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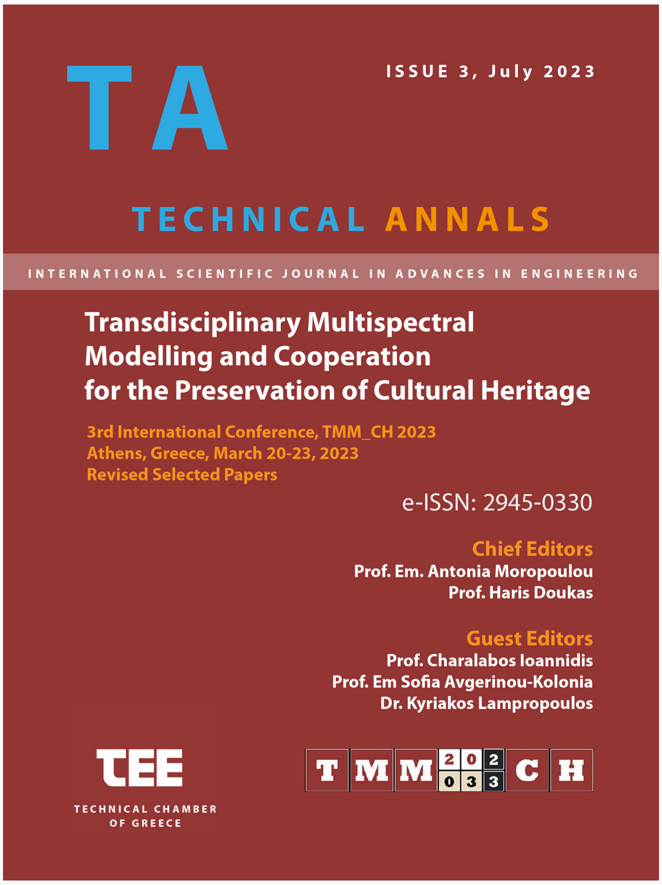

The interventions for the main dome of Hagia Sophia throughout its history and a preservation proposal

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The interventions for the main dome of Hagia Sophia throughout its history and a preservation proposal

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Abstract. Throughout its history, Hagia Sophia has faced seismic risks due to structural issues. The ambitious design led to the complete collapse of the main dome merely 21 years after its construction, and partial collapses occurred in the 10th and 14th centuries. Over time, the structure underwent various repairs and reinforcements. Following the collapse of the southeastern section during the 1346 earthquake, flying buttresses were installed, attaching to the main dome from four directions. However, during the Fossati repairs (1847-1849), these elements were removed and replaced with iron beams, framing the upper perimeter of the pedestal supporting the main dome. The current challenges faced by the main dome are primarily rooted in the design of the piers and arches rather than the dome itself. Since reconstructing these structural elements is impossible, efforts to address the dome's issues have concentrated on retrofitting the supporting system. This study critically assesses the current state of the main dome, examining past interventions. As a solution, it proposes reinforcing the main dome structure by installing a tension ring to enhance stability.

Keywords: Hagia Sophia; dome; arch; retroftting; tension ring; earthquake

1 Introduction

The magnificence of the previous Hagia Sophia structure, razed during the Nika revolt in 532, stood as a pivotal benchmark that Emperor Justinian aspired to surpass in his envisioned new church. So, the new construction would stand as an everlasting response, through its enormous size and uniqueness, to those who had revolted against the emperor. However, its ambitious dome, unparalleled in both preceding and subsequent Byzantine architecture, was also impacted by Hagia Sophia's structural problems from the beginning. These persistent issues were the primary cause behind the dome's collapses and the enduring earthquake risks throughout the structure's history.

Despite the symmetrical placement of the four piers supporting the main dome, their asymmetric edges in multiple directions pose challenges in equitably withstanding horizontal loads. The arrangement makes it challenging to unify them, adversely impacting the structure's earthquake resistance [1]. Another evident static issue, notably observed in the southeast-northwest section, lies in the columns' numerical arrangement between the ground and gallery floors. The ground floor features a 5-arcade arrangement between the main buttresses, whereas the gallery floor exhibits a pattern of 7 arcades. This discrepancy, stemming from the varied column sizes between floors, disrupts the vertical load transfer from the main dome and body walls in an intermittent and discontinuous manner [2] (see Fig. 1-2 [3]).

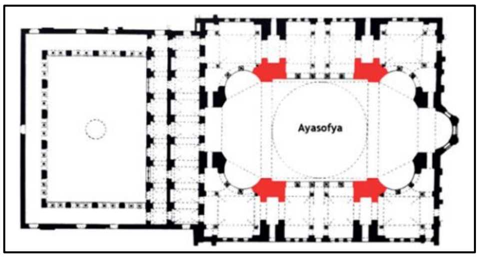

Fig. 1. Main piers in the plan of Hagia Sophia

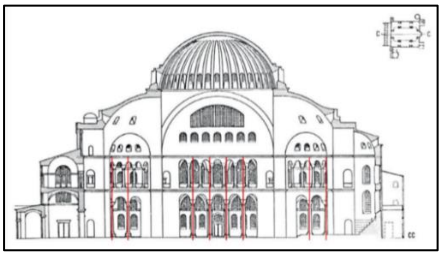

Fig. 2. Northwest-southeast cross-section

(Impressions in red are made by the authors.)

The vulnerabilities within Hagia Sophia's ambitious load-bearing system led to three collapses: a complete one merely 21 years after the main dome's construction, and partial collapses in the 10th and 14th centuries. Notably, during the last two reconstructions, it's probable that the collapsed and reconstructed main arches gained asymmetrical sections. As a result, the existing issues with the main dome don't solely originate from the initial construction but also from subsequent structural modifications. Continuous repairs and reinforcements have been essential throughout Hagia Sophia's history. However, since reforming the original structural elements like the main piers and arches is impossible, efforts have shifted towards interventions aimed at exterior support for the load-bearing system and the main dome.

2 The dome that was rebuilt three times

Following the earthquakes in August 553 and December 557, both the main dome and the southeastern semi-dome collapsed [4] due to a 6 magnitude earthquake on May 7, 558 [5] around 21 years after the consecration of Hagia Sophia. This destruction was linked to multiple factors, including the inadequate curvature in the initial dome's design, deformation of the main supporting pillars, and distortion of the dome caused by shear forces [6, 7]. Emperor Justinian (r. 527-565), witnessing the dome's collapse during his reign, appointed Isidorus, a young architect and nephew of one of Hagia Sophia's initial architects, for repairs. The prevailing belief regarding the resto-ration activity on December 24, 563, was that it involved altering the dome's shape and increasing its height by 20 Byzantine feet (equivalent to approximately 6.24 meters) [7, 8]. However, recent research indicates that the modified design of the restored dome did not increase its height but maintained the same height while curving the tambour with the dome [6, 9, 10] (see Fig. 3 [9]).

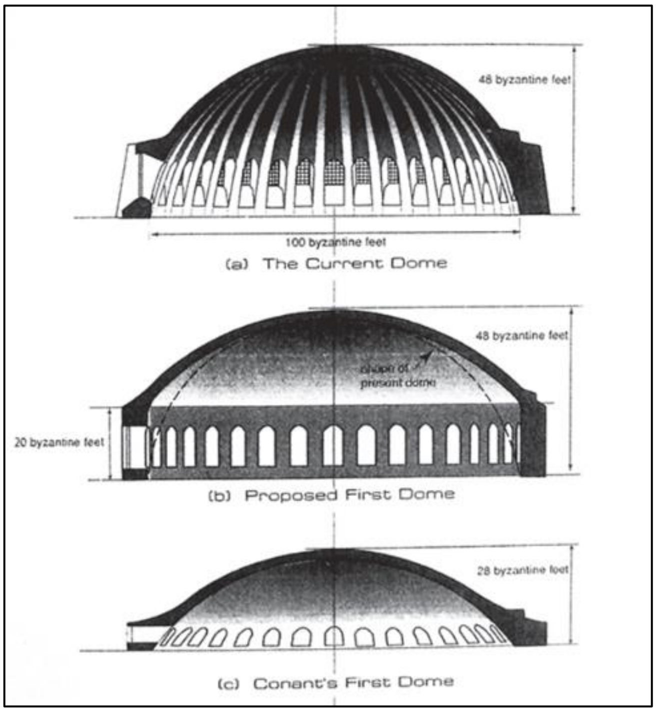

Fig. 3. Sections of (a) the current dome, (b) proposed first dome, (c) pre-proposed first dome

The significant earthquake of 989 directly impacted Hagia Sophia, resulting in the collapse of the northwestern section of its main dome. Armenian architect Trdat, known for his work on the Great Cathedral in Ani, the capital of Armenia, led this repair work. Before commencing the repairs, Trdat presented a model outlining his intended interventions [2, 11]. This restoration involved rebuilding 15 out of the 40 ribs of the main dome and reconstructing the northwestern semi-dome. Additionally, the main northwestern arch, which had undergone repairs in the previous century, was addressed. Hagia Sophia reopened for worship in 994 following these extensive restoration efforts [7].

In the fall of 1343, a series of earthquakes struck the city, followed by another on October 6, 1344, resulting in structural weaknesses within Hagia Sophia. Subsequently, on May 19, 1346, one-third of the main dome collapsed along with the southeastern semi-dome. The restoration efforts were overseen by Stratopedarch Astras and Giovanni Peralta, with completion in 1354 [7]. Notably, within this repair, the main dome was supported by flying buttresses in four directions. These buttresses, displaying Gothic characteristics depicted in Hagia Sophia's descriptions, can be specifically attributed to the repairs in the 14th century (see Fig. 4 [12]). The integration of these flying buttresses with the connections of the remaining 6th-century dome and the reconstructions from the 10th and 14th centuries display the meaningful support they offered to the main dome (see Fig. 5 [2]).

Fig. 4. Detail from Fossati's depiction before restoration

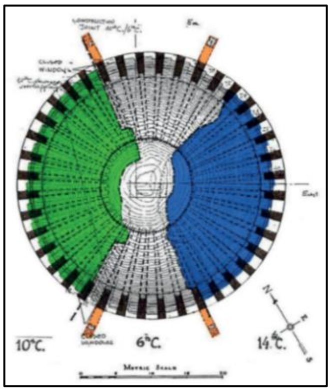

Fig. 5. Flying buttresses colored in orange

Hagia Sophia's main dome has remained intact since 1354, showcasing remarkable stability. Architect Sinan's interventions during the peak of his career in the late 16th century likely played a role in this achievement. Although he didn't intervene the dome, he retrofitted the existing Byzantine buttresses and introduced new ones, potentially reinforcing the structure and aiding in its preservation.

3 Fossati interventions

The most recent structural interventions on the main dome during the Ottoman period occurred between 1847-1849, conducted by Gaspare Fossati and his brother Guiseppe Fossati. Among the significant alterations in this repair was the removal of the flying buttresses that had supported the main dome for the past five centuries, forming a recognizable part of Istanbul's skyline. Instead of these buttresses, an iron frame was installed around the base where the main dome sits, concealed beneath the existing plaster. These elements became visible during the recent plaster rash over the surface (see Fig. 6-7 [13]). However, the structural function of this frame, intended as a substitute for the removed flying buttresses, remains a topic of debate [14, 15]. Its potential positive impact on the dome's structure is considered to be extremely limited due to its location and form.

Fig. 6. Iron frame intervention under the plaster

Fig. 7. Detail from the joint of the iron bracing

In the modeling work conducted in 2010 to investigate the functionality of the flying buttresses removed by the Fossati at Hagia Sophia, both the existing models and the structure itself were tested via static simulations using finite elements in a computer environment. The analysis aimed to examine the structural contribution of the buttresses to the main dome (see Fig. 8 [2]). This limited modeling study demonstrated that the flying buttresses serve an important structural function and contribute to the stability of the main dome [2, 16].

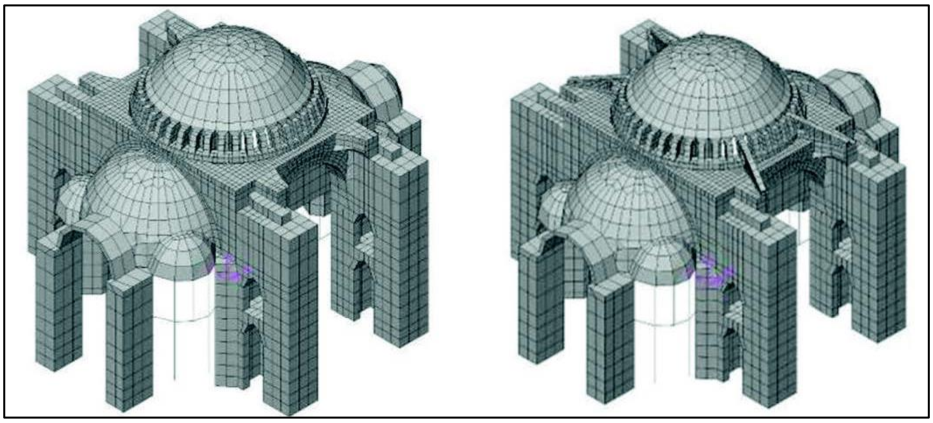

Fig. 8. View of the models of the current state and with the flying buttresses

4 Interventions in the 20th century

The most recent structural alteration to the main dome of Hagia Sophia involves the installation of vaults over the windows. A Japanese team from Tsukuba University identified these vaults as reinforced concrete elements in 1995 [17]. This intervention aligns with early 20th-century building technology. Historical records indicate that in 1909 [18], the windows appeared to be covered only with lead, whereas by 1936 [19], each window was observed to be covered with vaults similar to those seen today [20] (see Fig. 9). While there isn't specific documentation detailing this intervention, visual evidence suggests that the installation of vaults over the windows likely occurred during the early years of the Turkish Republic, established in 1923.

However, it's worth noting a decree dated August 1, 1926, which may offer insight into the timeline. This decree mentions damage of lead coverings and the need for repair, including some plaster windows, to be overseen by the Foundations Scientific Committee [2, 21]. Another decree, dated September 25, 1927, details payments to members of the Scientific Committee, including architect Kemaleddin and along with engineers Mr. Mehmed Fikri, Bahaaddin, Ziya, and Zühdü, involved in these repairs [2, 22]. Press coverage of this restoration revealed the use of 138 tons of lead [23]. Considering the architects involved in the repair, it's likely that an initiative such as covering the windows with reinforced concrete vaults would have been undertaken at that time.

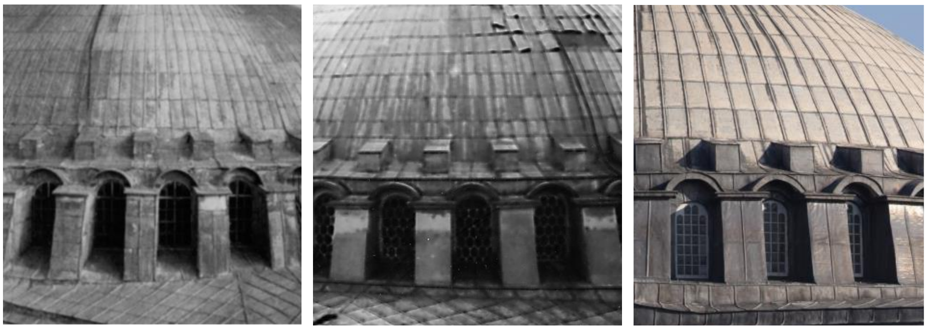

Fig. 9. Detail views from the dome windows in row from 1909, 1936 and 2010.

In a study conducted in 1993, it was observed that wooden construction was built on lower level to reduce the flatness of dome, which occured due to the fact that the 10th century segment in the western part of the main dome was higher than the 6th century segment in the southern part of the dome about 10-12 cm (see Fig. 10 [17]). The effect of this intervention, which is understood to have been made to show the main dome of Hagia Sophia symmetrically, which is actually asymmetrical due to its repairs, in city silhoutte, should be questioned in Hagia Sophia modelings.

Fig. 10. Views from the partial wooden sub construction under the lead cover

The last retrofitting project for the Hagia Sophia dome structure during the Republic period was proposed by Prof. Dr. Mustafa Erdik and Ülker Engineering and Consultancy in 1993 [14]. The proposal aimed to enable the semi-domes and main arches to work in unison during potential earthquakes by establishing a robust connection between them. The recommended method suggested for reinforcing the bond between the southeast and northwest main arches, upon which the semi-domes rely, was the use of anchors (see Fig. 11-12). The project proposed embedding the bodies of the anchors entirely into the semi-domes, with the heads designed to conceal the image without disrupting the facades of the southeast and northwest main arches. Modeling revealed that the planned anchoring bars would provide the required safety for the main dome. Despite this, the project was not accepted due to concerns about the radical structural interventions it would necessitate.

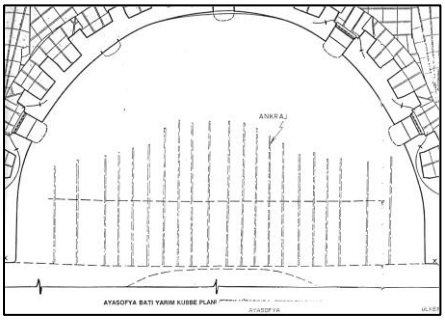

Fig. 11. Depiction of the anchors in plan

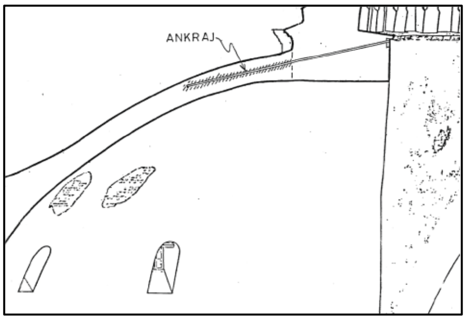

Fig. 12. Depiction of the anchors in cross-section

5 Current Situation

In the most recent measurements, the main dome's diameter in the northwest-southeast direction, supported by semi-domes, was 31.19 m, while in the northeast-southwest direction, it measured 32.55 m [24]. This elliptical plan can be related with the unsupporting of the main dome with the semi-domes in the northeast-southwest direction. And this asymmetry is evident not only in the dome's plan but also in the sections of the main arches on which the main dome rests. Our research involved measuring the cross-sectional areas of the main arches based on recent surveys of Hagia Sophia's dome. The northeast arch exhibits a gross cross-sectional area of 22.9 m^2, whereas the southwest arch measures 22.4 m^2 gross. Although the cross-sectional areas of these two opposing arches are similar, the same cannot be said for the other arches connected to the semi-domes. Specifically, the gross cross-sectional area of the northwest arch is 7.2 m^2, while the southeast arch, notably the weakest, measures 6.1 m^2. These values include allowances for plaster, hence why they are stated as gross areas. Considering the comparable shares of plaster in the sections, the net areas would show similar ratios to the gross areas.

The significant disparity in cross-sectional areas—where the northwest arch measures less than 1/3 of the northeast and southwest arches, and the southeast arch constitutes almost ¼ of their areas—highlights the structural issues within the main dome. Contrary to expectations, the cross-sectional areas of the northeastern and southwestern arches are not double that of the others. The notably thin sections of the northwest and especially southeast arches define the dome's asymmetrical structure, a result of its destruction and varied reconstruction over time. This structurally irreparable situation may be attributed to the reconstructions during the 10th and 14th centuries (see Fig. 13).

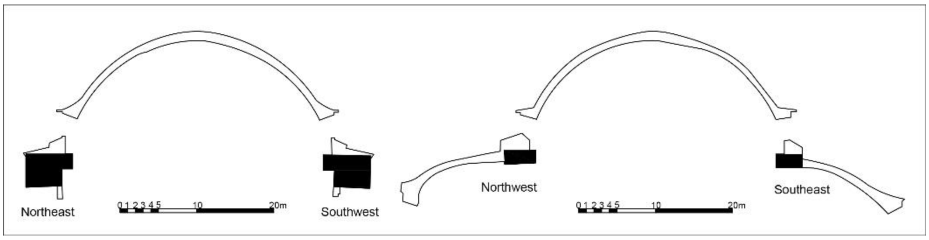

Fig. 13. The occupations of the main arches through the northeast-southwest and northwest-southeast cross-sections of the main dome

6 Conclusion and a preservation proposal

Thanks to the binding mortar's low density and high tensile strength [9], coupled with ongoing reparations spanning centuries, Hagia Sophia has maintained remarkable structural stability. Recent research notes the absence of collapse in the main dome since the 14th century, suggesting that immediate major interventions might not be necessary given consistent maintenance practices [25]. One recent study even suggests the structure is more resilient than its coverings [26]. However, there's a call for cautious reinforcement measures [25]. Rectifying the horizontal and vertical asymmetry in the supporting system is considered impractical, given the structural and decorative challenges it poses. Additionally, any structural interventions that could disturb the current disintegrated load balance that the structure coexists with for centuries, might pose unpredictable risks to Hagia Sophia.

The application of ring beams is a fundamental strategy in the retrofitting of historical masonry structures [27]. In the context of Hagia Sophia, it is identified that the primary collapse mechanism involves the main arches and semi-domes. Results indicate that due to the thrust of the dome the thick arches on the northeastern and the southwestern sides deflect outward while on the southeastern and the northwestern sides, the upper parts of the semi-domes deflect inward. The thrust of the dome arises because of the hoop stresses (peripheral thrust) developed in the lower portion of the dome. To resist lateral thrust, the options include using exceptionally thick walls or, more commonly, employing diagonal support or tension rings at the base. Normally the tension-resisting ring is provided in tension zone to carry the horizontal thrust resulting from the hoop tension. The tension rings prevent the dome walls from thrusting outward (see Fig.14). To minimize the cross-sectional sizes of reinforcing materials, composite materials based on high-strength fibers, mainly carbon, are used. An important advantage of using this sort of composite materials is their effortless adaptation to curved and rough/uneven surfaces.

The vulnerability arises during potential major earthquakes, where the main dome and semi-domes oscillate, posing a risk of hammering over the northwest and southeast arches, known to be the most delicate. This hammering effect could lead to the collapse of arches and semi-domes, with potential partial damage to the main dome [27] (see Fig.15). The proposed use of a tension ring introduces a preventive measure to limit the oscillation of the main dome, resulting in a more controlled and one-sided hammering. This approach aims to minimize damage to the semi-domes and slender main arches, crucial elements supporting the main dome. Positioned as an optimum solution, it seeks to protect Hagia Sophia's main dome without necessitating radical structural interventions.

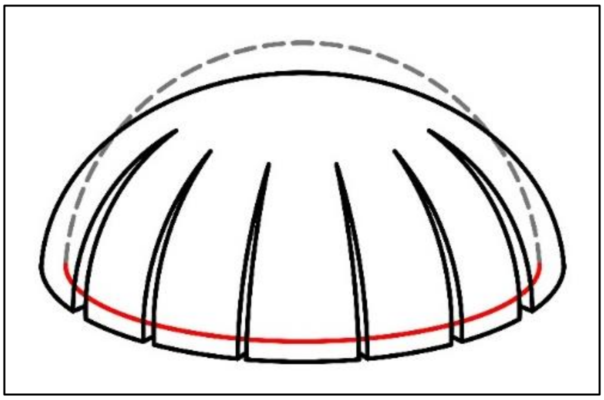

Fig. 14. Deformation of a dome: Tension ring preventing outward thrust

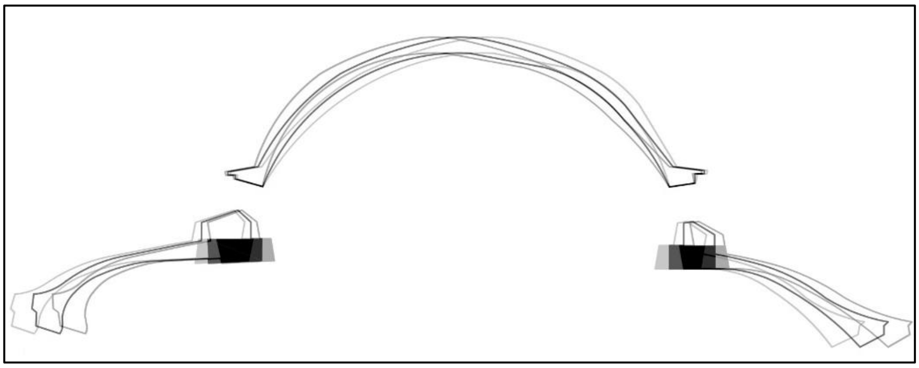

Fig. 15. Representation of the hammering effect on the main dome of Hagia Sophia

The use of CFRP (Carbon Fiber Reinforced Polymer) as a tension ring may be the most suitable material for the dome due to its superficial features that won't alter its silhouette. This choice also allows CFRP to be concealed beneath the lead covering easily. Similar interventions were made for the domes of the Outer Treasury in the

Topkapı Palace in 2009. The Outer Treasury that is a rectangular, one-story structure was built in the 16th century and covered with eight domes arranged in two rows. During the restoration process, the recent 20th-century concrete plasters inside the structure were completely removed, exposing the domes and walls along with traces of cracks. Over the centuries, ground movements might have exerted stress on the structure, potentially causing cracks above and below the domes. After extensive discussions, it was decided to reinforce each dome of the structure by applying carbon fiber tapes above the surface [28]. That intervention was one of the first CFRP uses for a cultural heritage in Istanbul after the earthquake in 1999 (see Fig.16).

Fig. 26. View from the crack under the dome and CFRP intervention above the dome.

Therefore, a comprehensive modeling study will prove the effect of using CFRP for the proposed tension ring, aiming to minimize interference with the visual integrity of Hagia Sophia. This proposal aims to deliver effective earthquake protection for the main dome of Hagia Sophia while preserving its appearance through the intervention of a ring of CFRP beneath the lead coverings. The preservation of Hagia Sophia's three-part structure, reflecting different historical periods, is crucial for its integrity (see Fig. 5). Hence, preservation efforts must align with its existing form, emphasizing retrofitting methods that uphold the dome's structural integrity and visual appeal. The study proposes a theoretical preservation method - tension ring encircling the main dome from the exterior (see Fig. 17). This proposed approach aims to provide supplementary support to the existing structure without altering its historical integrity, offering a potential solution to maintain its stability and safeguard its architectural significance.

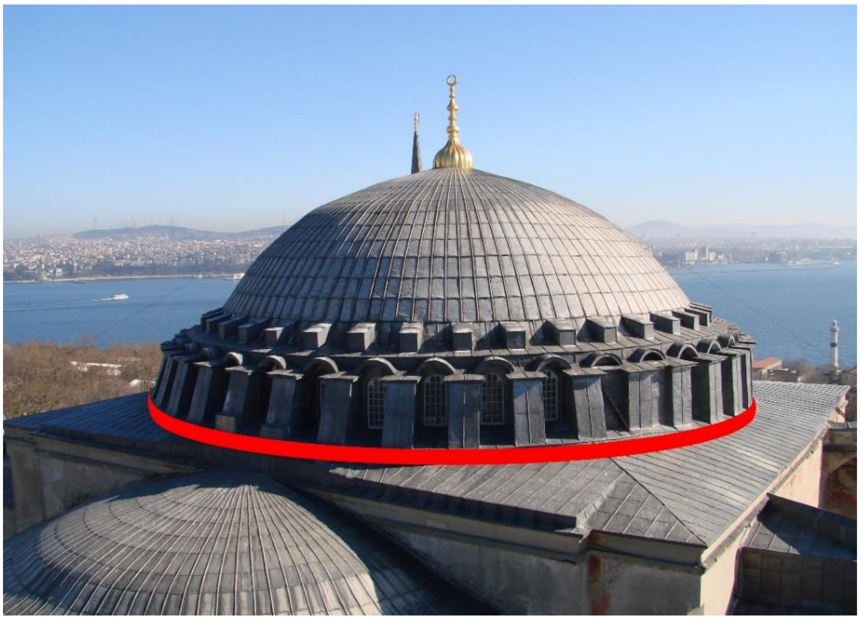

Fig. 17. Representation of the tension ring around the main dome of Hagia Sophia

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