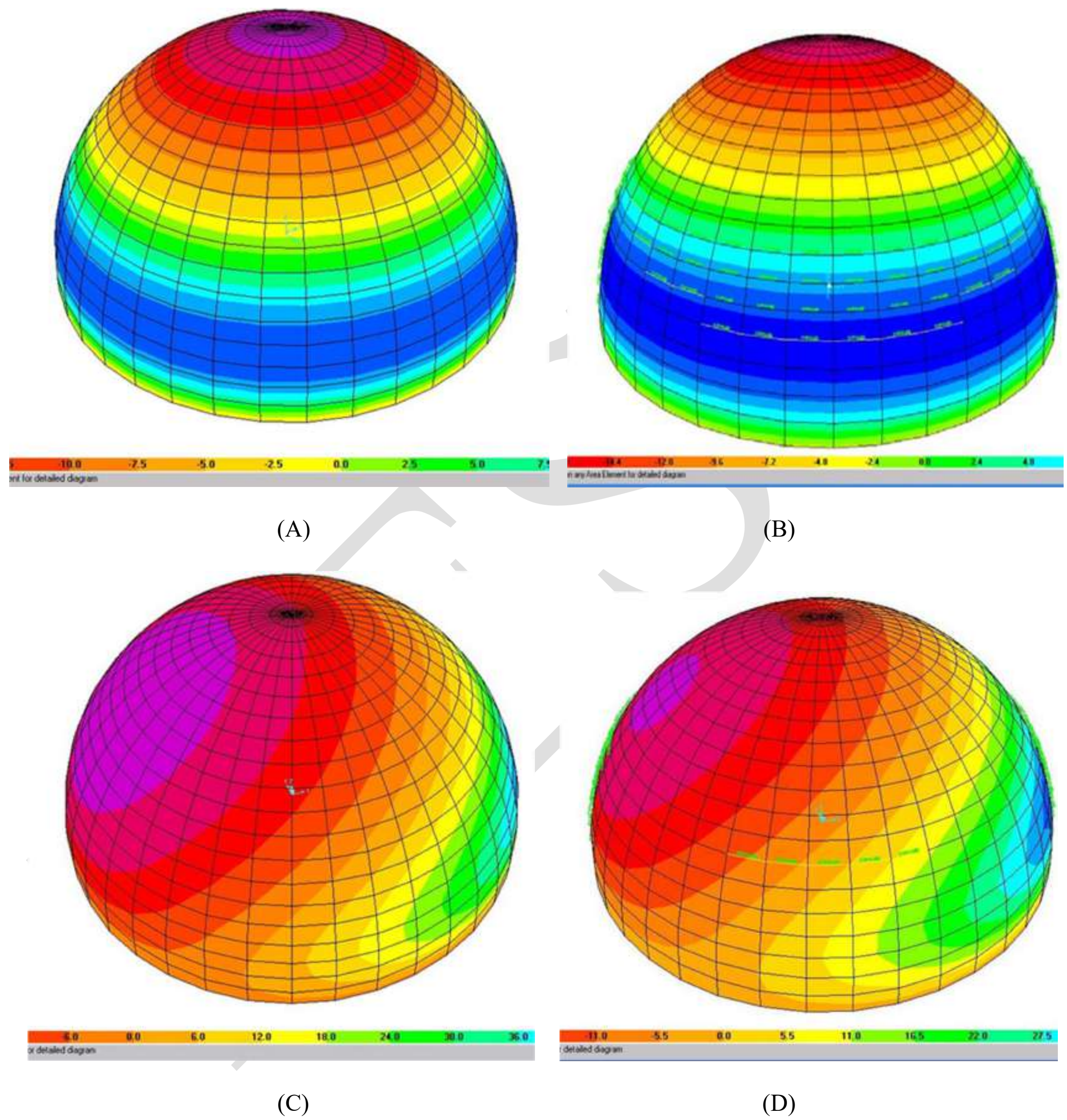

Figure 5 FEM modeling and principal stress patterns of the main dome (a) Existing dome under gravity loading(b) Retrofitted dome with combined outer steel ring and inner CFRP Sheets under gravity loading (c) Existing dome under earthquake loading (d) Retrofitted dome with combined outer steel ring and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

Retrofitting details of the main dome

The cracking patterns observed at the mosque include two distinct types (Figures 6a, b): the first type consists of cracks that traverse the entire height of the lower part of the masonry dome and are visible at the intrados; the second type consists of surface cracks limited to the dome's exterior. For the surface cracks, mortar injection, a typical passive intervention, is employed. Typical crack widths range from 0.8 cm to 2.0 cm. Due to the growth of cracks into the tension stress zone, additional CFRP sheets were applied to the inner surface of the dome (Figure 6a). The MBRACE CFRP sheets were spaced 1200 mm apart, with four layers applied at a quality of C1-30. The mechanical properties of the CFRP sheets include a fiber density of 1820 kg/m³, an effective thickness of 0.165 mm, a tensile strength of 4000 MPa, and a tensile modulus of elasticity of 230 GPa [BASF, 2007]. This analysis is relevant to the Seismic Assessment and Retrofit Strategies for 16th-Century Historical Structures in Northern India.

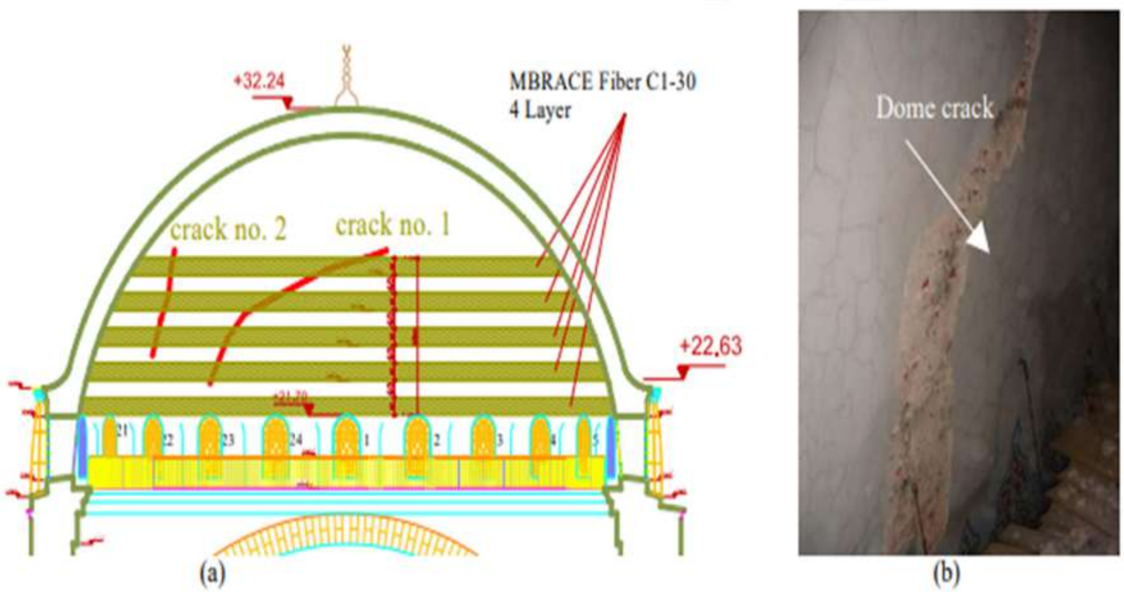

Figure 6 (a) Application of CFRP sheet layers on the inner surface of the main dome (b) A typical crack on dome

The stability of the dome is enhanced by the sub-vertical compressive stress zones, which stiffen the entire structure against tangential tensile stresses. To reinforce this stability, two steel plate rings, each 20 mm thick and 300 mm wide, were installed at the 20.60 m and 22.60 m levels of the main dome (Figure 6a). The connection and splice details of the rings are depicted in Figures 7 and 8. Each ring configuration includes a minimum of two splices, with connections secured by high-strength bolts. The steel plates are galvanized and connected using equal-leg angles with M33 high-strength bolts. A 50 mm gap between the angles is provided to introduce some prestressing force to the system via the bolts (Figure 8). This approach is relevant to the Seismic Assessment and Retrofit Strategies for 16th-Century Historical Structures in Northern India.

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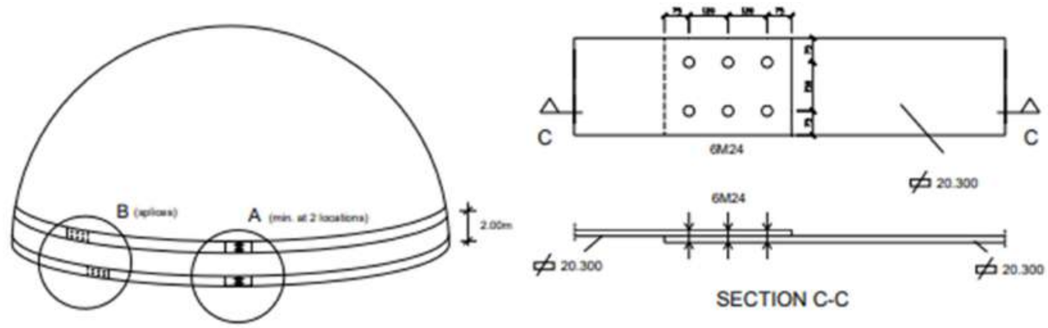

Figure 7 Typical ring configuration and splice detail

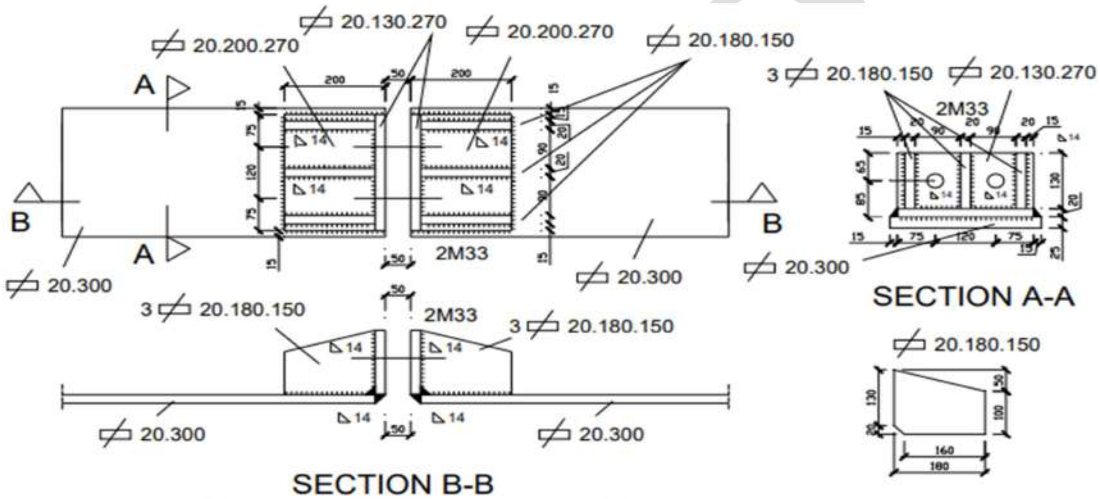

Figure 8 Detail A

3D Dynamic Analysis

To evaluate the seismic behavior and effectiveness of external confinement and CFRP sheets on the domed structure, a dynamic analysis was performed. This analysis involved elastic time history simulations based on the 17 August 1999 Kocaeli NS and 12 November 1999 Duzce 41N-29E strong ground motion records (Figure 9). This assessment is relevant to the Seismic Assessment and Retrofit Strategies for 16th-Century Historical Structures in Northern India.

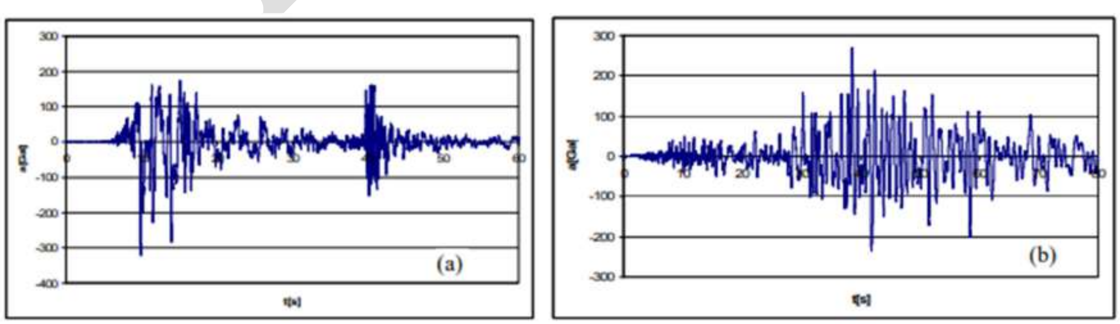

Figure 9 Strong motion records of the (a) 17 August 1999 Izmit Eq. (b) 12 November 1999 Duzce Eq.

The principal stress histories at the support points of the main dome, both before and after retrofitting, are shown in Figures 10a and 10b. These figures demonstrate a significant reduction in stresses by up to 65% following retrofitting. Additionally, the retrofit leads to a more uniform stress distribution across the dome. This analysis is pertinent to the Seismic Assessment and Retrofit Strategies for 16th-Century Historical Structures in Northern India.

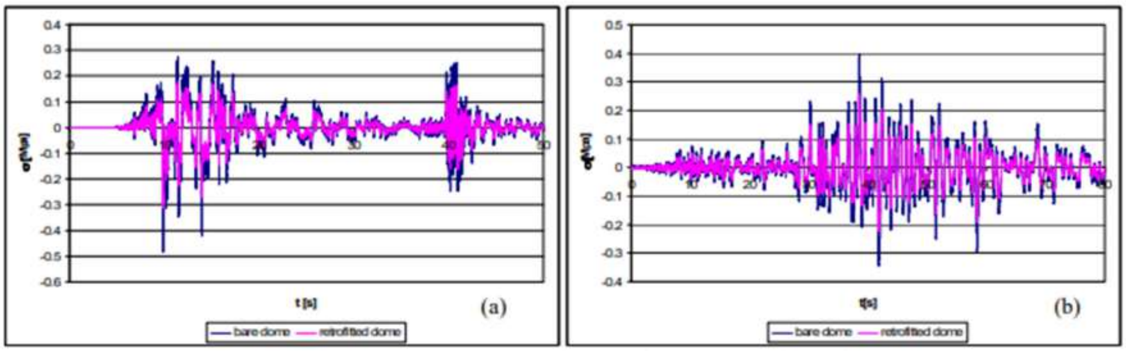

Figure 10. Normal Stress History at the Support Point of the Main Dome Before and After Retrofitting (a) 17 August 1999 Izmit Eq. (b) 12 November 1999 Duzce Eq.

3. Conclusion

In conclusion, the investigation and retrofitting of the Yavuz Selim Mosque highlight the critical role of targeted structural interventions in preserving historical architecture. The analysis revealed that the mosque's main dome faced significant challenges due to tensile stresses and cracking, exacerbated by recent seismic activity. The retrofitting measures, including the addition of CFRP sheets and steel rings, proved highly effective in mitigating these issues. The reduction in stress levels by up to 65% and the enhancement of stress distribution underscore the success of these interventions in improving the dome’s structural stability. The dynamic analysis, based on historical seismic records, validated the retrofit’s efficacy, demonstrating reduced stress concentrations and a more uniform stress distribution under both gravity and earthquake loads. This approach not only addressed the immediate structural vulnerabilities but also contributed to the long-term preservation of the mosque.

The findings of this study offer valuable insights for similar retrofitting projects on historical structures, particularly in seismically active regions. The integration of modern materials and techniques with traditional architectural elements provides a promising pathway for safeguarding and maintaining the structural integrity of heritage buildings. This case study underscores the importance of comprehensive seismic assessments and innovative retrofit strategies in ensuring the durability and resilience of 16th-century historical structures.

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