*Journal of Architectural Sciences and Applications*
JASA 2023, 8 (Special Issue), 487-509
Research article
e-ISSN: 2548-0170
https://dergipark.org.tr/en/pub/mbud

# Finite Element Analysis of Strengthening Method Using Carbon Fiber Reinforced Polymer and Glass Fiber Reinforced Polymer in Tensile Zones of Historical Domed Structures: Edirnekapi Mihrimah Sultan Mosque Dome

Hatice ÖZ [1*], Asena SOYLUK [2]
**ORCID 1**: 0000-0001-9305-3256 **ORCID 2:** 0000-0002-6905-4774

[1-2] *Gazi University, Faculty of Architecture, Department of Architecture, 06570, Ankara, Türkiye.*
**** e-mail:** haticeeoz96@gmail.com*

**Abstract**

*Historic buildings are remarkable monuments that carry cultural traces and heritage from the past to the present and from the present to the past in terms of historical sustainability. These assets worthy of preservation should be restored and strengthened under certain intervention criteria for the continuity of cultural accumulation. Although historical masonry buildings exhibit a very rigid performance under vertical loads, their tensile strength against lateral loads such as seismic forces created by earthquakes is low. Domes, an important architectural element of masonry buildings, are likely to be damaged under the influence of seismic forces. The retrofitting analyses were performed with CFRP and GFRP in the dome tensile zones and readings were made on the Modulus of Elasticity. Since Edirnekapı Mihrimah Sultan Mosque is a structure sensitive to seismic force due to its location and the earthquakes experienced by the structure, it was deemed suitable for finite element model analysis.*

***Keywords:*** *Finite element analyses, Edirnekapı Mihrimah Sultan Mosque, CFRP, GFRP, seismic vulnerability.*

# Tarihi Kubbeli Yapıların Çekme Bölgelerinde Karbon Fiber Takviyeli Polimer ve Cam Fiber Takviyeli Polimer Kullanılarak Güçlendirme Yönteminin Sonlu Elemanlar Analizi: Edirnekapı Mihrimah Sultan Camii Kubbesi

**Öz**

*Tarihi yapılar, tarihsel sürdürülebilirlik açısından geçmişten günümüze, günümüzden geçmişe kültürel izleri ve mirası taşıyan dikkat çekici anıtlardır. Korunmaya değer bu varlıkların, kültürel birikimin devamlılığı için belirli müdahale kriterleri altında restore edilmesi ve güçlendirilmesi gerekmektedir. Tarihi yığma yapılar düşey yükler altında oldukça rijit bir performans sergilemelerine rağmen, depremlerin yarattığı sismik kuvvetler gibi yanal yüklere karşı çekme dayanımları düşüktür. Yığma yapıların önemli bir mimari unsuru olan kubbelerin sismik kuvvetlerin etkisi altında hasar görmesi muhtemeldir. Güçlendirme analizleri kubbe çekme bölgelerinde CFRP ve GFRP ile gerçekleştirilmiş ve Elastisite Modülü üzerinden okumalar yapılmıştır. Edirnekapı Mihrimah Sultan Camii, bulunduğu konum ve yaşadığı depremler nedeniyle sismik kuvvetlere duyarlı bir yapı olduğundan sonlu elemanlar modeli analizi için uygun görülmüştür.*

***Anahtar kelimeler:*** *Sonlu eleman analizleri, Edirnekapı Mihrimah Sultan Camii, CFRP, GFRP, sismik hasar görebilirlik.*

**Citation:** Öz, H. & Soyluk, A. (2023). Finite element analysis of strengthening method using carbon fiber reinforced polymer and glass fiber reinforced polymer in tensile zones of historical domed structures: Edirnekapi Mihrimah Sultan Mosque Dome. *Journal of Architectural Sciences and Applications*, 8 (Special Issue), 487-509
**DOI:** https://doi.org/10.30785/mbud.1317703

***Received:*** *20/06/2023 –* ***Accepted:*** *05/12/2023*

## 1. Introduction

Historical buildings are values that extend from the past to the present, carry social, cultural, and economic traces from the lives of ancient people, and need to be protected. Over time, they have been exposed to deterioration and even extinction from time to time due to climatic reasons, biological reasons, natural disasters, and human causes. Cultural heritage should be protected as it is one of the most important concepts for the past, present, and even future of societies. Modern cultures now hold the view that built cultural heritage should endure forever as a symbol of diversity and culture. They also give the next generation the vital responsibility of preserving the existence of these structures for future generations. As one of life's unavoidable events, destruction, architects and engineers have considerable expectations for this act of culture (Lourenço, 2013). Natural disasters, one of the causes of deterioration in historical monuments, are uncertain when and where they will occur and may cause unexpected major damage to structures. Natural disasters, which can have devastating effects such as earthquakes, can cause irreversible damage not only to the materials of the buildings but also to the building systems by affecting the structures with a very large moment force. Historical buildings are usually made of stone, brick, etc. They are masonry structures built using building materials. Although there is no great difficulty in bearing vertical loads in masonry structures, depending on traditional construction techniques and material properties, they are sensitive to seismic movements, i.e. lateral loads, created by earthquakes. Due to the lateral loads revealed by the earthquake, adverse effects can be observed in historical buildings, especially in structural elements such as domes, vaults, and buttresses that receive tensile stresses. Historical structures that were built using conventional earthquake-resistance techniques deteriorate with time, especially as a result of material aging and fatigue. The systems of historic structures may be strained under the effect of an earthquake, and damages like cracking, separation, and separation from the vertical, up to partial or total collapse may occur (Zakar & Eyüpgiller, 2020). Based on these reasons for deterioration, historical buildings should be protected for the continuity of cultural heritage. Historical buildings shed light on the life of societies in terms of cultural, economic and social sustainability. Therefore, they are value-prioritized structures so that they need to be protected. Although conservation techniques and methods in architectural restoration differ for the material and the architectural, structural features of building worth protecting. Consolidation, reinforcement, maintenance, repair, improvement, reconstruction, reuse, etc. considered as basic restoration techniques and methods. Materials forming domed masonry structures can be listed as resistant to external effects, low ductility, brittle, compression resistant, and very weak against tensile. For this reason, masonry structures are highly resistant to vertical loads because the technique and material used meet this. However, masonry structures made with traditional methods are vulnerable to lateral loads and weak against tensile stresses, as reinforcement materials are not used in masonry structures. In domed structures, seismic movements caused by earthquakes affect the structure as a lateral load. Unsymmetrical loadings, different settlements, and seismic effects cause tensile stresses to increase and intensify in the living elements of the structure. Where tensile stresses are concentrated, cracks occur perpendicular to the stresses. This may cause a rupture and loss of load transfer continuity in the structural element and local cracks, spills, and collapses. These possible damages in the load-bearing elements may become quite dangerous and permanent (Çelik, 2016). Historical masonry structures deteriorate over time due to environmental and natural factors. To prevent the deterioration of the stones and reduce the degree of their deterioration, reinforcing and water-repellent protective chemical materials are used in line with the conservation works (Karakaş & Acun Özgünler, 2022). CFRP and GFRP materials are examples of these materials used with the development of technology in recent years.

### 1.1. Literature Review

The purpose of this literature review is to examine the current state of knowledge on the main effects of seismic movements on masonry structures primarily domes, reinforcement of seismic deformations of masonry domes by using Carbon Fiber Reinforced Polymer (CFRP) and Glass Fiber Reinforced Polymer (GFRP), and analysis of how the modulus of elasticity affects with using those composite elements in strengthening of deformations. With the increasing importance of reinforcement of historical buildings by using Fiber Reinforced Polymer materials in Architectural Restoration and Conservation, and Structural Engineering, it is crucial to understand the existing research environment.

Firstly, studies on earthquake effects on masonry structures were analyzed, and a background on the basic deformations that seismic movements cause and may cause in masonry structures was prepared. Lourenço, Roca & Modena's (2010) "Masonry Structures: Behaviour and Design" by Lourenço, Roca & Modena (2010) provides an overview of the behavior and design of masonry structures and covers topics such as the mechanical behavior of masonry materials, structural analysis of masonry buildings, design methods for masonry structures, and seismic behavior and retrofitting of masonry buildings. According to Elghazouli et al. (2018), a study named "Seismic Vulnerability of Historical Masonry Buildings" and Pujades & Lanzón's (2017) research with the name "Seismic Vulnerability and risk assessment of historical masonry structures: A Review" unveal the vulnerability of historic masonry buildings to seismic events and also provides a detailed survey of the literature on seismic vulnerability and risk assessment. In addition, the latter study presents several case studies related to the mentioned areas of study. The authors argue that further research is needed to enhance the accuracy of seismic risk assessment methods for historical masonry structures to help conserve these important cultural heritage assets. In addition to these, when the studies in the field of Architectural Conservation and Restoration are examined, Zakar& Eyüpgiller (2020), "Architectural Restoration Conservation Techniques and Methods" and Croci, (2000), "The Conservation and Structural Restoration of Architectural Heritage" was observed to be an important study when the literature was searched. The Venice Charter (1964), which is one of the main sources of Architectural Restoration experts, and the 1974 ICOMOS Nostra Declaration are also very important basic sources used in this study.

Case studies from all over the world on the retrofitting of domes using CFRP and GFRP and providing a design guide are; Sesigür, Çelik & Çılı (2007) "Structural components, damage patterns, repair and retrofitting in historic buildings", Çelik, (2016), "Historical Building Repair and Retrofit Guide", Döndüren et al. (2017), "Types of Damage In Historical Buildings". In addition, Aiello, Contrafatto, & Ricciardi, (2019) "Fiber Reinforced Polymers for Strengthening Historical Buildings: A Review", Değirmenci & Sarıbıyık (2015). The studieas namely, Innovative Approaches and Use of FRP Materials in Strengthening Historical Buildings, Nassery (2018), "Carbon vs. Glass Fiber Reinforcement", Le et al. (2019), "Strength and stiffness characteristics of GFRP composite plates with different stacking Sequences", Neto & Brandt (2017), "Tensile and compressive properties of carbon fiber reinforced polymer composites" provide information about the general properties of FRP elements especially CFRP and GFRP materials, how they are used as reinforcement materials and how they increase the strength of structures.

According to the studies, the application of CFRP or GFRP reinforcement significantly increased the masonry dome's elasticity modulus. Articles that answer questions such as what is the modulus of elasticity, how does the modulus of elasticity of the dome and the architectural element and material applied on it change, how many times it increases when GFRP and CFRP elements are used in masonry structures can be listed as follows; Shariati et al. (2013), "Strengthening of Stone Masonry Domes Using CFRP and GFRP Composites: An Experimental Study", Galati, Nanni, Ceroni & Sacco (2017), "Strengthening of masonry arches with FRP composites: Experimental investigation and numerical simulation", Kheirikhah et al. (2019), "Strengthening of masonry domes with carbon fiber reinforced polymer (CFRP) composites", Bournas et al. (2014), "Reinforcement of masonry domes with CFRP and GFRP."

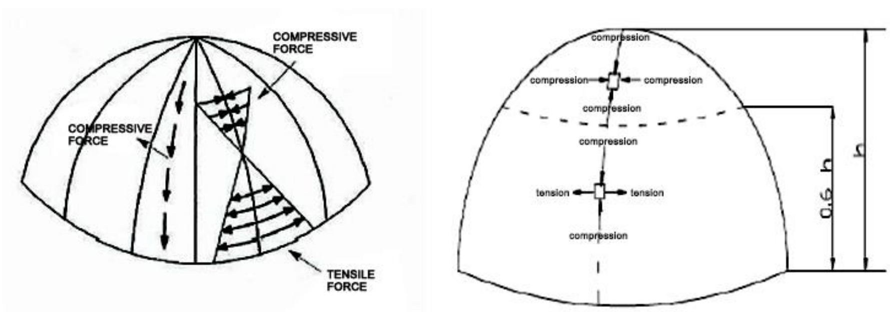
### 1.2. Seismic Behavior of Domes and Structural Reinforcement

#### 1.2.1. Seismic Behavior of Masonry Structures

Cultural heritage structures such as historical buildings and monuments that have survived today may be damaged over time due to earthquakes, gravity, climatic conditions, ground conditions, etc. Earthquakes may cause different seismic behaviors in masonry structures due to different material properties and traditional construction techniques, together with the seismic, in other words, lateral loads that seismic loads bring. The factors affecting these behaviors can be listed as geometrical configuration, quality of construction materials, and structural detailing. Geometric configurations are one of the factors affecting the seismic behavior of masonry structures. Building height, plan dimensions, and aspect ratios of the masonry buildings play a decisive role in the seismic behavior of masonry structures. For example, although tall and narrow structures tend to experience higher displacement, relatively short and wide structures tend to experience higher acceleration. According to Lourenço et al. (2010), this is mainly due to the fact that short and narrow masonry structures tend to be subjected to larger mass and inertia forces, and the center of gravity of long and narrow masonry structures is higher, and more prone to overturning (Lourenço et al., 2010). As in every structure, the quality of the construction material used in masonry structures, the type of mortar, which is the binding material, and structural details are effective on the seismic behavior of the structure. Poor quality of the material used or the use of incomplete mortar causes brittle behavior in the structure and the formation of weak points against the tensile strength against the lateral loads caused by the earthquake. In other words, low-quality materials tend to produce structures that are not resistant to earthquakes. In addition, the lack of reinforcements in masonry buildings as a handicap brought about by conventional construction techniques is also a significant factor (Lourenço et al., 2010). Structural detailing of masonry structures is also one of the factors affecting their seismic behavior, but if effective connections are missing or incomplete, the structure may be adversely affected by the earthquake and damaged or even collapse. Inadequate structural detailing can lead to vulnerable behavior and the development of weak parts within the structure. Structural connections should provide the most effective way of transferring loads between architectural elements. When this order and flow are interrupted, the mentioned damage and collapse are inevitable (Lourenço et al., 2010).

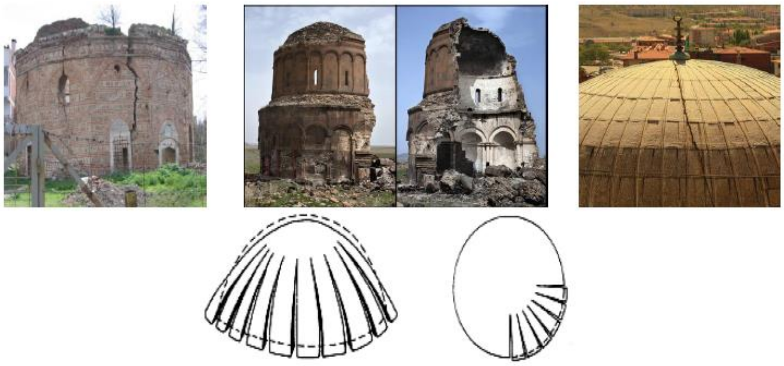
### 1.2.2. Seismic Behavior of Domes

The most prevalent kinds of domes used in traditional architecture are those with positive Gaussian curvature due to the fact that they can hold the weight of snow, wind, and earthquakes in addition to their self-weight, as well as additional external impacts on their surface such as temperature change and ground settlement (Türkmen & Bilgin, 2002). The areas where earthquake damage to masonry domes typically occurs are influenced by a number of variables, such as the area's seismic danger level, the dome's structural qualities, and the level of workmanship of the building materials and construction methods utilized. Each dome has a similar load-bearing system (Figure 1).




**Figures 1.** Load-bearing mechanism of domes (Sesigür et al., 2007)

Damage on masonry domes generally can be seen in Figure 2 occurs in the tensile zone. In the tensile zone, masonry domes typically sustain damage. Vertical cracks in this area may result from tensile stresses in the dome skirt. The base of the dome, namely the skirt, where the dome faces the supporting architectural elements and the zone that is primarily vulnerable to damage caused by the high tensile stress and strains triggered by seismic movements. Vertical loads are transmitted from the keystone to the nearby stones and to the dome base a dome created by rotating an arch around its vertical axis. The adjacent stones are affected diagonally by the weight force pressing vertically on the stones. As a result, the load gathered at the base of the dome consists of both horizontal and vertical components. This horizontal force typically results in damage to the dome (Çelik, 2016).



**Figures 2.** Damages on domes as a result of earthquakes, weather conditions, gravity, ground, etc. (Döndüren, Şişik & Demiröz, 2017)

### 1.2.3. Reinforcement of Masonry Domes With Carbon Fiber Reinforced Polymer and Glass Fiber Reinforced Polymer

In cases where the original material texture is lost due to deterioration and the building element is insufficient to fulfill its load-bearing function, sheathing, in other words, the method of increasing the cross-section is used. Covering a vault with a reinforced concrete layer is one example of sheathing (Croci, 2000). Reinforcement with Fiber Reinforced Polymer tapes, which is one of the structural reinforcement methods, is a new method and is advantageous in many respects compared to other methods. Aramid, carbon, and glass fibers can be used as Fiber Reinforced Polymer material (Değirmenci & Sarıbıyık, 2015). Against some of the disadvantages of traditional methods used in the reinforcement of historical buildings, Fiber Reinforced Polymers can be applied unidirectional and multi-directional, as well as Fiber Reinforced Polymers (FRP) have very thin cross-sections and give great resistance to environmental and structural effects on the elements to which they are applied, preventing many sheathing options (Zakar & Eyüpgiller, 2020). FRP materials are applied regionally and superficially directly on the architectural element and increase the strength of the element. Figure 3-4 shows an example of reinforcement of the deformation in the vault with FRP tape application.

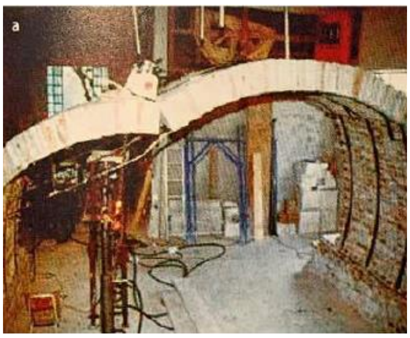



**Figure 3.** Deformation on vault (Zakar & Eyüpgiller, 2020)


**Figure 4.** Application of FRP materials (Zakar & Eyüpgiller, 2020)

The use of modern reinforcement materials such as CFRP and GFRP is becoming more and more widespread due to the development of technology and the advantages of modern reinforcement materials such as CFRP and GFRP over traditional methods in the strengthening of historical buildings and structural elements such as domes. In general, the reason for using Fiber Reinforced Polymers in the reinforcement of domes is the high strength, light weight, durability, and long life of these polymers. Retrofitting of historic buildings is carried out in order to protect the building against various environmental factors and to protect it from future damage by preserving the original texture of the building. The use of CFRP materials in the retrofitting of historic structures was first successfully applied to a bridge in Venice in 1997. This application broke new ground in the preservation of historic structures (Aiello et al., 2019). Before CFRP materials were used to reinforce historic structures, steel or wood materials were usually used. However, the use of these materials can change the original texture of the structures and deteriorate their aesthetics. The most important reason why CFRP materials are used in the reinforcement of historic buildings is that they are lightweight and have high-strength properties. These materials can protect the structure from future damage by increasing the durability of the structure without changing the original texture of the structure. The use of CFRP materials in the strengthening of historical buildings is frequently preferred, especially in applications such as crack repair and reconstruction. These applications make the structure safer while preserving the original fabric of the structures (Aiello et al., 2019). It is very important that the CFRP material does not spoil the historical texture and aesthetics of the architectural element to which it is applied. Article 10 of the Venice Charter states that *"Where traditional techniques are inadequate, the monument may be strengthened by using any modern technique for conservation and construction which has been validated by scientific data and experiments (*Venice Charter, 1964*)."* In other words, modern methods can be used for the preservation and transfer of cultural heritage to future generations. However, these interventions also should be reversible to the original state of the building.

There are two different application methods of CFRP materials in the reinforcement of historic domes, namely the wrapping method and the plate method. In the wrapping method, which is applied by wrapping CFRP strips on the dome surface, the surface of the dome is first cleaned and prepared before starting the application. Then, an adhesive is applied to the dome and the CFRP strips are wrapped one by one and firmly attached. The wrapping method can be easily applied to surfaces of different sizes. In this way, it can be applied anywhere on the dome and provides a more flexible reinforcement. Adhering CFRP sheets to the dome surface is the Plate Method. With this technique, an adhesive is used to attach CFRP sheets to the masonry dome's surface. Despite being considered a simpler application approach, the sheet method might be challenging since it necessitates a precise fit to the dome's surface (Khalil & Bakhoum, 2017). Depending on the structure, state, and needs of the dome, the use of carbon fiber-reinforced polymers may be tailored. The repair procedure is specialist work, according to Article 9 of the Venetian Charter, and should be carried out by expert teams (Venice Charter, 1964).

The Basilica of Santa Maria Maggiore in Rome from the fifth century is used as an example of the wrapping technique by Campione et al. (2009). Given that it is one of the oldest basilicas in Rome, this basilica has significant architectural value. The basilica's masonry dome was strengthened using CFRP strips and the wrapping strategy. Inside the basilica, the CFRP strips were positioned and wrapped around the dome. To keep the dome from collapsing, this procedure was accomplished. The investigations' findings showed that the CFRP strips improved the dome's strength and gave the structure stability (Champione et al., 2009). One of the most important reasons for the increase in the strength of the structure is that the CFRP material increases the modulus of elasticity of the material on which it is applied. Since the modulus of elasticity increased, the resistance of the dome against shrinkage also increased. In this way, the dome was protected from the danger of collapse. The Cefalù Cathedral in Italy is an example of the plate technique. Since the cathedral was constructed in the 12th century, it is a valuable piece of cultural heritage. On the side dome of the cathedral's transept, CFRP plates were installed. It was intended to strengthen and rigidify the dome in this way. This strengthening intervention was also meant to safeguard the building against potential earthquakes because Italy is a nation known for its volcanic earthquakes. The construction was made lighter and more resistant to damage in the future thanks to the addition of CFRP sheets. Due to the strengthening procedure that was given to the building as a consequence of these works, the historical significance of Cefalù Cathedral has been maintained and will be handed on to future generations (Biscontin et al., 2009). As seen in the example, retrofitting with CFRP makes the structures resistant to earthquakes while at the same time preserving their historical value without damaging them.

GFRP is one of the modern reinforcement materials made from glass fiber. GFRP and CFRP have very similar properties. For example, the application methods are the same; wrapping and plate methods. As they are both lightweight materials, they do not impose an extra load on the structure and even increase the modulus of elasticity of the material of the structural elements like domes, giving it strength. The dome retrofitting work at the Kariye Museum of the Fatih Sultan Mehmet Foundation University in Istanbul, Turkey, is a case study of dome retrofitting implementing GFRP. A church from the Byzantine Empire era that was briefly adopted as a mosque during the Ottoman period is currently used as the Kariye Museum. GFRP material had been used to reinforce the dome since the building's dome section's weaknesses and deformations raised the possibility of the dome collapsing. The dome's inside was covered with GFRP sheets in order to fortify it and repair any fractures (Özmen & Taşdemir, 2017). By doing so, the dome's risk of collapsing was decreased, and the process of reinforcing was finished without adding any more stress to the building. Thus, the dome of the Kariye Museum was repaired by becoming stronger. Two of the most important things in this repair are that the method used does not harm the authenticity and historical continuity of the building.

Although CFRP and GFRP have many similar properties, there are also advantages and disadvantages that outweigh each other. CFRP is carbon-reinforced, while GFRP is made of glass-based materials such as glass fibers. On the other hand, their mechanical properties, such as strength, stiffness, and density, can also be different. CFRP material provides higher strength to the element to which it is applied due to the high-strength properties of carbon fibers. Thus, it can carry more loads of the same size. GFRP material, on the other hand, provides lower strength compared to CFRP material due to the lower strength properties of glass fibers (Nassery, 2018). If needed to talk about stiffness as another mechanical property, carbon fibers offer more stiffness to the structural element to which it is applied due to their higher stiffness compared to glass fibers. Thus, the material is more resistant under high loads and flexes less. This does not mean that GFRP material does not give stiffness to the material. Comparing the two, it can be said that CFRP is more effective in terms of stiffness (Fiberline Composites, 2021). If we evaluate and compare in terms of density, CFRP has a lower density compared to GFRP material (Fiberline Composites, 2021). However, this weight can be neglected as it is hardly enough to make a big difference. In other words, when their densities are compared in terms of weight, it can be neglected that they create an advantage or disadvantage over each other in strengthening historical buildings. Because CFRP is a stronger material than GFRP when the application areas are compared, CFRP is employed in sectors like the aviation and aerospace industries that demand high performance. In applications where somewhat lesser performance than CFRP is required, GFRP is employed. It should be noted, however, that CFRP and GFRP are both useful materials for reinforcing old masonry domes. The production process is more complicated and the CFRP raw material, carbon fiber, is often more costly. Consequently, the price of CFRP material is greater. Glass fiber, the primary component of GFRP, is less expensive and more readily available, making GFRP products more accessible (Fiberline Composites, 2021). Applications for structural reinforcement are chosen based on the demands, requirements, and circumstances of the structure. As a result, choosing the right material requires consideration of a variety of aspects, including structural needs, prices, design requirements, durability, and others. As a result, the requirements of the structural design dictate the qualities of the material to be utilized in any application for structural strengthening.

On the other hand, Sarıbıyık (2017) in their analysis titled "Effect of Using FRP Composites as Hybrid in the Strengthening of Concretes" wrapped a single layer of CFRP material on one of the same cylindrical concrete specimens and a single layer of GFRP material on the other. These two specimens were compressed at the same rate and it was observed that the strength of the CFRP material increased by 98% compared to the unreinforced version of the sample cylinder. The strength of the GFRP-wrapped specimen increased by 42% on average. The same experiment was then repeated on a single-layer CFRP-wrapped specimen and a double-layer GFRP-wrapped specimen. In this step, it was observed that the strength of the specimen wrapped in two layers of GFRP increased by 10% more compared to the specimen wrapped in one layer of CFRP (Sarıbıyık, 2017). Since GFRP is more cost-effective, it may be preferred in two layers rather than using CFRP.

### 1.3. Modulus of Elasticity and Masonry Domes

The Modulus of Elasticity, a Mathematical constant, represents the elastic properties of any material and specifies how much the material deforms under a certain stress and how much it can return to its original shape when the stress is removed (Beer et al., 2015). This constant, also known as Young's Modulus, is especially important in fields such as architecture, construction, engineering, and physics to predict the behavior of the material under any load or force. In addition to predicting possible behavior periods, it is one of the main factors determining what will be done in the next step, especially in structural strengthening. The stiffness, density, and molecular composition of the material are key variables that affect the modulus of elasticity. For instance, a stiffer material often has a larger elasticity modulus (Callister & Rethwisch, 2018).

One of the underlying reasons for the reinforcement of masonry stone historical domes using CFRP and GFRP is that these composite materials increase the modulus of elasticity by compressing the material of the domes on which they are applied and increase the resistance of the dome against possible seismic movements. What is important in this study is to determine to what extent CFRP and GFRP materials increase the modulus of elasticity of the reinforced material.

Bournas et al. (2014), reveal in the "Reinforcement of Masonry Domes with CFRP and GFRP" the effects on the modulus of elasticity of a masonry dome by using Carbon Fiber and Glass Fiber reinforced materials and analyzing different conditions under different loadings. This research revealed that both CFRP and GFRP are effective in increasing the strength and stiffness of architectural elements such as the masondy dome. The unreinforced dome used in the analysis had a modulus of elasticity of about 3 GPa. After strengthening the dome with CFRP or GFRP, the modulus of elasticity increased by about 50-100% depending on the type of reinforcement used. This increase in stiffness indicates that the dome exhibits a more resistant behavior to deformation under potential stress, which may help to prevent cracking or collapse of the structure. Moreover, CFRP provided better levels of strengthening compared to GFRP, especially in out-of-plane bending. The study additionally revealed that the types of reinforcement utilized greatly affected the failure modes of the dome, with Glass Fiber Polymer reinforced domes showing a more brittle collapse response than CFRP-reinforced domes (Bournas et al., 2014). As a result of the study, although CFRP material provides higher strength support than GFRP materials, both are preferred composite materials for strengthening structures. On the other hand, a ratio between 20% and 100% was reached. This ratio can be a reference for the modulus of elasticity ratio increase of the dome of Edirnekapı Mihrimah Sultan Mosque, which will be analyzed in this article.

Another study was conducted by Elnashai (2003) entitled "Seismic Retrofit of Masonry Walls Using CFRP Sheets: An Overview of the State of the Art". In this study, it was tried to observe how much the modulus of elasticity increased by using CFRP and GFRP separately on masonry structures. It was found that the modulus elasticity of masonry structures retrofitted using CFRP increased between 50% and 100%, while the modulus elasticity increase rate of structures retrofitted using GFRP varied between 30% and 70% (Elnashai, 2003). These percentages may vary depending on the damage condition of the structures, material specifications and properties of CFRP and GFRP materials, and the direction of the applied strengthening method.

## 2. Material and Method

In this research, the effects and results of the strengthening technique with CFRP (Carbon Fiber Reinforced Polymer) and GFRP (Glass Fiber Reinforced Polymer) materials on the elasticity modulus of historical stone masonry domes will be analyzed using the SAP2000 Finite Element Model Analysis interface.

### 2.1. Finite Element Model Earthquake Analysis on Edirnekapı Mihrimah Sultan Mosque Dome by Using CFRP and GFRP

Edirnekapı Mihrimah Sultan Mosque, one of Mimar Sinan's most important buildings with a dome covering system, was built in the second half of the 16th century in Istanbul. The main dome of the mosque, which has a rectangular plan measuring approximately 50x35 square meters, has a diameter of 20 meters, and its height from the skirt to the top is 11 meters. The detailed dimensions of the dome, arches, and pendentives are shown in Table 1 (Çamlıbel, 1988). The finite element model of Mihrimah Sultan Mosque was completed using 438 nodal points, 433 shell elements, and 1642 edges.

While developing the finite element model, the values entered for each element analyzed in the study are as follows: Modulus of Elasticity E=13000 $N/mm^2$, Poisson's ratio υ=0,1667, unit volume weight w=2,200E-05 $N/m^3$.

Based on the findings of the literature review, in this study, for the mathematical analysis of the dome of Edirnekapı Mihrimah Sultan Mosque using finite elements in the SAP2000 program, an average value will be taken that the modulus of elasticity increases by approximately 80% when the dome is reinforced with a single layer of CFRP material and by 50% when GFRP is used.

**Table 1.** Geometrical features of Edirnekapı Mihrimah Sultan Mosque (Çamlıbel, 1998)

| | Diameter of Main Dome (m) | Arch Thicknesses (m) | Arch Heights (m) | Main Dome Thickness (m) | Pendant Thicknesses (m) |
|---|---|---|---|---|---|
| **Edirnekapı Mihrimah Sultan Camii** | 20.0 m | 1.60 m | 2.40 m | 0.60 m | 1.0 m |

## 3. Findings and Discussion

### 3.1. Displacement

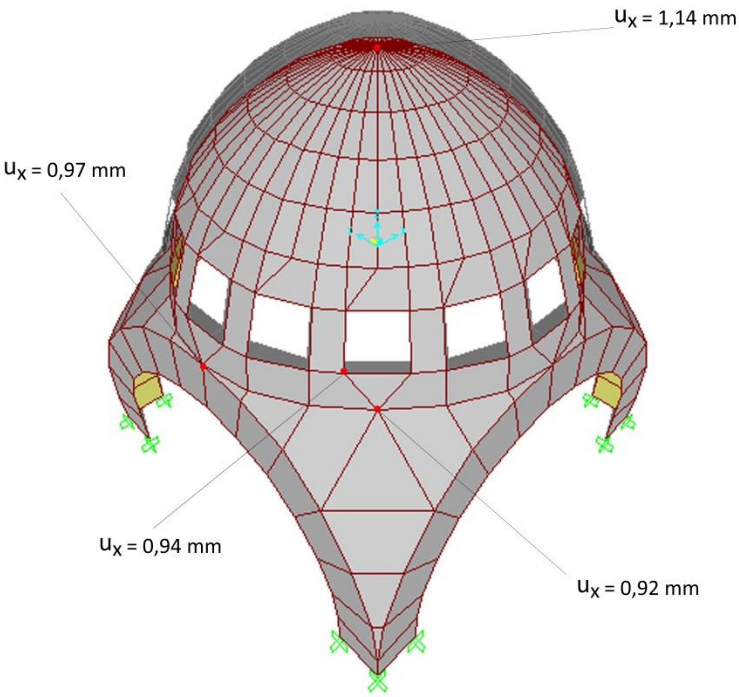



**Figure 5.** Existing situation displacement (Gravity).

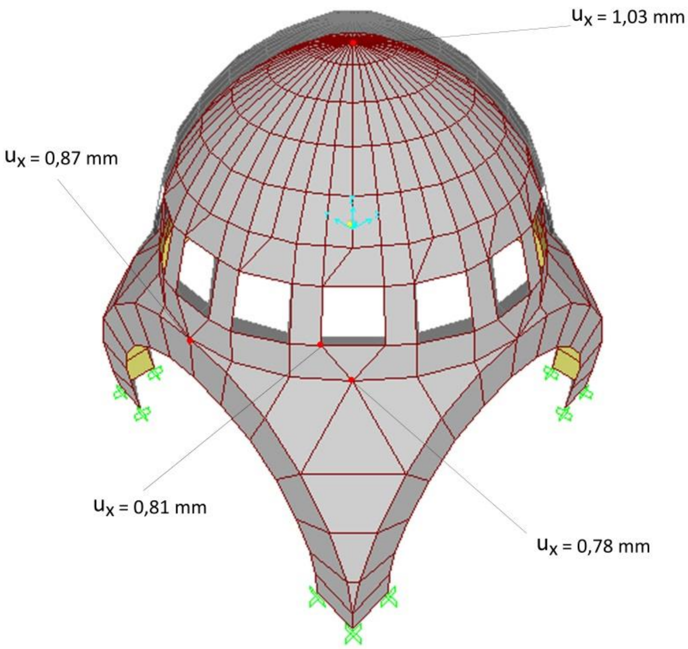



**Figure 6.** Reinforcement with CFRP displacement (Gravity).

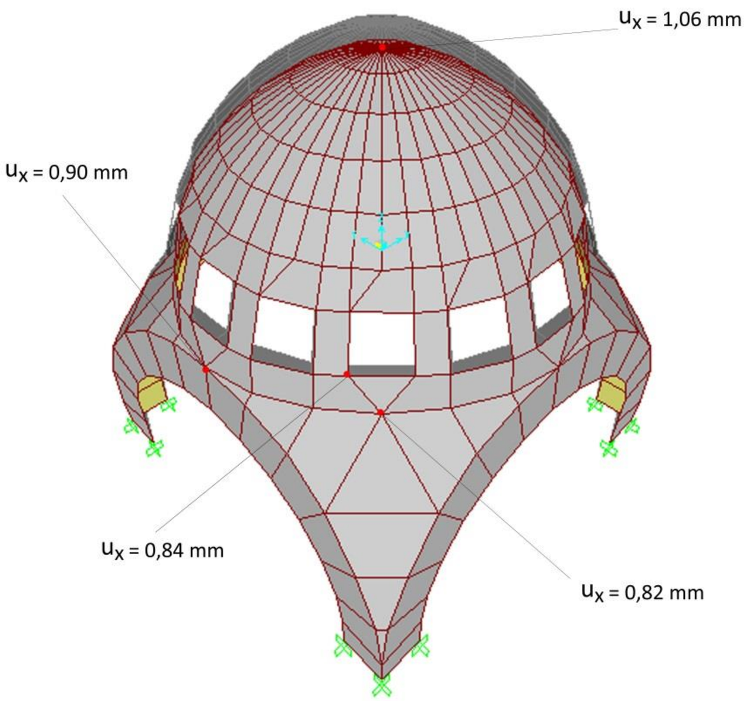



**Figure 7.** Reinforcement with GFRP displacement (Gravity)

The result of the displacement analyses is that the carbon fiber reinforced polymer named CFRP reduced the displacement in the dome, arch, and pendants and provided strength and rigidity to the structural elements. On the other hand, in the domes, arches, and pendants where glass fiber reinforced polymer namely GFRP is applied in terms of changing the modulus of elasticity, although not as much as CFRP, it is seen from the analysis results that it is quite advantageous compared to the existing situation.

### 3.2. Modal Analysis

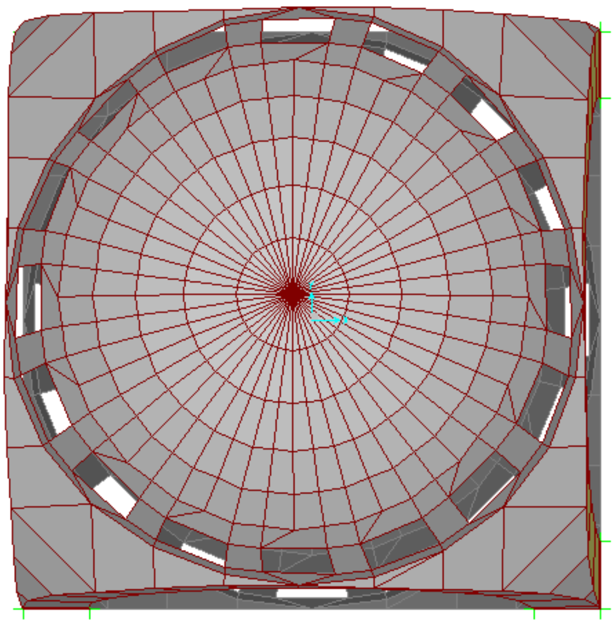


**Figure 8.** Mode 1 T=0,14126

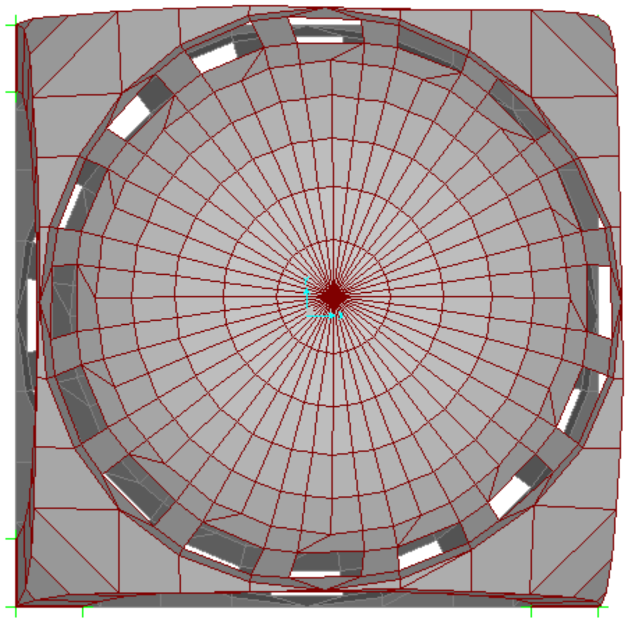


**Figure 9.** Mode 2 T=0,14123

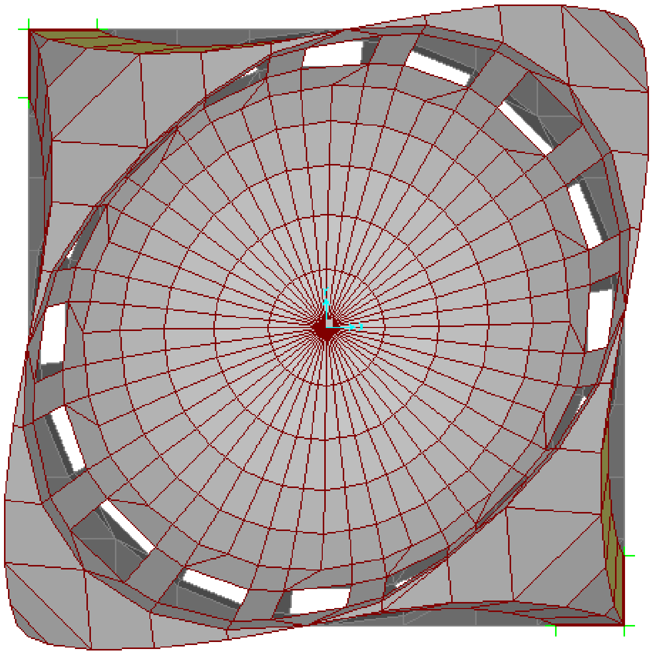


**Figure 10.** Mode 3 T=0,11018

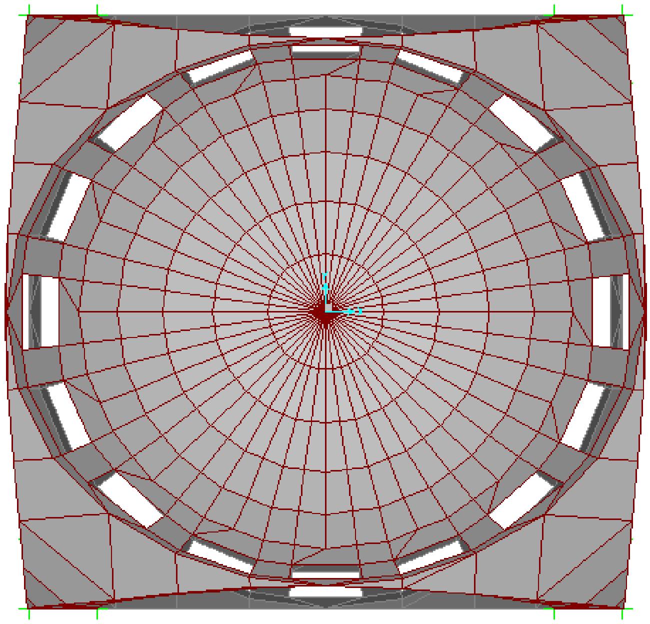


**Figure 11.** Mode 4 T=0,10117

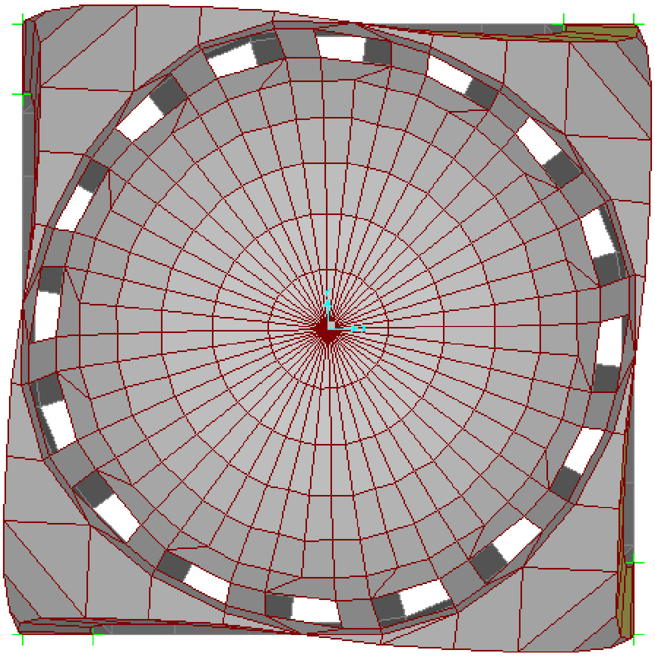


**Figure 12.** Mode 5 T=0,08295

**Table 2.** Periodical changes in modes

| | Mode 1 | Mode 2 | Mode 3 | Mode 4 | Mode 5 |
|---|---|---|---|---|---|
| **Existing** | T=0,14126 | T=0,14123 | T=0,11018 | T=0,10117 | T=0,08295 |
| **CFRP** | T=0,13616 | T=0,13616 | T=0,10203 | T=0,09609 | T=0,07978 |
| **GFRP** | T=0,13759 | T=0,13759 | T=0,10449 | T=0,09759 | T=0,08069 |

### 3.3. Translation in X and Y direction

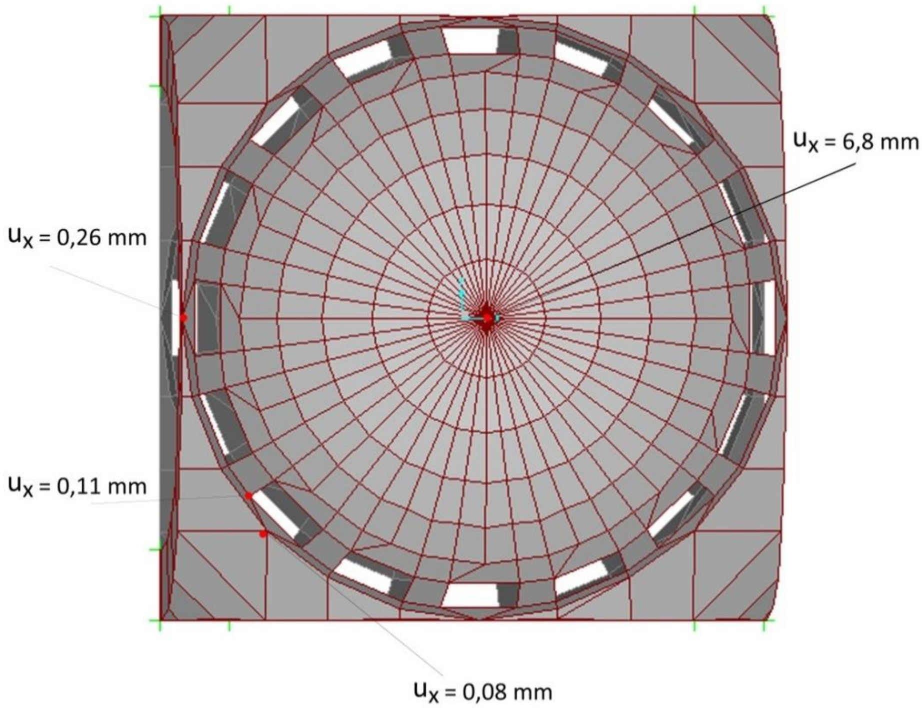



**Figure 13.** Translations in X-direction (Existing)

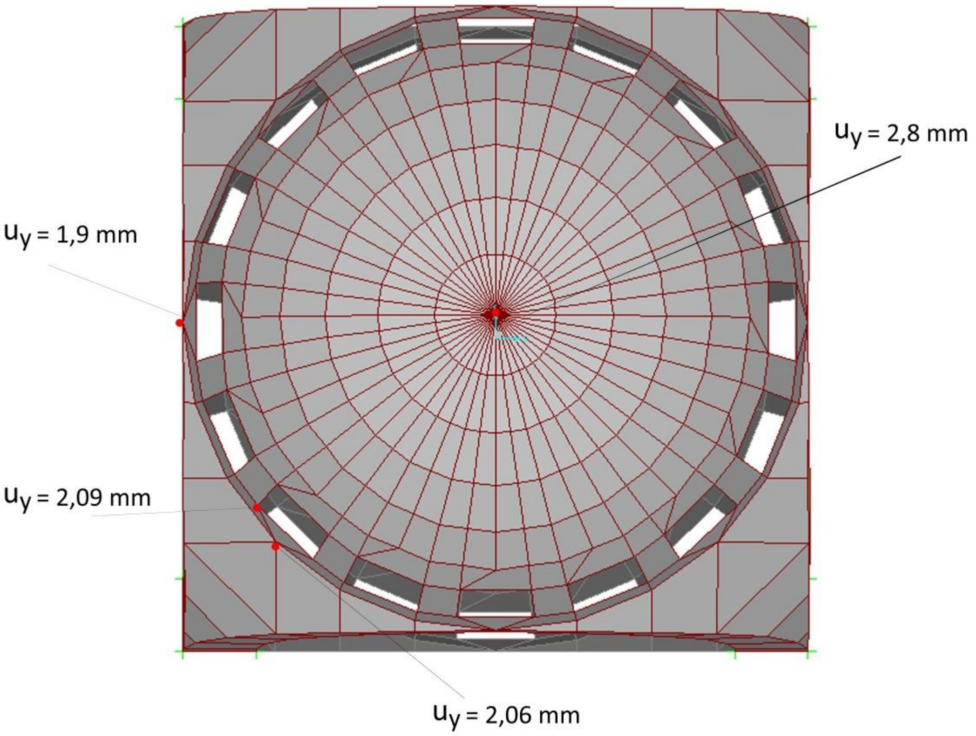



**Figure 14.** Translations in Y-direction (Existing)

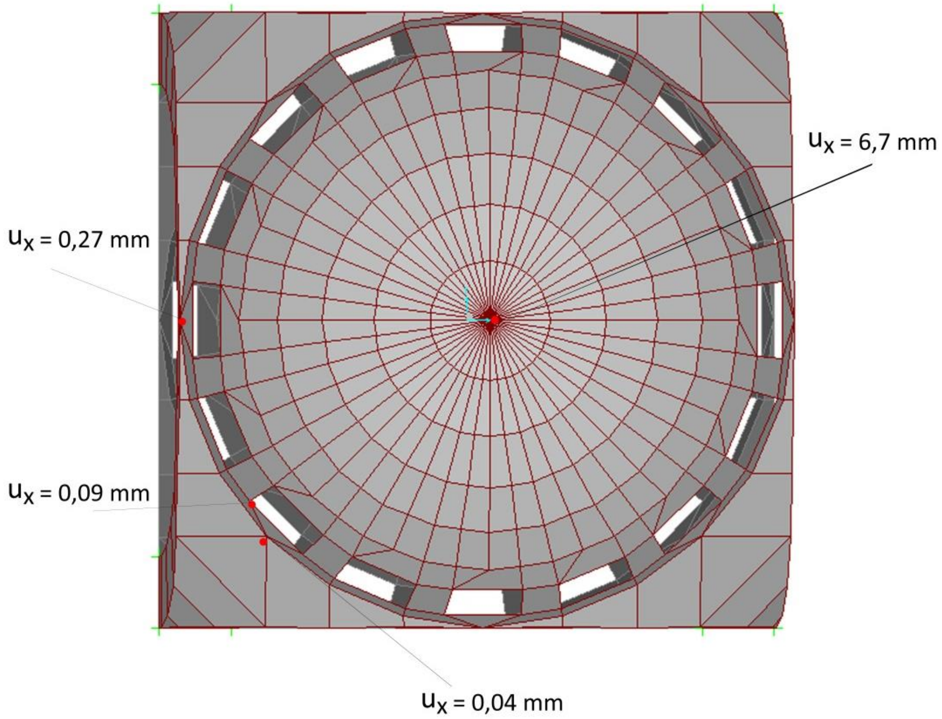



**Figure 15.** Translations in X-direction **(CFRP)**

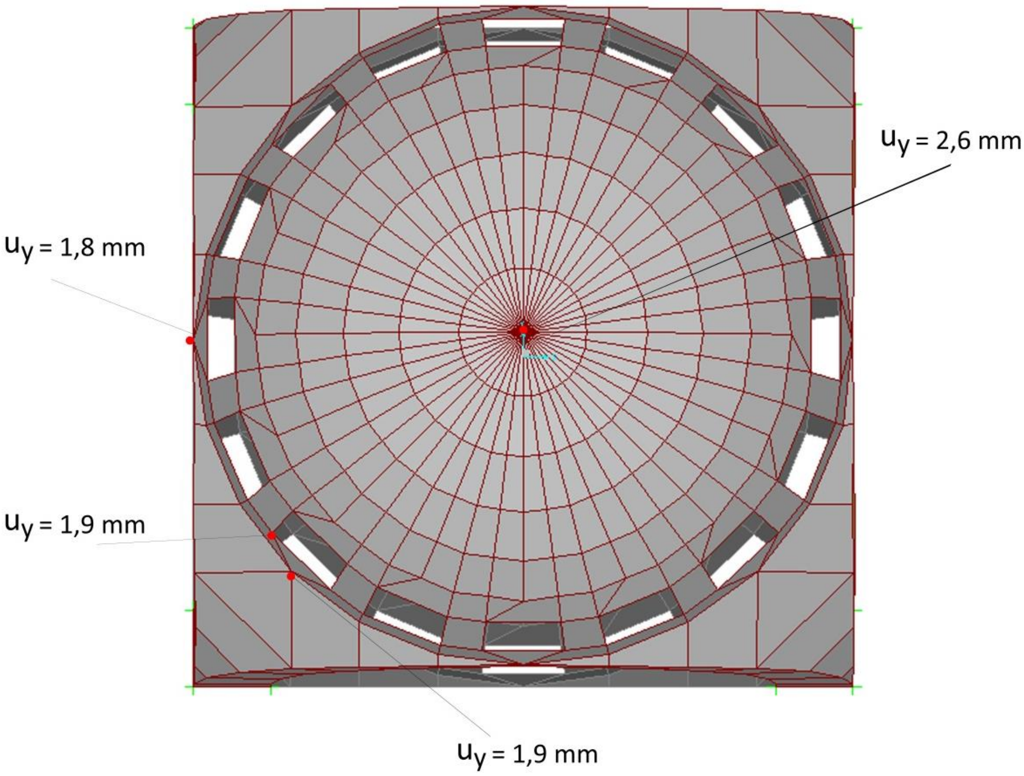



**Figure 16.** Translations in Y-direction (CFRP)

Based on the finite element analysis of the Edirnekap Mihrimah Sultan Mosque's dome strengthened with CFRP compared to the existing condition, it can be clearly seen that there is a remarkable difference in values in the translations in the X and Y directions between Figure 13 & 15 and similarly Figure 14 & 16.

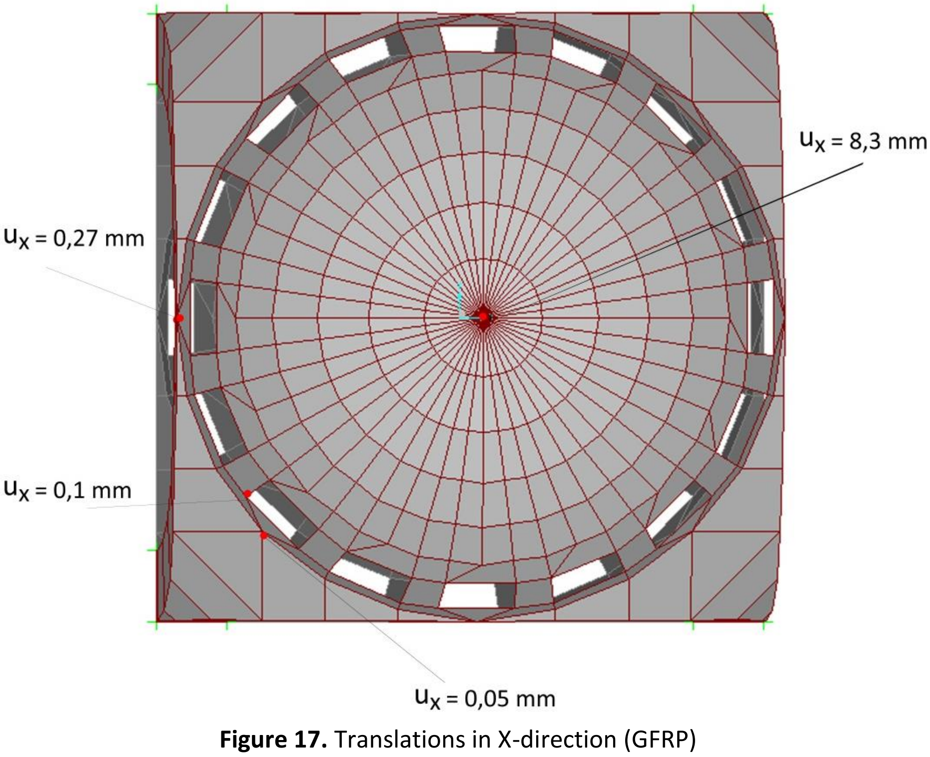



**Figure 17.** Translations in X-direction (GFRP)

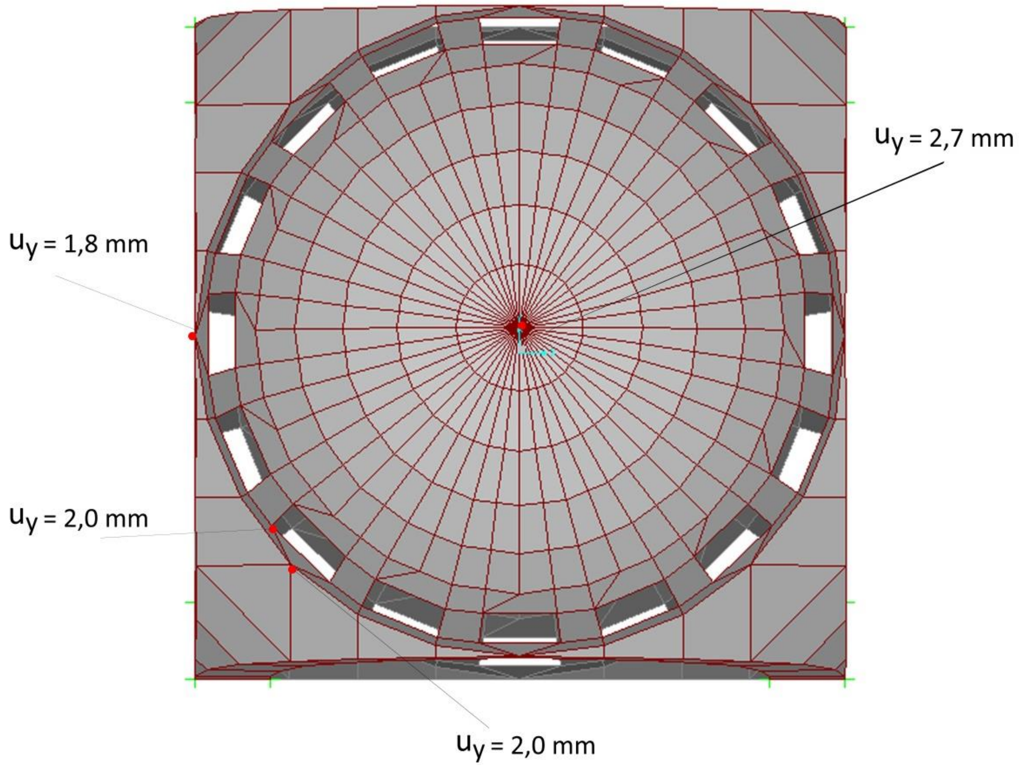



**Figure 18.** Translations in X-direction (GFRP)

Similarly, Figures 13 & 17 and Figures 14 & 18 have a difference of translation values in both X and Y directions. This is because of the reinforcement with dome, arch, and pandantive by GFRP.

### 3.4. Changes in Stress Values

Not only the S11 diagrams are compared with each other, but the best tensile value is also undoubtedly provided by CFRP S22 and SMAX diagrams prove it by their values of tensile forces and the colors of the diagrams. CFRP material undertook the tensile force and clearly showed that the tension in architectural elements was relieved with the color change in the tension regions of the dome, pendant, and arch of Edirnekapı Mihrimah Sultan Mosque in Table 3-4-5.

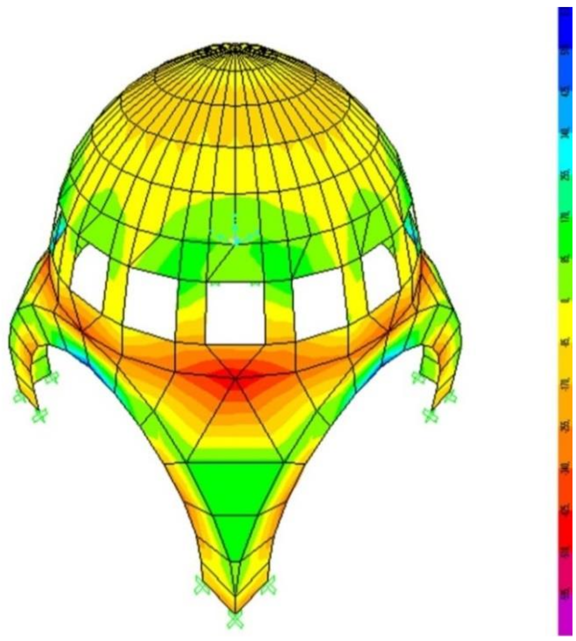


**Figure 19.** Existing situation, **S11** Diagram

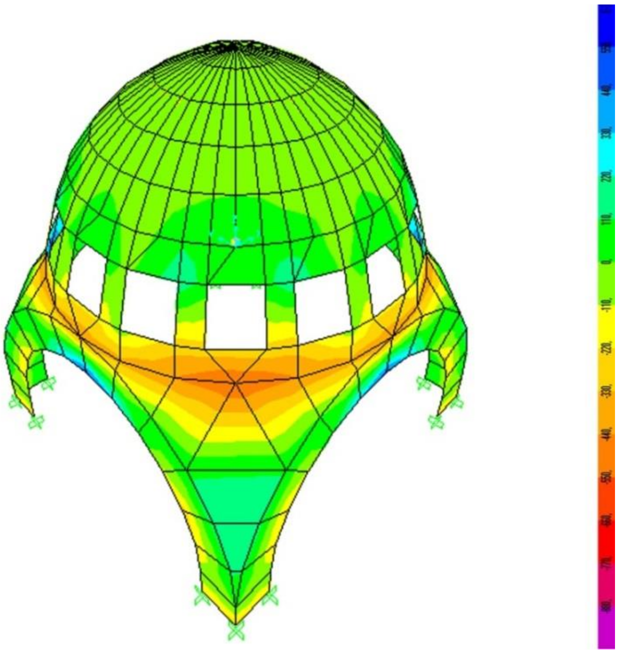


**Figure 20.** Reinforcement with CFRP, **S11** Diagram

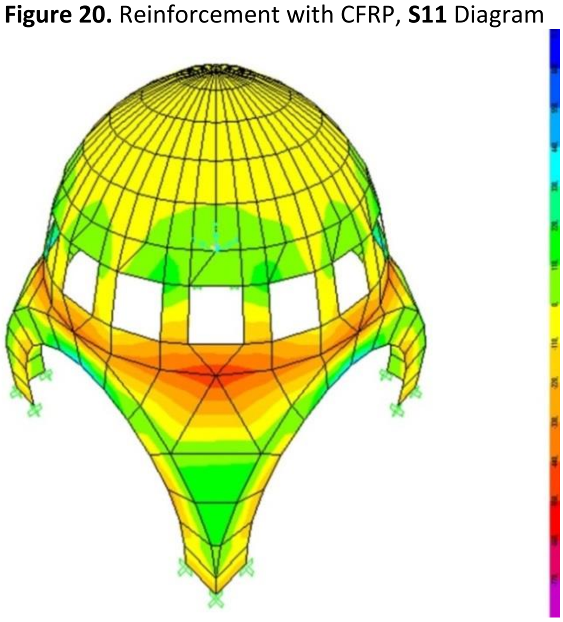


**Figure 21.** Reinforcement with GFRP, **S11** Diagram

**Table 3.** Maximum stress values for S11

| S11 | DOME | ARCH | PANDANTIVE |
|---|---|---|---|
| **Existing** | 0,519198 N/mm² | 0,339854 N/mm² | 0,519198 N/mm² |
| **CFRP** | 0,557528 N/mm² | 0,263608 N/mm² | 0,557528 N/mm² |
| **GFRP** | 0,548240 N/mm² | 0,264302 N/mm² | 0,548240 N/mm² |

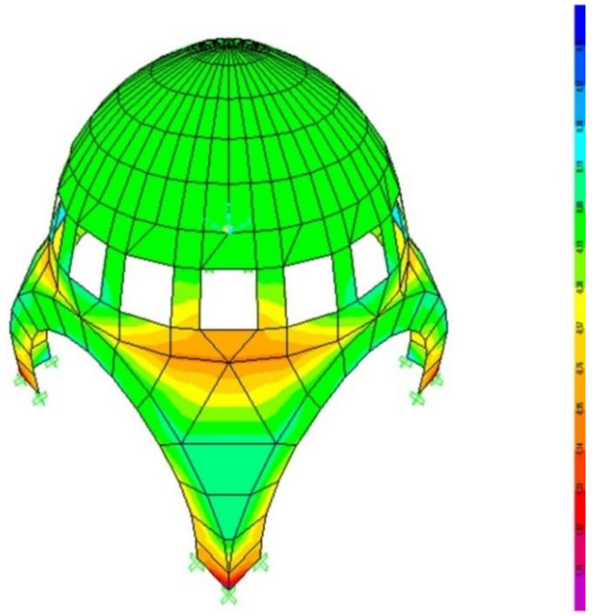


**Figure 22.** Existing situation, **S22** Diagram

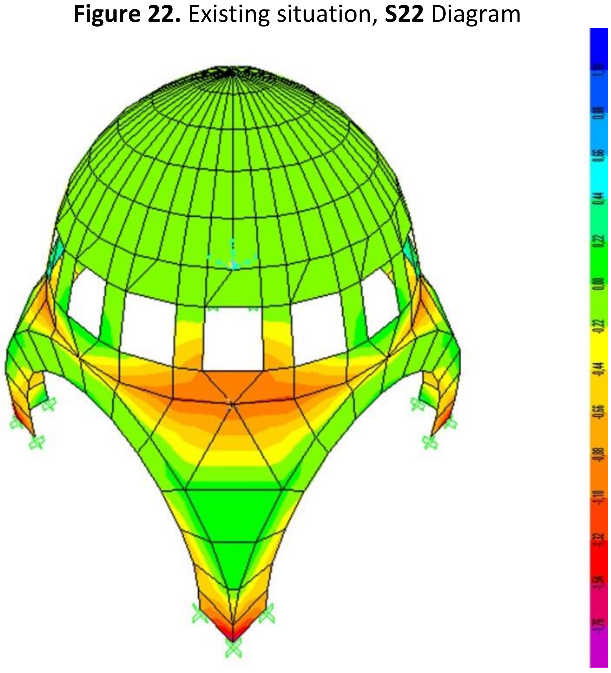


**Figure 23.** Reinforcement with CFRP, **S22** Diagram

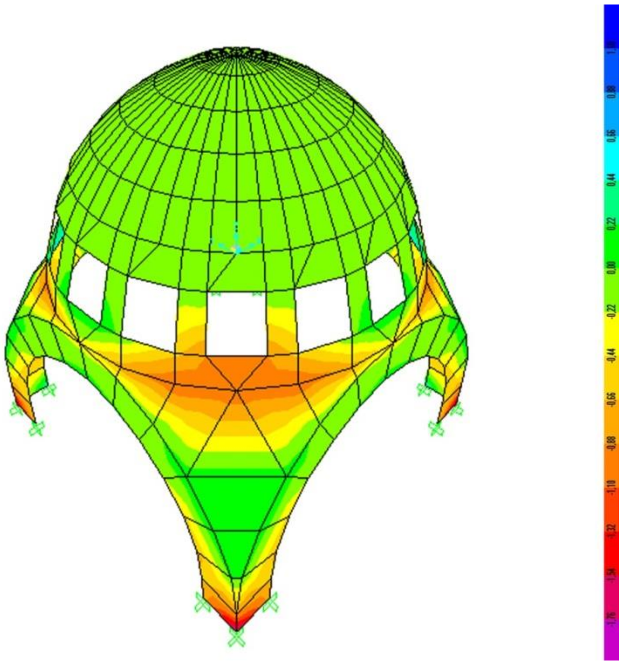


**Figure 24.** Reinforcement with GFRP, **S22** Diagram

**Table 4.** Maximum stress values for S22

| S22 | DOME | ARCH | PANDANTIVE |
|---|---|---|---|
| **Existing** | 0,996795 N/mm² | 1,841217 N/mm² | 0,996795 N/mm² |
| **CFRP** | 1,112980 N/mm² | 1,804036 N/mm² | 1,112980 N/mm² |
| **GFRP** | 1,080321 N/mm² | 1,812442 N/mm² | 1,080321 N/mm² |

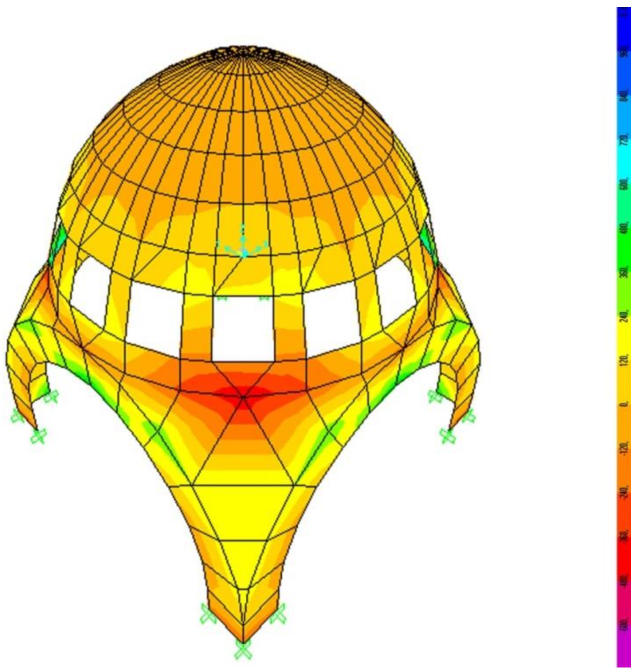


**Figure 25.** Existing situation, **SMAX** Diagram

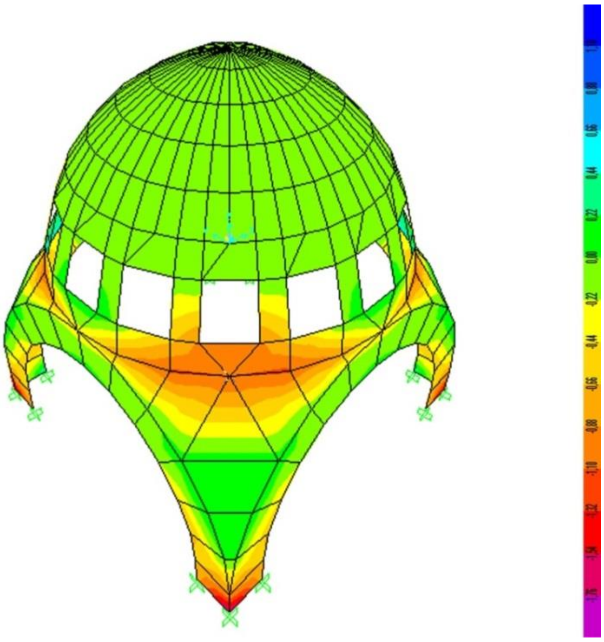


**Figure 22.** Reinforcement with CFRP, **SMAX** Diagram

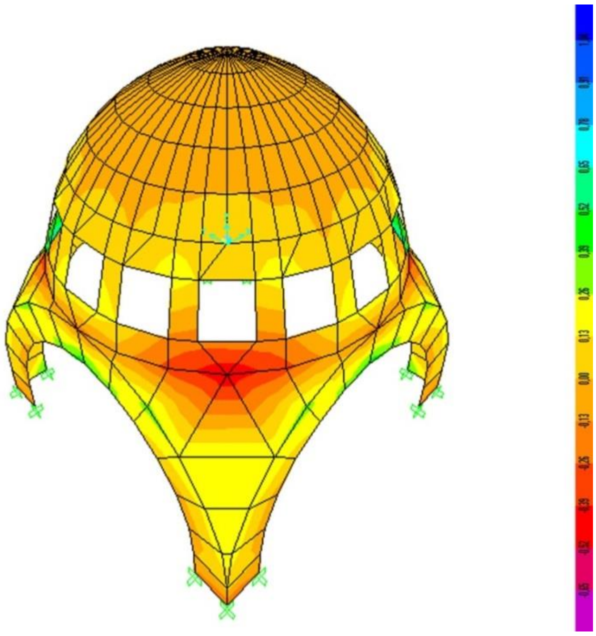


**Figure 23.** Reinforcement with GFRP, **SMAX** Diagram

**Table 5.** Maximum Stress Values for SMAX

| SMAX | DOME | ARCH | PANDANTIVE |
|---|---|---|---|
| **Existing** | 0,461704 N/mm² | 0,250276 N/mm² | 0,461704 N/mm² |
| **CFRP** | 0,510786 N/mm² | 0,247356 N/mm² | 0,510786 N/mm² |
| **GFRP** | 0,498753 N/mm² | 0,247778 N/mm² | 0,498753 N/mm² |

Structural systems under static and dynamic loads determination of the behavior and structural elements The most preferred method for obtaining the stress state is the finite element method (Soyluk & Tuna, 2011). The effect of CFRP and GFRP materials used in the finite element analysis on the seismic behavior was found to increase the tensile strength by taking the tensile stress on itself and reaching the intended performance. Thus, as can be seen from the numerical values in Tables 3-4-5, CFRP and GFRP materials have taken over the tensile stresses and supported the existing masonry architectural elements.

## 4. Conclusion and Suggestions

CFRP and GFRP materials are very effective materials that have been used in recent years to strengthen the structural systems of buildings.

As a result of the analyses, the strengthening of the dome tensile zone, pendentives, and arches using CFRP and GFRP is seen in the tables and diagrams of displacements, tensile stresses, and translations in these zones. Reductions in displacement and displacement are seen in the use of CFRP compared to the existing situation. Correspondingly, these reductions are also seen in GFRP compared to the existing situation. On the other hand, CFRP gave relatively more favorable results than GFRP. With respect to stress, the situation is again as expected, CFRP and GFRP materials have reduced the stress in the dome by taking the tensile on their own. Notwithstanding the superior strengthening properties of CFRP, the pricing of GFRP is lower than CFRP. In this regard, if forced to choose between CFRP and GFRP, GFRP would be a better alternative. Since, according to the quantitative results of the analysis, GFRP obtained results approaching those of CFRP and its material properties for strengthening are in accordance with the static requirements of the structure.

CFRP and GFRP materials are not only long-lasting and maintenance-free materials but also do not damage the historical texture of the building in terms of application and are a reversible form of intervention. That is why CFRP and GFRP materials are highly useful and convenient materials for the reinforcement of historical buildings, with the advantages brought by modern technological advancements. Thus, it will also be in accordance with the ethics of architectural restoration and conservation of cultural heritage.

This study is noteworthy for the field of architecture because it reveals that, owing to their previously indicated advantages, state-of-the-art materials like GFRP and CFRP can result in outstanding outcomes when utilized in structural reinforcement. In addition, since CFRP and GFRP materials are examined and analyzed in depth, it is also a guide to the decision of which one will be more suitable for the structure to be intervened when a choice between the two materials CFRP and GFRP has to be made.

Another important feature of the study is that since a comparison was made using two different fiber-reinforced polymers, carbon, and glass, on the same structural elements of the same glass, when a choice between the two is required, an intervention option is proposed based on the results of which one will be advantageous. For instance, GFRP can be used if cost is a priority, and CFRP can be used if structural strengthening is a more priority input than cost.

**Acknowledgements and Information Note**

The article complies with national and international research and publication ethics. Ethics Committee approval was not required for the study.

**Author Contribution and Conflict of Interest Declaration Information**

All authors contributed equally to the article / Or 1st Author %50, 2nd Author %50 contributed. There is no conflict of interest. There is a conflict of interest.

## References

Aiello, M. A., Contrafatto, S. & Ricciardi, S. (2019). Fiber reinforced polymers for strengthening historical buildings: A review. *Procedia Structural Integrity*, 23, (p. 152-159).

Beer, F. P., Johnston Jr, E. R., Mazurek, D. F. & Cornwell, P. J. (2015). *Mechanics of material (p.*73). McGraw-Hill Education.

Biscontin, G., Russo, S. & Valente, S. (2009). Masonry strengthening with fiber-reinforced polymers: recent advances and applications. *Journal of Composites for Construction*, 13(5), 373-384. doi: 10.1061/(ASCE)CC.1943-5614.0000051

Bournas, D. A., Triantafillou, T. C. & Sofianos, A. I. (2014). Strengthening of masonry structures with fiber-reinforced polymers: Recent advances and perspectives. *Composite Structures*, 111, 378-392. doi:10.1016/j.compstruct.2014.01.027

Callister Jr, W. D. & Rethwisch, D. G. (2018). *Materials science and engineering: an introduction (pp. 129)*. John Wiley & Sons.

Çamlıbel, N. (1998). Analytical Investigation of Structure in Sinan Architecture (Doctoral Dissertation, pp.630). Yıldız University Faculty of Architecture, Istanbul.

Campione, G., Papia, M. & Pecce, M. (2009). A review of the behaviour of masonry domes reinforced by fibre-reinforced polymers. Proceedings of the Institution of Civil Engineers-Structures and Buildings, 162(4), 177-190.

Çelik, O. C. (2016). *Historical Building Repair and Retrofit Guide*. BASF.

Croci, G. (2000). *The Conservation and Structural Restoration of Architectural Heritage*. Advances in Architecture Series. Computational Mechanics Publication/WIT Press, UK.

Değirmenci, İ. & Sarıbıyık, M. (2015). Innovative approaches and use of frp materials in strengthening historical buildings. *Academic Platform Journal of Engineering and Science*, 338-347.

Döndüren, M. S., Şişik, Ö. & Demiröz, A. (2017). Types of damage in historical buildings. *Selcuk University Journal of Social and Technical Researches*, *13*, 45–58.

Elghazouli, A. Y., Garcia, R. & Jimenez, M. J. (2018). Seismic vulnerability of historical masonry buildings. Proceedings of the ICE-*Civil Engineering*, 171(6), 255-265.

Elnashai, A. S. (2003). Seismic retrofit of masonry walls using CFRP sheets: An overview of the state of the art. *Engineering Structures*, 25(9), 1231-1243. https://doi.org/10.1016/S0141-0296(03)00105-4

Fiberline Composites. (2021). What is the difference between GFRP and CFRP? Retrieved from https://fiberline.com/en-en/about-composites/composite-materials/gfrp-vs-cfrp/

Galati, Nanni, Ceroni & Sacco (2017). "Strengthening of masonry arches with FRP composites: Experimental investigation and numerical simulation.

Karakaş, Z. S. & Acun Özgünler, S. (2022). Koruma Kararlarını Etkileyen Parametrelerin Belirlenmesine Yönelik Bir Anket Çalışması . *Journal of Architectural Sciences and Applications*, 7 (1), 364-382 DOI: 10.30785/mbud.1090550

Khalil, E. & Bakhoum, M. (2017). Reinforcement of historic masonry domes with composite materials: *A review. Procedia Engineering,* 199, 2114-2119. doi: 10.1016/j.proeng.2017.09.711

Kheirikhah, M. M., Faghih Shojaei, M. & Eftekhari, M. M. (2019). Strengthening of masonry domes with carbon fiber reinforced polymer (CFRP) composites. *Journal of Building Engineering*, 22, 221-231.

Le, H. R., Li, J. & Tan, V. B. C. (2019). Strength and stiffness characteristics of GFRP composite plates with different stacking sequences. *Composite Structures*, 210, 495-508.

Lourenço, P. B. (2013). Conservation of cultural heritage buildings: Methodology and application to case studies. *Revista ALCONPAT*, *3*(2), 98–110. https://doi.org/10.21041/ra.v3i2.46

Lourenço, P. B., Roca, P. & Moden, C. (2010). Masonry Structures: Behavior and Design. *Springer Science & Business Medi*a, (p.28-29, 40-41. 45-46).

Nassery, K. (2018). Carbon vs. Glass Fiber Reinforcement. CompositesWorld. Retrieved from https://www.compositesworld.com/articles/carbon-vs-glass-fiber-reinforcement

Neto, E. A. D. S. & Brandt, A. M. (2017). Tensile and compressive properties of carbon fiber reinforced polymer composites. *Materials Research*, 20(6), 1607-1614.

Özmen, H. & Taşdemir, M. A. (2017). Strengthening of historical domes with composite materials: a case study. *Journal of Composites for Construction*, 21(5), 04017034.

Pujades, L. G. & Lanzón, M. (2017). Seismic vulnerability and risk assessment of historical masonry structures: *A review. Bulletin of Earthquake Engineering*, 15(8), 3173-3201.

Sarıbıyık, A. (2018). Effect of using FRP composites as a hybrid in the strengthening of concretes. *Sakarya University Journal of Science*, 1–1. https://doi.org/10.16984/saufenbilder.343562

Sesigür, H., Çelik, O. & Çılı, F. (2007). Structural components, damage patterns, repair and retrofitting in historic buildings, *IMO Istanbul Bulletin*, 89, 10-21.

Shariati, M., Esfahani, M. R. & Kianoush, M. R. (2013). Strengthening of stone masonry domes using CFRP and GFRP composites: An experimental study. *Journal of Composites for Construction*, 17(2)

Soyluk, A. & Tuna, M. E. (2011). Dynamic analysis of historical Şehzade Mehmet Mosque for Seismic base isolation application. *Gazi Üniversitesi Mühendislik Mimarlık Fakültesi Dergisi* , 26 (3). Retrieved from https://dergipark.org.tr/tr/pub/gazimmfd/issue/6689/88775

The Venice Charter. (1964). The International Charter for the Conservation and Restoration of Monuments and Sites. Retrieved May 07, 2023, from https://www.icomos.org/en/participer/179-articles-en-francais/ressources/charters-and-standards/157-thevenice-charter

Türkmen, M. & Bilgin, H. (2002). *Structural Behavior of Domed Cover Systems in Traditional Architecture",* Balıkesir University Faculty of Engineering - Architecture, IV. Engineering Architecture Symposium, Balıkesir, Turkey.

Zakar, L. & Eyüpgiller, K. K. (2020). *Architectural Restoration Conservation Techniques and Methods* (*Mimari Restorasyon Koruma Teknik Ve Yöntemleri)*. (p. 50 and p. 83).