DOI: https://doi.org/10.36719/2706-6185/54/14-25

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Diagnostic Studies and Structural Analysis during the Restoration of St. Sophia Cathedral

Abstract

The historical architectural masterpiece Hagia Sophia stands in Istanbul, Turkey, as one of the most impressive structures ever built. The cathedral suffered multiple earthquakes and fires throughout fifteen centuries, which caused partial building collapses that required extensive reconstruction work. The current state of the building structure needs detailed knowledge about its actual condition for proper modern conservation work. The research combines various diagnostic methods, which include geometrical survey and crack mapping, and non-destructive testing with ground-penetrating radar, ultrasonic testing, and thermography, and structural monitoring, and laboratory material analysis to determine Hagia Sophia's present condition for developing a complete conservation plan. The dome shows ongoing vertical and ring-shaped cracks, while the supporting columns show signs of uneven weight distribution, and the building materials match those used during the Byzantine era. The building shows stability, but it faces risks from earthquakes and ongoing decay. The proposed conservation plan includes protective measures and scheduled maintenance checks and ongoing surveillance to protect this cultural treasure for future generations.

Keywords: *Hagia Sophia, restoration, structural analysis, conservation, dome, diagnostic investigations, environment, seismic activity, non-destructive testing method*

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Müqəddəs Sofiya kafedralının bərpası zamanı diaqnostik tədqiqatlar və struktur təhlili

Xülasə

Tarixi memarlıq şah əsəri olan Ayasofya Türkiyənin İstanbul şəhərində indiyə qədər tikilmiş ən təsirli tikililərdən biri kimi dayanır. Katedral on beş əsr ərzində dəfələrlə zəlzələ və yanğınlara məruz qalıb və bu da genişmiqyaslı yenidənqurma işləri tələb edən qismən binaların çökməsinə səbəb olub. Bina strukturunun hazırkı vəziyyəti müasir konservasiya işləri üçün onun faktiki vəziyyəti haqqında ətraflı məlumata ehtiyac duyur.

Tədqiqat Ayasofyanın hazırkı vəziyyətini müəyyən etmək üçün həndəsi tədqiqat və çat xəritələşdirmə, dağıdıcı olmayan sınaq, yerə nüfuz edən radar və ultrasəs sınaqları, termoqrafiya, struktur monitorinqi və laboratoriya material təhlili daxil olmaqla müxtəlif diaqnostik metodları birləşdirir. Günbəzdə davam edən şaquli və halqavari çatlar var, dayaq sütunlarında isə qeyri-bərabər çəki paylanması əlamətləri müşahidə olunur və tikinti materialları Bizans dövründə istifadə edilən materiallarla eynidir. Bina sabitlik göstərir, lakin zəlzələlər və davam edən çürümə riskləri ilə üzləşir. Təklif olunan konservasiya planına bu mədəni xəzinəni gələcək nəsillər üçün qorumaq məqsədilə qoruyucu tədbirlər, planlaşdırılmış texniki xidmət yoxlamaları və davamlı müşahidə daxildir.

Açar sözlər: *Ayasofya, bərpa, struktur təhlili, konservasiya, günbəz, diaqnostik tədqiqatlar, ətraf mühit, seysmik aktivlik, dağıdıcı olmayan sınaq metodu*

Introduction

The historical architectural masterpiece Hagia Sophia exists in Istanbul Turkey as one of the most significant buildings from past times. The Byzantine Empire constructed this magnificent building as a cathedral during 537 CE, yet it survived 1,500 years of earthquakes and fires and structural breakdowns. The building's distinctive dome has experienced multiple collapses and reconstruction attempts since its initial construction.

The current conservation work at Hagia Sophia needs complete diagnostic studies to determine the building's current state and establish suitable restoration methods. The successful preservation of historic buildings through rehabilitation depends on thorough damage assessment of their construction according to conservation principles (Borri, Corradi, 2019). This study investigates the diagnostic methods which analyze Hagia Sophia's structural state through its dome collapse history and its current structural problems indicated by crack patterns.

Research

The evaluation of historic masonry structures including Hagia Sophia needs experts to conduct historical studies and material testing and perform sophisticated diagnostic procedures. The understanding of building structural behavior enables conservation experts to create suitable protection plans which maintain historical value and ensure structural stability.

Figure 1. Hagia Sophia exterior view from the Sultanahmet Park

2.Historical background and dome collapses

The construction of Hagia Sophia took place during Emperor Justinian I's reign from 532 to 537 CE. The building featured a central dome which measured 31 meters in diameter while reaching heights of 56 meters above the ground during its construction in the 6th century.

The dome of the building suffered its first major structural failure when it partially collapsed during an earthquake in 558 CE because of construction flaws and seismic activity. The eastern section of the dome collapsed during the earthquake which caused damage to the altar and surrounding buildings according to historical records. The initial collapse exposed critical design flaws which existed in the original construction of the building.

2.1 Medieval period reconstructions

The dome underwent reconstruction between 558-562 CE through a new design which elevated its structure by 6 meters to enhance stability. The dome experienced multiple structural failures during the Middle Ages because of its design weaknesses.

- The western section of the dome suffered damage from an earthquake that caused a partial collapse in 989 CE.
- The eastern section of the dome collapsed in 1346 CE which led to a major reconstruction effort.
- The Byzantine period saw numerous earthquakes that continuously harmed both the dome structure and its supporting framework.

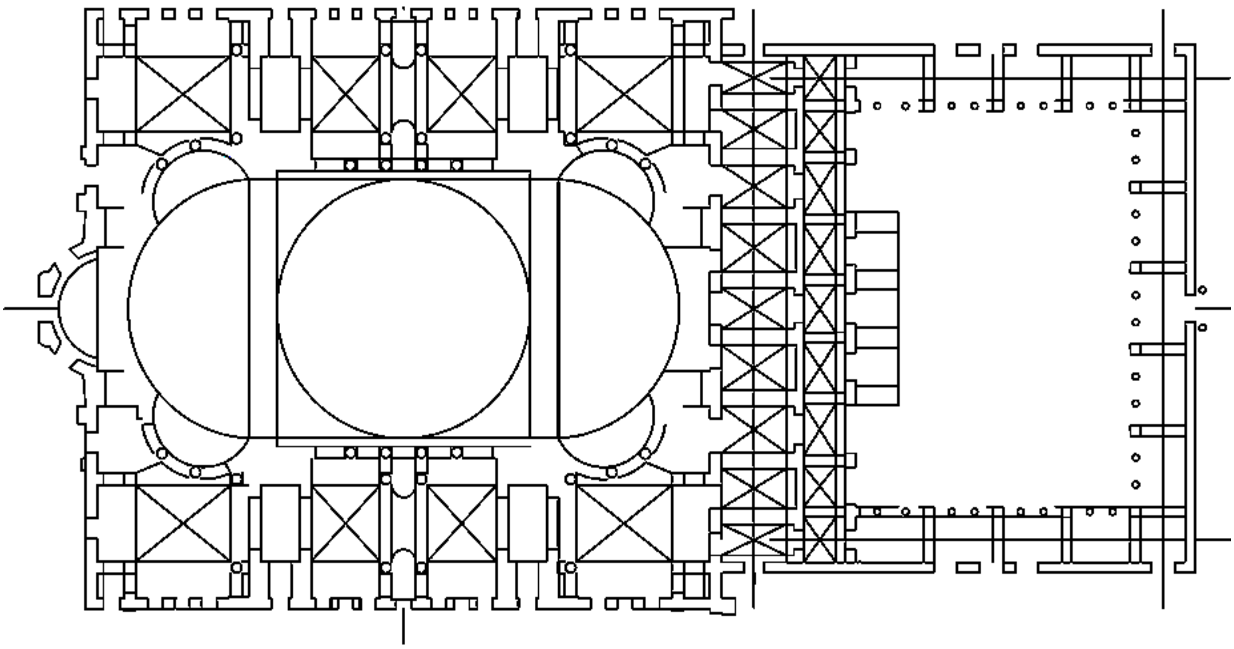


Figure 2. Ground plan diagram of Hagia Sophia from the 6th-century construction.

2.2 Ottoman period modifications

The Ottoman Empire transformed Hagia Sophia into a mosque after their 1453 conquest of Constantinople through multiple extensive architectural and structural modifications to support its new religious purpose. The Ottoman Empire understood both the historical value and engineering requirements of the building, so they started a prolonged process to repair its deteriorating structure which had accumulated damage from multiple seismic events throughout the centuries.

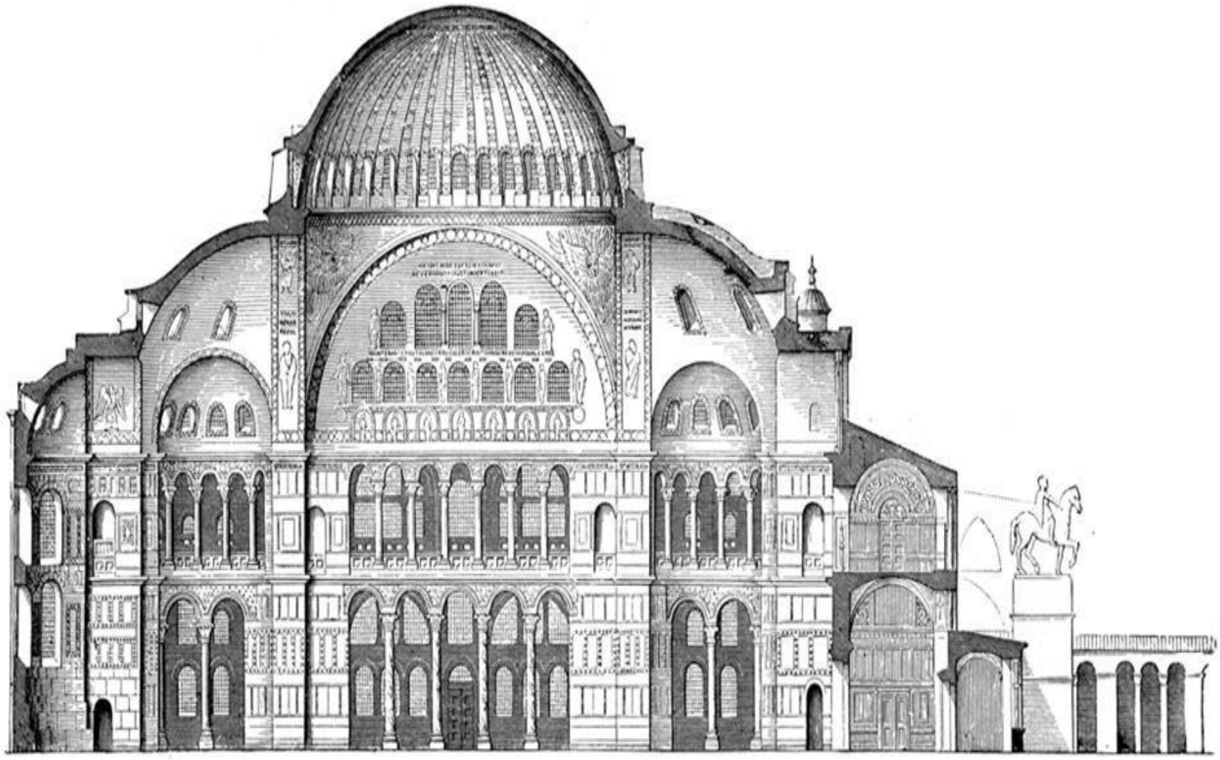
Major interventions included:

- The construction of external buttresses grew incrementally to fight dome expansion while protecting wall stability from further damage.
- The installation of iron tension chains at the dome base enhanced its resistance to spreading while improving the mechanical performance of the central dome system.
- The supporting piers and arches and semi-domes received additional reinforcement to fix

damage that earthquakes had caused throughout history.

▪

Figure 3. Historic longitudinal cross-section of Hagia Sophia (reconstruction view)



The construction of heavy masonry minarets served both religious purposes and provided additional structural support through their vertical stiffness and weight distribution The building suffered ongoing earthquake damage throughout the Ottoman period despite receiving multiple major restoration projects. The monument required ongoing repair work and structural modifications to maintain its structural stability. The extensive restoration work performed on the building enabled its survival through the ages while determining its current structural design.

3. Diagnostic investigations

The assessment of Hagia Sophia through modern diagnostic methods follows established procedures for historic building evaluation (Guidelines on Cultural Heritage - Technical Tools for Heritage Conservation and Management, 2012). The conservation guidelines specify that field investigations need to follow a structured approach which includes (Binda, Lualdi, Saisi, & Zanzi, 2011):

1. Geometrical and crack pattern survey
2. Survey of masonry texture and wall sections
3. Assessment of local stress conditions
4. Material sampling for laboratory analysis
5. Detection of hidden features using non-destructive testing

3.1 Non-Destructive Testing Techniques

Multiple non-destructive testing (NDT) methods have been used in recent diagnostic campaigns to study Hagia Sophia's present structural behavior without causing any harm to its historical structure. The techniques enable researchers to study masonry wall internal structures while detecting concealed flaws and measuring the structure's reaction to prolonged loads and seismic forces. The combination of multiple NDT methods enables researchers to understand deterioration processes fully which leads to the creation of suitable conservation plans (Structural Assessment Methods for Historic Masonry, 2011).

The research on Hagia Sophia employs five main NDT methods which include remote sensing and radar-based subsurface imaging and ultrasonic transmission analysis and thermography and endoscopic inspection. The combination of data from these methods enables researchers to build an accurate picture of the monument's structural state while identifying potential stability issues at their earliest stages. The methods prove essential for historic buildings because they allow researchers to conduct minimal invasive testing that protects both the building's original state and its materials.

3.1.1. Ground Penetrating Radar (GPR)

The investigation of historic masonry structures benefits significantly from GPR technology. The authors in their recent study demonstrate that radar technology serves as an effective survey method which enables researchers to analyze multiple issues affecting ancient buildings (Binda, Lualdi, Saisi, & Zanzi, 2011). The GPR investigations at Hagia Sophia have achieved three main objectives through their use of the technology.

- The technology helps users detect both internal voids and structural discontinuities in buildings.
- The technology enables users to create detailed maps of the internal composition of both large piers and walls.
- The system helps users track where water enters the building structure.
- The system enables users to find all past restoration work and support additions.

3.1.2. Ultrasonic testing

The internal state of masonry materials becomes assessable through ultrasonic testing because it measures how sound waves travel through the material. The testing method detects three main types of damage:

- Areas of deteriorated mortar joints.
- Internal cracking not visible on surfaces.
- Variations in material density and quality.
- Delamination between different masonry layers.

3.1.3 Thermographic analysis

The thermal imaging technique from infrared thermography shows temperature variations which expose structural issues:

- Moisture infiltration patterns
- Detachment of surface materials
- Variations in wall thickness and composition
- Heat loss through structural defects

3.2. Structural Monitoring Systems

The long-term behavior of Hagia Sophia depends on continuous structural monitoring because the building shows high sensitivity to earthquakes and ground settlement and environmental changes (Heritage Conservation Guidelines, 2012). The building site contains multiple monitoring instruments which track deformation patterns and material responses and oscillations during different time periods. The monitoring systems enable staff to identify potential instability issues while creating evidence-based conservation plans.

3.2.1 Crack Monitoring Gauges

The monitoring system for cracks in masonry structures allows users to track how cracks expand or shrink and move within building elements. The devices track structural movements either continuously or at scheduled intervals to detect active building deformation and monitor environmental effects and previous repair outcomes.

3.2.2 Tilt meters

The tilt meters track small angular shifts that occur in major structural elements including piers and columns and arches. The monitoring of tilt at Hagia Sophia remains crucial because the building has experienced settlement and seismic events throughout its history to detect rotational movements and structural differences that threaten overall stability.

3.2.3 Accelerometers

The building's seismic responses and ambient vibrations get recorded by accelerometers. Engineers use frequency shift analysis and damping ratio evaluation and modal behavior assessment to check structure health and identify concealed weaknesses in the dome and semi-domes and piers. The collected data enables engineers to create precise numerical models and evaluate how well the structure withstands earthquakes.

3.2.4 Environmental sensors

The environmental monitoring systems monitor how temperature and humidity and moisture levels change inside the structure. The structural materials experience degradation and cracks spread while salt forms crystals and biological organisms grow because of these environmental factors. The ongoing environmental data collection helps conservation teams create strategies that match the actual requirements of building materials.

4. Crack pattern analysis and structural issues

The diagnostic program delivered a complete assessment of Hagia Sophia's present structural state which showed multiple crack patterns that stem from aging materials and settlement differences and multiple earthquake-induced stressors. The dome contains two main crack patterns which run in different directions. The meridional cracks in the dome structure start at the top and extend down to the base (Figure 4) because they develop from tensile forces and thermal expansion and local stiffness reduction. The dome's lower rings develop circumferential cracks (Figure 5) because they experience high compressive forces and unbalanced hoop tension and progressive drum deformation.

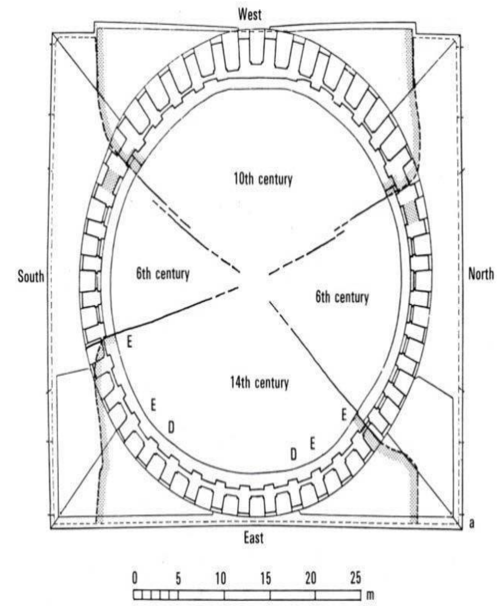


Figure 4. Crack pattern taken from Mainstone

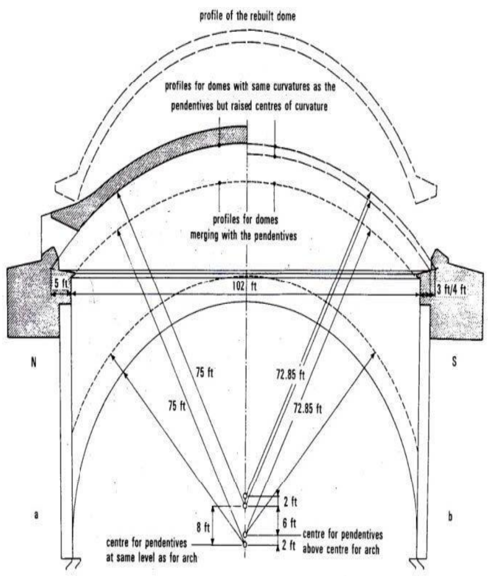


Figure 5. Reconstruction taken from Mainstone

The piers of the structure display major cracks which indicate both compressive force overload and ongoing settlement and shearing forces that developed from past earthquakes.

The structural system redistributes forces which causes extensive cracking to appear in the dome and semi-dome and pendentive transition areas (Mainstone, 1988). The masonry courses show horizontal cracks and separations which suggest sliding mechanisms that might occur during earthquakes or because of creep-related phenomena that develop over time.

The historic Byzantine masonry underwent material analysis which showed excellent brickwork construction with hydraulic lime mortars that demonstrated self-healing properties. The structure has experienced deterioration through time because of salt crystallization and freeze–thaw cycles and moisture entry and airborne contamination which has caused mortar joint deterioration and crack expansion.

The building's massive weight and irregular weight distribution together with environmental elements affect its structural behavior.

The monitoring data from current measurement activities shows Hagia Sophia maintains worldwide stability but shows gradual measurable distortions and seismic responses to small earthquakes.

The ongoing small movements in the structure demonstrate why extended monitoring and specific conservation work needs to focus on protecting weak points while maintaining the original historic construction materials.

4.1 Meridional cracks

The dome shell shows cracks which start at the crown and extend down to the base while following the paths of longitude. The following factors can be identified through these cracks:

- The dome shell experiences hoop tension stresses which occur because of its shape.
- The base of the dome lacks sufficient structural support.
- The dome structure experiences stress because of temperature changes between expansion and contraction.
- The supporting structures have experienced settlement.

4.2 Circumferential cracks

The base of the dome shows horizontal cracks which show evidence of:

- The dome's base experiences too much compression force.
- The ring reinforcement system fails to provide sufficient support.
- The supporting piers experience different levels of settlement which causes problems.
- The system experiences problems because of uneven load distribution.

5. Material characterization

The research studies demonstrate how loads move through Hagia Sophia while showing the reasons behind past structural breakdowns and future potential failures. The dome bears more than 10 000 tonnes of weight which passes through pendentives and arches to reach four main piers. The uneven weight distribution caused by additional structures built later creates excessive stress at the points where piers meet arches.

The seismic evaluation demonstrates how the tall narrow building structure remains exposed to lateral forces because its masonry joints lack sufficient flexibility (Binda, Cardani, Tiraboschi, 2003).

The structure experienced previous collapses because of weak supporting structures and settling foundations and restricted design capabilities. The current cracks in the structure match exactly with areas that failed in the past because gravity and seismic forces continue to affect the structure.

5.1 Masonry analysis

The material property assessments together with load evaluations produce safety factors that stay within acceptable limits despite these obstacles. The dome structure along with its supporting elements show sufficient strength to handle typical building loads. The building needs long-term preservation through two main steps which involve stopping deterioration and improving earthquake resistance. The laboratory testing of masonry samples demonstrated that the construction materials and methods followed these patterns:

5.1.1 Brick composition

- The construction used Roman-style thin bricks which measured between 3-4 cm in thickness.
- The high-fired clay materials demonstrate excellent durability properties.
- The construction materials showed different levels of quality because they came from different time periods.
- The construction site contained materials from previous buildings which were reused for the project.

Figure 6. Mortar composition found in Hagia Sophia

5.1.2 Mortar analysis

The analysis demonstrates that hydraulic lime mortars contain two essential components which include crushed brick aggregate and brick thermal expansion compatibility. The mortar exhibits self-healing properties and demonstrates excellent long-term durability because of its crushed brick aggregate.

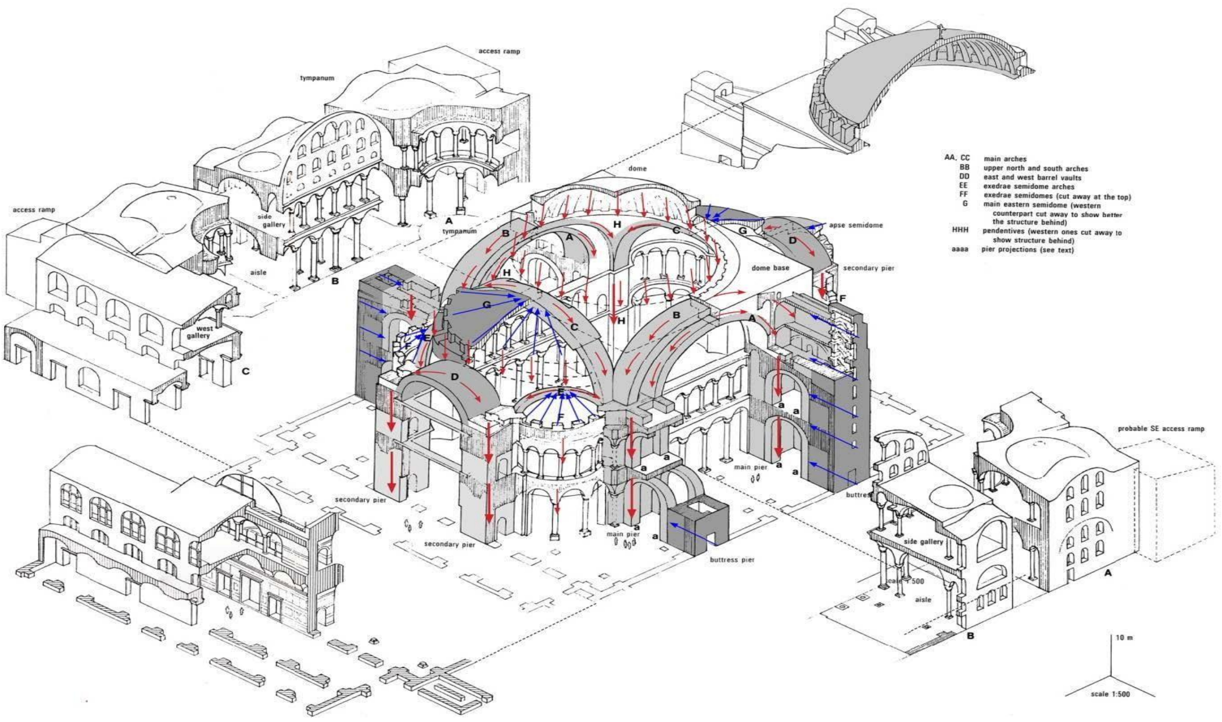
5.2 Structural material properties

Research conducted in laboratories and field sites has delivered better knowledge about the mechanical properties of Hagia Sophia's ancient masonry structures. The material properties serve as essential data for creating structural models and performing seismic evaluations and conservation strategy development.

The brick–mortar material shows compressive strength between 8–15 MPa because of the excellent Byzantine fired bricks and their combination with lime-based mortars. The material shows adequate resistance to vertical loads but experiences critical stress when facing lateral forces and seismic events because it tends to fail through brittle mechanisms. The measured tensile strength of historic masonry materials falls between 0.8–1.2 MPa which demonstrates their susceptibility to tensile stress failure.

The masonry structure experiences tension- related damage through dome and arch and pendentive areas which results in the development of meridional and circumferential cracks. The low tensile strength of masonry materials demands the implementation of tie-systems and compressive rings and reinforcement methods which have been used in both historical and contemporary restoration work.

Figure 7. Hagia Sophia: figure taken from Mainstone with defined structural scheme (1988)



The elastic modulus of the masonry fabric shows stiffness, but material heterogeneity and mortar deterioration and historical repair methods create significant anisotropic effects which result in a wide range of values from 2,000 to 4,000 MPa. The different material properties throughout the monument create changes in its global stiffness which determines its response to earthquake movements.

The material properties show that Hagia Sophia's masonry structure maintains its strength but needs special modeling approaches and protective structural measures because of its ancient construction characteristics.

5.3 Deterioration assessment

Material investigations show that Hagia Sophia faces long-term stability issues because of multiple environmental and chemical and mechanical deterioration processes. The identification of vulnerable areas requires knowledge about these deterioration mechanisms to develop suitable conservation strategies.

5.3.1 Salt crystallization

The porous masonry structure allows water to enter while it carries dissolved salts from the foundation soil and atmospheric pollutants and historical water leaks. The evaporation of moisture leads to salt crystallization inside pores which produces expansive forces that damage mortar bonds and break down brick material into powder. The repeated process of surface deterioration through time results in plaster layer separation and increased material brittleness.

5.3.2 Freeze–thaw damage

The structure's exterior elements including its upper dome sections and exterior support structures and roofing connections experience temperature changes which produce freezing and thawing events. The freezing process of water in microcracks causes expansion that makes fissures grow larger until the material breaks down. The mechanism produces maximum damage in areas where water cannot drain properly and when original waterproofing systems have broken down.

5.3.3 Chemical decay

Urban activities release sulphur dioxide and nitrogen oxides which combine with lime-based mortars to produce acidification that results in gypsum crust formation. The crusts create moisture traps which lead to hidden structural deterioration. Acid rain speeds up the process of calcium compound extraction from mortar which weakens its bond strength and changes its surface permeability.

5.3.4 Mechanical damage

The most damaging factor that causes structural problems in Hagia Sophia stems from seismic events. Historic masonry structures fail to withstand dynamic forces from earthquakes because these forces exceed their tensile and shear strength limits which results in fresh cracks and reactivation of existing ones. The structure experiences progressive deformation and localized crushing because of historical modifications and uneven load distribution and long-term settlement and mechanical imbalances.

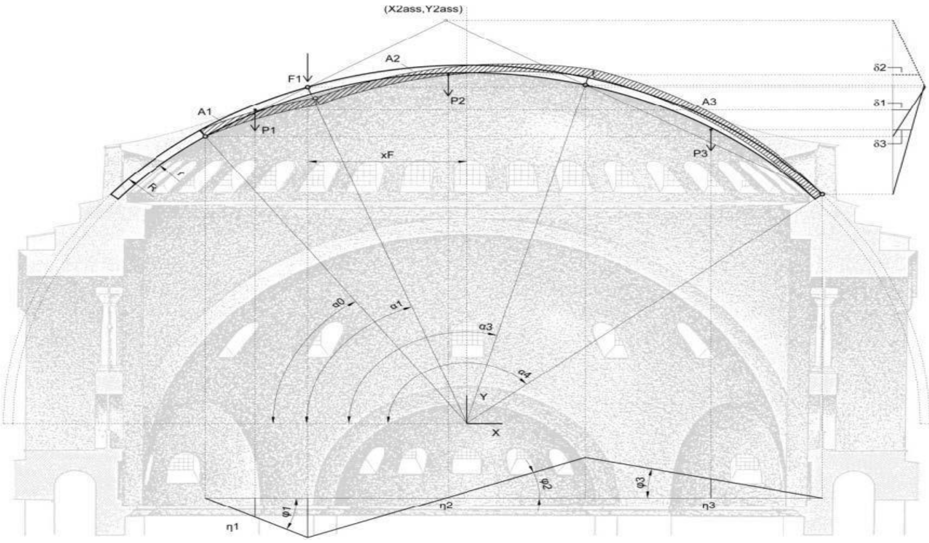


Figure 8. Hagia Sophia: mechanism of collapse of the original dome.

The structure shows global stability but requires continuous monitoring and preventive conservation and periodic reinforcement because of ongoing environmental and mechanical stress.

6. Interpretations and findings

The research shows that Hagia Sophia maintains worldwide structural stability, but it still faces specific weaknesses which affect its dome structure and its supporting arches and major piers. The building's structural weaknesses stem from multiple factors which include time-based deterioration and past construction changes and ongoing structural stress. The discovery of these patterns enables developers to create preservation plans which protect the monument's original character while providing enduring protection for the structure.

6.1 Structural Behavior Understanding

The diagnostic studies have delivered vital knowledge about Hagia Sophia's structural behavior which enables better comprehension of how forces and stresses and deformation patterns spread across the monument:

6.1.1 Load distribution

The dome's enormous weight exceeding 10,000 tons generates intricate force paths that affect the supporting framework of the structure. Investigations show:

- The four main piers receive uneven weight distribution.
- The pier-arch interfaces experience maximum stress levels.
- The pendentives transfer loads which produce tension areas throughout the structure.
- The dome loads interact with earthquake-induced lateral forces that affect the structure.

6.1.2 Seismic vulnerability

The analysis demonstrates that the structure faces risks during earthquake events because of its design characteristics:

- The building structure faces increased risk of lateral forces because of its tall design compared to its foundation size.

• The structural connections between building elements depend mainly on gravity and mortar for their strength.

• The masonry construction lacks sufficient flexibility when structures experience stress.

• The structure becomes vulnerable to complete collapse when essential structural components fail.

6.2 Historical Collapse Analysis

The original dome system of Hagia Sophia experienced multiple collapses throughout history because of its structural weaknesses which modern diagnostic tests confirmed. The dome structure became highly vulnerable to seismic forces and outward thrust because the building did not receive enough lateral support during its initial construction phase. The building experienced instability because its massive piers settled at different rates while early mortar and brickwork materials contained defects. Researchers who study previous building failures will gain essential knowledge about structural behavior because they can identify how tensile stresses and insufficient confinement and geometric limitations affected the building. The acquired knowledge will help experts develop effective conservation plans for the future.

6.2.1. 558 CE Collapse

The first building failure occurred because of four main factors:

The building foundation did not settle properly and the dome lacked proper lateral support and the original mortar contained defects and the designers might have made errors in their load calculations.

6.2.2 Later Medieval Collapses

The building experienced multiple subsequent failures because of:

The building suffered from progressive earthquake damage that accumulated over time while the structure experienced progressive settlement and mortar joint deterioration and maintenance issues during unstable political periods.

6.3 Current condition assessment

The diagnostic program has determined the present state of building stability through its complete assessment:

▪ The structure maintains stability but needs continuous surveillance for its protection [ICOMOS – ISCARSAH (2017)].

▪ The analysis pinpointed particular sections which need immediate focus for repair work.

▪ The current rate of deterioration remains under control when proper conservation measures are implemented.

▪ The structure maintains sufficient safety factors for typical operational loads.

7. Conservation approach

The ICOMOS Charter on architectural heritage analysis and conservation and structural restoration serves as the foundation for Hagia Sophia restoration work which focuses on preserving historic materials through minimal intervention (ICOMOS, 2003). Charter - Principles for the Analysis, Conservation and Structural Restoration of Architectural Heritage]. The restoration plan includes three essential goals (Feilden, 2003):

▪ The system monitors structural stability instead of performing major changes to the building.

▪ The restoration team should perform documented reversible repairs by selecting materials which have equivalent mechanical and chemical properties to the original building materials.

▪ The site requires controlled management of environmental elements which cause materials to deteriorate.

▪ The site needs development of emergency protocols which address seismic occurrences.

The reinforcement work will concentrate on strengthening essential connections and better securing them while keeping all additions non-intrusive to preserve original authenticity (ICOMOS Charter, 2003).

The monument will receive protection through a scheduled maintenance system which will run alongside regular evaluation sessions using new diagnostic methods.

Conclusion

The designers of Hagia Sophia along with successive cultures have managed to protect this building throughout fifteen centuries of disasters. Modern conservation work requires scientists to conduct thorough diagnostic tests while maintaining proper respect for historical heritage values. The research unites multiple fields of study to examine Hagia Sophia through geometric survey and non-destructive testing and structural monitoring and material analysis. The research shows that the building maintains overall stability but faces ongoing threats from earthquakes and natural deterioration. The research team uses crack pattern analysis and load distribution studies to determine vulnerable areas which leads to a proposed conservation plan based on protective measures and minimal alterations. The continued observation of Hagia Sophia together with strict adherence to international conservation standards will enable this historic site to remain unaltered for upcoming generations (Conservation Principles for Historic Buildings, 2003). During the restoration of Hagia Sophia, Turkey demonstrated to the world an exemplary system and model for the preservation of cultural heritage of different faiths and civilizations.

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Received: 02.09.2025
Accepted: 02.12.2025