Heritage Conservation in Crisis: A Case Study on Post-Earthquake Church Restoration in Samos Island, Greece

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Abstract

This paper details the methodology for recording, documenting, and restoring six historic Orthodox churches on the island of Samos, Greece, severely damaged by 2020 Aegean Sea earthquake, occurred on October 30. An interdisciplinary team from the Faculty of Engineering from Aristotle University of Thessaloniki led this 12-month project, funded by the Greek Ministry of Culture. The restoration process began with a thorough on-site data collection, employing advanced 3D surveying techniques like Terrestrial Laser Scanning (TLS), photogrammetry, Unmanned Aerial Vehicles (UAVs), and traditional topographic methods including GNSS. This was complemented by historical documentation. The collected data included images, videos, measurements, and reports and were processed to create detailed 3D models of each church's interior and exterior, along with 2D CAD orthoimages for precise measurements and architectural documentation. Structural assessment utilized these 3D models and on-site identification of the load-bearing stone masonry systems. Bearing capacity under seismic loads was evaluated using Equivalent Static Analysis, adhering to regulatory frameworks (EC8-3, Greek KADET). Material mechanical properties were quantified through laboratory testing of samples from the structures. Strengthening proposals prioritize safety, compatibility, reversibility, and minimal intervention, guided by predicted failure modes. Demand/capacity ratios, considering both loads and displacements, were calculated for the defined performance level, accounting for the churches' functional use and monumental value. The proposed strengthening solutions aim to upgrade the load bearing capacity of the structures after ensuring the out of plane stability of the walls forming the facades.

1. Introduction

1.1 Motivation

On October 30, 2020, a strong earthquake of magnitude M_L 6.7 struck the Aegean Sea, approximately 20 km northeastwest of from the city of Samos Greece. While the earthquake caused significant and widespread damage, particularly in İzmir, Turkey, Samos also experienced substantial impact, as the earthquake triggered a localized tsunami and caused extreme structural damage, particularly in the towns of Karlovasi and Vathy (Kalogeras et. al., 2020; Triantafyllou, 2021).

Among the structures heavily affected were numerous historic Orthodox churches, which are integral to Samos's cultural and religious heritage. Most of the affected temples were built in the 20th century using traditional masonry techniques, rendering them particularly vulnerable to seismic forces. These churches include the Dormition of the Virgin Mary in Ano Bathy, St. Nicholas in Neo Karlovasi, St. Nicholas in Kokkari, St. John Chrysostom in Neo Karlovasi, the Transfiguration of the Saviour in Pythagoreio, and St. Spyridon in Vathi, and became the primary focus of the restoration project. Damage to these churches ranged from severe cracking and partial collapse to non-structural issues like detached plaster.

Following the immediate emergency response, which included search and rescue operations, provision of aid, and initial building inspections, access to most of the churches was prohibited for safety reasons the focus shifted to the critical task of restoring these damaged churches. Structural scaffoldings were installed to stabilize the buildings. This endeavour was paramount not only for ensuring their continued functionality for religious services but also for safeguarding their invaluable cultural heritage.

Thorough documentation enables us to evaluate the effectiveness of the reconstruction efforts. By analysing what worked well and what didn't, we can develop improved strategies for future projects (ICOMOS, 2023).

Restoring cultural heritage after a major disaster is a complex process that requires an interdisciplinary approach (Luca, 2023). It addressing challenges arising from religious, societal, and economic changes (Obed Livingstone Banda et al., 2024). A core principle that guided our efforts was respect for the monument's original structure and historical authenticity.

The restoration project was funded by the Greek Ministry of Culture and implemented by the Faculty of Engineering of Aristotle University of Thessaloniki over a 12-month period. The project involved close collaboration between architects, civil engineers and surveyors to ensure a comprehensive understanding of the affected monument and its structural integrity.

1.2 Historical overview

Saint Spyridon in Bathy **(Church 1)** was founded in 1892 during the reign of Alexandros Karatheodoris and its construction was completed in 1907, with the sponsorship of the merchant Alexandros Paschalis. On 11 November 1912, Themistocles Sofoulis (Gikarinis,1998). proclaimed the union of Samos with Greece in the church. The church is a basilica with a dome, and its magnificent exterior is completed by the two tall bell towers, located to the left and right of the central entrance. Its cathedral church of Vathi (Varvounis, 1998).

The Transfiguration of the Saviour in Pythagoreio **(Church 2)** was built in 1824 in memory of Battle of Gerontas (Tsakos, 2003). Its initial form was a single room with an arch. It waslater extended to the north and south with rectangular extensions, and a front was added to the west side.

The Dormition of the Virgin Mary in Ano Bathy (**Church 3)** was built around 1802 AD. It features three aisled church with a dome.

The four-chambered Byzantine style church of Saint Nicholas in Neo Karlovasi **(Church 4),** featuring a central dome two imposing bell towers overlooking the bay of Karlovasos, functions as both an architectural landmark and a focal point for local community identity and cultural heritage. The church was founded on 30 April 1904 and completed on 30 September 1906, with the valuable assistance of the eminent tanner Georgios Vliamou and under the supervision of the architect Angelos Angelidis.

Saint Nicholas in Kokkari **(Church 5),** has a history, which begins on May 31, 1902. After a few months, on September 18, 1902, the church was founded by Metropolitan Athanasios Kapouralis of Samos. In 1933 the construction was continued. In 1938 the work of finishing the church was completed, but the events of the Second World War delayed the interior decoration again, in order to make the church functional. Finally, on December 8, 1963, 61 years after its foundation the temple opened (Varvounis, 2022)

The architectural style of Saint John Chrysostom in Neo Karlovasi **(Church 6),** is described as three-aisled with a dome.

Figure 1. Study area of Samos and distribution of 6 temples, Greece (Basemap ©esri)

2. Methodology

2.1 Workflow

To create a tangible record with accurate geometry of an object's physical characteristics, geometric documentation involves the collection of precise 2D and 3D data. Through diverse measuring techniques, it meticulously captures the shape, size, dimensions, and orientation, producing outputs such as 2D architectural drawings, detailed 3D digital models, and advanced Building Information Modeling (BIM) representations (Prasidya, 2025).

The crucial data collection phase incorporates various techniques, beginning with meticulous planning of fieldwork to optimise on-site efforts. This involves establishing a strategic sequence of scanning positions for terrestrial laser scanning to ensure comprehensive spatial coverage, as well as precise flight planning for aerial photogrammetry using Structure from Motion (SfM) methodologies, specifically via Unmanned Aerial Vehicles (UAVs). All steps were performed after approval from the responsible authorities Once collected, the raw data undergoes rigorous processing, including immediate on-site checks and continuing with intensive offline techniques such as scan registration, noise filtering, and mesh generation. This processed data then forms the basis for creating detailed 3D models, ranging from simple mesh representations to intelligent, information-rich Building Information Models (BIMs) (Prasidya,2025). These precise 3D models are indispensable for structural assessment, enabling detailed geometric analyses, accurate defect mapping and advanced finite element analysis to evaluate the structure's integrity and seismic performance comprehensively.

2.2 Data collection

The process of data acquisition involved a range of techniques, including photogrammetry, terrestrial laser scanning, and topography. The primary stage in all these methods is the field recognition of the working area, the collection of adequate data coverage, and the preliminary checking of their quality and quantity in the field. The measurements were conducted from January 2024 to June 2024 and their quantitative characteristics presented below (Table 1,2). A significant challenge during the scanning process of the churches areas was the presence of extensive scaffolding, erected for initial structural stabilization and assessment.

Metric	Unit	Church 1	Church 2	Church 3
Ground resolution	mm/pix	1.03	7	6.62
Images		1462	1371	825
Area	km2	1380	0,0286	1380
Scans		61	39	35

Table 1. Quantitative characteristics of collected data

Metric	Unit	Church 4	Church 5	Church 6
Ground resolution	mm/pix	1.25	1.03	1.03
Images		811	886	562
Area	km2	344	2400	0,0245
Scans		33	43	33

Table 2. Quantitative characteristics of collected data

2.2.1 Data collection with Terrestrial Laser Scanner

For high-precision data of the interior space of the temples, two terrestrial laser scanners were employed: a FARO Focus S70, with an accuracy of +/- 1mm. and a Leica BLK360 G1, with an accuracy of 6mm at 10m. These instruments facilitated comprehensive terrestrial laser scanning within the interior spaces of the temples, capturing intricate architectural details and structural parts. Scanning positions were planned, ensuring an overlap of approximately 40% between two sequential set-ups. In some locations, targets were positioned to assist the scan registration accuracy. While the Leica BLK360 provided convenient real-time process monitoring via an iPad interface, it sometimes introduced workflow delays. In contrast, the FARO

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Focus S70 offered on-site registration capabilities, significantly simplifying the following data processing phase.

2.2.2 UAV imagery

The exterior spaces of the churches were captured using a DJI Mavic 3 Enterprise drone. Each temple was surveyed through two planned flights: a nadir (planar) flight for general coverage of the area which was imported in the UAV through a .kml file, and an oblique flight specifically targeting architectural features such as bell towers and domes. To support accurate image alignment and enhance photogrammetric reconstruction in Agisoft Metashape, Ground Control Targets (GCTs) that were easily detectable and compatible with the software were strategically placed on site, supplementing both the planned UAV flights and manual captures of intricate architectural features.

2.2.3 Setup and measurement of Ground Control Points

Terrestrial topographic methods were used for the measurement of Ground Control Points (GCPs) using GNSS equipment. These checkpoints are of paramount importance ensuring georeferenced of final products e.g. CAD plans, orthoimages and point clouds. The points were obtained in the Greek Geodetic Reference System 1987 (GGRS87) using permanent reference satellite stations of the Hellenic Positioning System (HEPOS). The measurements also included ellipsoidal heights, and the distribution of points across the designated area was optimized to ensure the proper transformation in the desired reference system (Figure 2).

Figure 2. Distribution of markers with yellow flag St. Nicholas Karlovasi

2.3 Data processing

All acquired datasets underwent meticulous processing using specialized software platforms, following a standardized workflow of data importation, rigorous quality assessments, iterative processing refinements, and final output production. The scaffolding, present both in the interior and exterior of the monument, introduced considerable "noise" into the raw point cloud data, significantly complicating the subsequent data processing and increasing extremely the overall processing time.

The process was implemented in a device with RAM 63.15 GB CPU AMD Ryzen 9 7950X 16-Core Processor, GPU AMD Radeon (TM) Graphics (gfx1036) with NVIDIA GeForce RTX 4080.

2.3.1 3D point cloud processing

Raw terrestrial scans that were not preregistered in the field were imported, into SCENE software and a manual cloud-to-cloud registration process was performed. This was achieved by carefully selecting at least three common and well-distributed points between the datasets. After initial registration, a bundle adjustment was performed to globally refine the alignment of all scans. To ensure the quality of the registration, a thorough evaluation of the registration accuracy was carried out, measuring overlap percentage between the registered scans. Before finally exporting the data, a comprehensive review of both qualitative (visual inspection of alignment and data consistency) and quantitative (numerical error metrics) indexes was conducted to confirm the accuracy and reliability of the final point cloud. The final datasets were exported as standardized ".e57" point cloud files.

Scans captured with the Leica BLK360 were processed using Leica Cyclone Register 360 (Cyclone,2023). Following the import of the scans, the detection of targets was successfully achieved. The scans were pre-aligned in the field, a process that facilitated the ensuing fine alignment. Subsequently, noise filtering eliminated any moving objects. Next, setups with mutual visibility were consolidated into a single bundle. Prior to the exportation of the data to the.e57 format, a thorough examination of the quality metrics, specifically the overlap percentage and the overall bundle error, was conducted. Upon satisfaction with the quality results of this examination, the final version of the point cloud for every temple was created.

2.3.2 Image-based modelling

UAV-based datasets were processed through Agisoft Metashape (Agisoft Metashape, 2024) in a structured workflow (Figure 3). Initial processing entailed two critical tasks: photo alignment, which established the spatial relationships between individual images (Bethel, 1995) and tie points creation, which serve as common reference points across multiple photographs. A noise filtering was applied afterwards, refining thus the data by removing extraneous points and improving the overall quality, and the accuracy of the produced 3D models.

The refined data was then used to generate a dense point cloud, producing a highly detailed collection of 3D coordinates that accurately depicted the surface of the scanned area. A mesh model was then constructed from the dense point cloud, forming a continuous, textured surface that accurately depicted the monument and its surrounding environment. The final processing workflow was concluded by deriving essential topographic products: the Digital Terrain Model (DTM), the Digital Surface Model (DSM) and precise contour lines for each of the churches. These were all meticulously created to accurately represent the geometry and the structure of every temple of the study area. From the model of each temple, 4 ortho-imaged views were created.

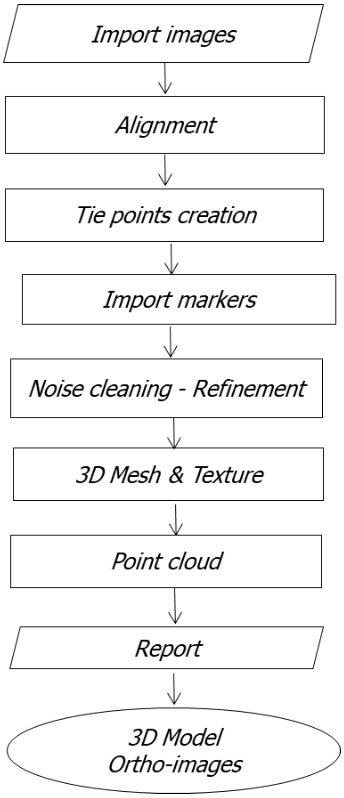

Figure 3. UAV based workflow for 3D reconstruction of the temple

2.3.3 Merging the clouds

Cloud Compare (Cloud Compare, 2024) software served as a crucial intermediate tool for the seamless merging of diverse point cloud datasets. Following their individual processing, both the TLS and the UAV derived data were exported in the standardized .e57 format. The two datasets were then imported into CloudCompare. Point clouds generated from the UAV data already incorporated coordinates in the GRS87 Greek grid, which facilitated the integration of coordinates for the second dataset derived from TLS. Alignment was achieved by manually marking at least four equivalent points across both datasets, followed by assessing the alignment quality through Root Mean Square (RMS) error measurements, and finally, conducting a fine registration of the data. Both point clouds were then unified within the identical coordinate system, and successfully merged into a single, comprehensive point cloud. The final merged point cloud was exported in various formats compatible with structural assessment software.

2.4 Results

The restoration of these churches in Samos represented a complex but vital undertaking to preserve both religious life and a significant part of Greece's cultural legacy in the aftermath of a devastating natural disaster. Our aim was to ensure stability and facilitate preservation with respect to each church’s specific characteristics. The resulting highly accurate and georeferenced 3D models, derived from the merged point clouds, serve as a foundational digital asset for the restoration project. This comprehensive 3D documentation enables detailed sketches, damage assessment, restoration planning and long-term monitoring.

Figure 4. 3D model of St. Nicholas Kokkari

Figure 5. 3D textured model of St. Nicholas Kokkari

Figure 6. Point cloud of St. Nicholas Kokkari

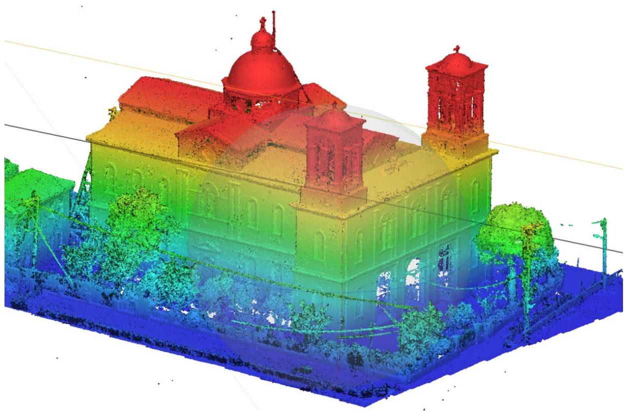

Figure 7. Point cloud with elevation of St. Nicholas Kokkari

High accuracy 2D architectural drawings, including detailed views, plans and sections, crucial for architectural and engineering analysis were extracted from these models. These rectified orthoimages allowed direct and precise measurements to be taken directly from orthofacades with high accuracy, making them an asset for their architectural documentation, and enabling vulnerability analyses, and construction monitoring. Each exported plan included scale and elevation information data which was derived from the UAV-based measurements, ensuring comprehensive dimensional fidelity.

Figure 8. Floor plan with scale bar in Saint John

The outputs were representative models (Figure 4), textured models (Figure 5), point clouds (Figure 6), elevation point clouds (Figure7) orthoimages (Figure8) and extracted architectural drawings from this endeavour.

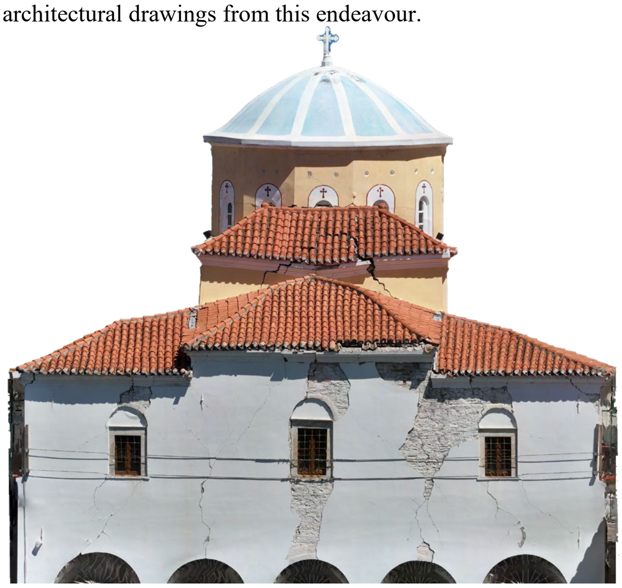

Figure 9. East View facade ortho-image depicting damages in Dormition of the Virgin Mary in Ano Bathy

The baseline 3D models serve as critical references for long-term monitoring of the monument's condition and the evaluation of restoration efforts. It consists of a thorough and quantifiable assessment of disaster-related damage.

For instance, in the case of Saint Nikolaos in Kokkari, documentation prior to structural interventions, such as the removal of one of the two bell towers allows subsequent reconstruction efforts to be carried on with a high degree of accuracy and authenticity (Figure 10).

Figure 10. Saint Nikolaos Kokkari (©Samos Voice Copyright 2024)

3. Structural assessment

The adopted methodology for the structural assessment is based on the modern Eurocode 8 - Part 3 and Greek Code for Interventions of Masonry Structures regulations (KADET) [1-4]. The first step for the investigation of the structural integrity of such structures is the development of a reliable and validated models. The above-mentioned 3D models were utilized, focusing on the geometry of the structural system and the structural details, to form finite element models, fig. 2. In these numerical models, stone or clay masonry structural members are represented by shell elements, while reinforced concrete, steel or wooden parts are represented as frame elements.

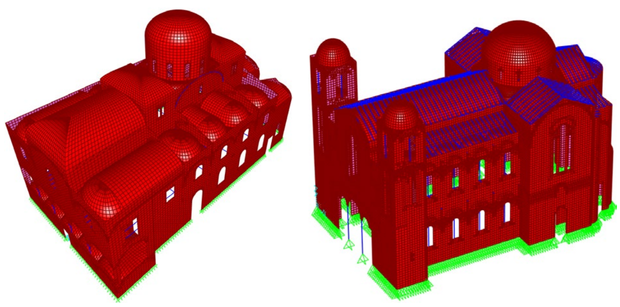

Figure 11. Numerical model of Dormition of the Virgin Mary (left) and St. Spyridon (right)

The structural system of the examined churches consists of load bearing clay masonry walls and stone masonry walls, with the thickness ranging between 30cm-40cm and 60cm-90cm respectively. Internally, two support zones are formed along the longitudinal axis of the church. These zones include columns and piers, defining the aisles of the church, and supporting the superstructure formed either by wooden roofs or vaults and domes.

The determination of the mechanical characteristics of the masonry elements is based on the compressive strength of the masonry units and the used mortar. The normalized compressive strength of the clay masonry units was measured at the Laboratory between 16MPa and 20MPa and that of the stone units between 45MPa and over 100MPa, figure 3. Subsequently, the mechanical characteristics of masonry walls are determined using analytical models adopted by KADET. The calculated compressive strength of stone or clay masonry elements is 1.0-2.0MPa and 4.0-5.0MPa respectively. The corresponding Young's Modulus was estimated 1.0GPa-1.50GPa and 2.0-3.0GPa.

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Figure 12. Compression test on a clay solid unit (left) and on a stone unit (right)

Numerical simulations begin with modal analysis, to define the dynamic characteristics of the system. Masonry structures, as the examined churches, exhibit great stiffness. Therefore, the dominant translational eigenmodes vary between 0.20sec-0.30sec for the longitudinal direction and 0.45sec-0.55sec for the transversal direction. These main eigenmodes activate over 70% of the structure's mass. Figure 4 depicts the deformed shape of dominant transversal eigen mode for St. John Chrysostom. In the same figure, EC8's Design Spectrum is shown together with the calculated Spectrum's of the Samos Earthquake main excitation. The design response spectrum of the Eurocode 8 is dependent on the Seismic Zone (ground acceleration 0.24g), the selected Performance Level (Significant Damage B1) and the behavior factor q, which was selected 1.5 for unreinforced masonry. As can be seen, within the period range of the transversal main eigenmode, the seismic demand of the Samos earthquake exceeds that proposed by EC8, which partly explains the severity of the observed damages.

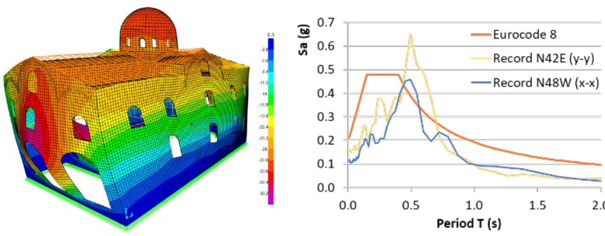

Figure 13. Dominant translational eigenmode in transversal direction (left) and the design Spectrum proposed by EC8 compared with the recording of Samos Earthquake in 2020

The developed models are validated, in terms of the observed damages, compared with the is situ observations after the catastrophic event on October 30, 2020. As shown in figure 5, they are capable to predict stress concentration, due to seismic actions, in the same locations, as the damage patterns of the existing structures.

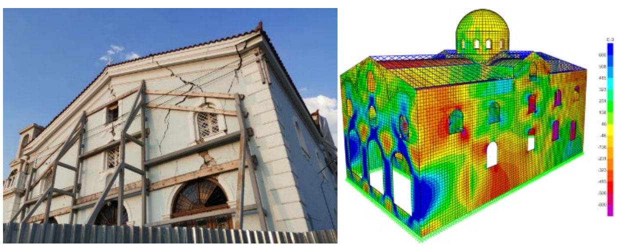

Figure 14. Dominant translational eigenmode in transversal direction (left) and the design Spectrum proposed by EC8 compared with the recording of Samos Earthquake in 2020

Based on the validated models, the investigation of the restoration and the structural upgrade is conducted. To ensure the structural integrity of the structures, the out of plane stability of the walls that form the facades is checked. This assessment is done in terms of inelastic displacements, compared with the regulatory limits for the selected Performance Level, regarding the out of plane rotation around a vertical and a horizontal axis.

Existing unstrengthen structures cannot resist the out of plane developed forces, leading to out of plane failure mechanisms. In order to mitigate this behavior, reinforced concrete beams are simulated, at the top of the masonry walls, together with the application of steel tie rods. These measures reduce the predicted deflections, under the permitted limits. Following, the in-plane response of the structural members is assessed. The load bearing capacity of piers and spandrels is calculated against flexure, sliding and diagonal compression and compared with the predicted demands. When the demand/capacity ratio exceeds 1.0, the structural member examined should be retrofitted. The strengthening methods focus on safety, compatibility, reversibility and minimal intervention.

4. Conclusions

3D models have the potential to function as instruments for emergency preparedness and response, thereby aiding in the prevention of future disasters, while concurrently providing accurate and detailed documentation. The disaster risk reduction efforts in Samos, which were implemented in the aftermath of the earthquake, exemplify a holistic approach to heritage management. This approach entailed the provision of immediate relief, stabilization, and recovery from the disaster, in addition to the implementation of strategic protection measures. The implementation of these measures was intended to enhance long-term resilience and to safeguard the irreplaceable cultural and spiritual significance of the historic churches in the area.

The presented methodology for the structural assessment of the examined churches includes the development of 3D numerical models, with accurate geometry and representation of their structural system. The numerical predictions are considered reliable, as the mechanical properties are derived by laboratory measurements and the predicted failures are compared with the actual damage patterns following the Samos Earthquake. The proposed strengthening solutions aim to upgrade the load bearing capacity of the structures after ensuring the out of plane stability of the walls forming the facades.

In conclusion, this paper exemplifies the indispensable role of advanced 3D documentation and interdisciplinary collaboration in the challenging context of post-disaster cultural heritage restoration. Such an approach enables informed decision-making for restoration interventions, thereby ensuring both the structural integrity and historical fidelity of the damaged heritage. In future, this work process may contribute to the critical engagement of both academic and non-academic stakeholders, fostering a comprehensive and effective response to safeguarding invaluable cultural assets.

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