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3D Modeling & Analysis Techniques for the Apollo Temple in Delphi

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Abstract: This paper demonstrates the application and usage of advanced 3D modeling techniques on monuments through the Apollo Temple in Delphi case study. Firstly, it combines 3D scanning and unmanned aerial vehicle (UAV) photogrammetry to produce an accurate 3D model of the monument, and afterward, it performs finite element modeling (FEM) analysis for both static and dynamic cases. Collapsing scenarios in the case of earthquakes are produced, predicting which parts would first collapse and under which regime the collapsing mechanism would be activated. From the results disclosed herein, the frequency profile of the seismic activity that could lead to resonance with the structure's dynamic characteristics, and therefore to excessive damages or collapse, was identified. Static structural analysis pinpoints that maximum stress exhibited on the columns' base never exceeds 0.1338 MPa. Among others, the main novelty of this paper is that it consists of an integrated and multidisciplinary paradigm that advances the available historical knowledge for a quite heavily investigated site.

Keywords: FEM; HBIM; Delphi

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1. Introduction

Heritage protection and adequate conservation are necessary to pass our historical values to the next generations [1]. Understanding these values enables several opportunities in different fields, such as education, economic revenue, understanding of history, community cohesion, and identity. Specifically in Greece, archaeological remains are vital to the local community and culture and play a key role in tourism attraction and economic revenue. For this reason, documenting, protecting, and preventing damage to this delicate heritage is essential.

Despite the foreseen growing interest in heritage building information modeling (HBIM) in the architectural and archaeological sector [1,2], even in Greece, which is notorious for its high seismic activity [3], most monumental structures still need to be documented in terms of state-of-the-art BIM possibilities. The reason for this exhibited "friction" in 3D modeling seems to relate to the fact that BIM and FEM implementations still entail high costs in terms of time, labor, and resources [1,4]. As stated by Autiero et al. [5], even though the study of certain structural multi-drum columns, typical in Greece and Italy, are of particular interest for understanding the seismic behavior of certain structural typologies in general, these elements require some highly sophisticated processing, as they exhibit non-linear and quite complex dynamic behavior [5].

On the other end of the spectrum, HBIM, with its inherent strength in data interoperability and dissemination [1,2], has led various researchers to develop new multidisciplinary and holistic approaches to diagnosis and assessment [4,6,7]. Asteris et al. [4] utilized 3D finite element analysis in masonry structures to predict the type and scale of damage under different seismic scenarios. Autiero et al. [5] focused on multi-drum free-standing grey-tuff columns and investigated how energy propagates through the vertical and longitudinal axis. Fabbrocino et al. [8] implemented FEM modeling in heavily eroded stone drums externally supported by metallic belts and investigated jacketing efficiency. Panagouli and Christodoulou [9] investigated the behavior of metallic dowels in 3D dynamic responses to mitigate the horizontal displacement of multi-drum columns. Pitilakis et al. ran a complex numerical analysis and compared model output with in situ observations [10]. In their analysis, the dynamic response of a multi-stone structure was compared to the response expected by a monolithic structure [10]. Stavroulaki et al. used terrestrial laser scanning to create a finite element model and carry out a strength evaluation of a masonry bridge [11]. Barbieri et al. [7] conducted a FEM analysis in a Baroque masonry church. They emphasized the importance of the geometrical survey, which, combined with a diagnostic tool, could provide better insight into the underlying mechanisms governing the static and dynamic behavior of the entire building.

Summing up, the consensus in the FEM community is that dry-stone structural elements are hard to model [2,3,5,12], since their seismic response relates to a variety of different factors, such as the assumed material [3,5,8,10], the type of interface/bonding between adjacent blocks [3,9,10,13], the sustained load from the epistyles, the slenderness [5], the number of blocks in total [3], the vibrational mode [5,6,12], the orientation of the ground motion [3,7,9], and the model assumed for meshing and solving the simulation, either linear or non-linear, within the FEM environment [4,6,7].

Following previous research outcomes, this research aims to demonstrate and validate a 3D model of the Apollo Temple that aligns with modern FEM prerequisites. This site is a unicum to international cultural heritage, represents a major typology of dry-stone structures, and can provide useful insights into FEM modeling. An additional side benefit of this paper is the enrichment of the available as-is knowledge of the monument, which could ease future maintenance and prevention works. As stated by Barbieri et al. [7], true safeguarding of an asset, within the notion of interdisciplinarity and interoperability, requires good historical documentation combined with a detailed representation of its geometry and an assessment tool, which, in this particular case, is realized through a discrete element methodology [7].

Delphi is an ancient archaeological site by Mount Olympus in Greece that is of crucial historical, cultural, and archaeological importance [14]. Therefore, documenting its condition and preventing damage from physical disasters such as earthquakes is pivotal, especially since Greece is an active seismic area.

This paper is organized as follows: It begins with a brief literature review on modeling techniques for HBIM and structural analysis, specifically focusing on current trends and advantages of HBIM application on heritage assets. Additionally, a few applications of HBIM for structural analysis purposes are analyzed. Then follows a historical introduction of the selected case study—the Apollo Temple in Delphi—its usage during antiquity, and its present condition, with a concise reference to the aims and objectives. Section 2 comprises the Materials and Methods, focusing on 3D laser scanner survey techniques, segmentation methods, and FEM procedures—all analyzed in a brief literature review. The chosen methods are presented and justified. The penultimate section refers to 3D model optimization for importing into commercial finite element modeling (FEM) software and testing under static and dynamic conditions. Finally, different collapsing scenarios in the case of earthquakes are estimated, predicting which parts would collapse first and which collapsing regime would be activated, depending on the frequency content of the expected earthquakes.

Advanced 3D modeling techniques presented herein, combining aerial and terrestrial apparatus, are used on the Apollo Temple in Delphi to produce an accurate 3D model of the monument that conforms with the latest heritage building information modeling (HBIM) requirements [1,6,15]. Mechanical properties of the associated materials are defined and justified based on their petrological origin. Last but not least, numerical modeling and finite element analysis are emphasized in the discussion and conclusion section, especially within the seismic vulnerability assessment, which is of great interest to other researchers [6,16].

1.1. 3D Modeling Techniques for HBIM and Structural Analysis

In recent years, 3D modeling techniques have been increasingly used in the built heritage sector. There are several advantages to using 3D modeling specifically for heritage buildings. These include but are not limited to [1]:

- Documentation of heritage buildings and artifacts for conservation and restoration purposes;
- Historical techniques and material studies;
- Building technique analysis;
- Digital reconstructions of destroyed or partially demolished buildings;
- Digital scenarios of reconstruction options
- Support of conservation, restoration, and strengthening studies
- Academic research;
- Archiving;
- Virtual tours;
- Tourism endorsement.

During the last few years, building information modeling (BIM) has started to be used in the heritage field [1]. BIM is a natural evolution of computer-aided design (CAD) [17], which can be considered "the use of computer systems for the creation, modification, analysis, and optimization of a design" [18].

BIM can be defined as a process [19] in which a building is digitally crafted, thus allowing it to be managed completely during different building phases (i.e., design, maintenance, etc.) [20]. Its power lies in the information it can hold, such as metadata, which makes it possible to summarize different building data types such as geometry, material properties, cost, and timeline—in one single file [20]. BIM was originally designed for new buildings. However, heritage is now within the scope of BIM [21] since several of its fundamentals could be extremely beneficial in the heritage sector, e.g., connecting virtual building elements to archival photos or texts [22], the ability to display different history timelines [23], producing tags/notes on elements that need ordinary/extraordinary maintenance or intervention [24], and depicting uncertainty [14], which are only some examples of this rapidly developing technology.

Additionally, BIM is a by-design tool for broadening process standardization in the architecture, engineering, and construction (AEC) field, a classic issue to be solved [1,25]. Maravelakis et al. [26], reflecting on the lack of standards in the 3D modeling industry, suggested alternatives for enabling full metadata documentation when digitizing heritage buildings.

Several researchers have been studying BIM and its application to heritage. One of the first pivotal works in this field is Murphy's historic building information modeling (HBIM) study [27], wherein the authors created a 17th-/18th-century classical European architecture-style parametric library. Similarly, Baik's work [23] focused on creating a Jeddah-specific parametric library, including construction techniques. Before these studies, several attempts to produce 3D models of heritage buildings and connect them to databases, such as Axaridou et al.'s work [28]. In these studies, the authors managed to create a 3D model and link it to a repository where it is possible to browse data [28]. Maravelakis et al. [29] applied these findings to 3D point clouds created by light detection and ranging (LiDAR) to produce a 3D web-based point cloud viewer.

Other researchers have focused on more technical matters—such as automation of the survey process [30,31], integration between BIM and other technologies such as finite element analysis (FEM) [32,33] or non-finite element analysis [33,34], geographic information system (GIS) [35], Internet of Things (IoT) [25,36,37] machine learning (ML) [38], and others, to cite a few examples; however, this list is far from exhaustive.

Regarding finite element analysis (FEM), in particular, the major premise is that static and dynamic structural behavior of the object under investigation can be accurately modeled, thus providing facility management agents and stakeholders with a unique tool for real-time monitoring in a non-invasive, non-distractive manner [15,39–43]. However, the inherent complexity of CH artifacts [1,15,40], strict legislation concerning archaeological uncertainty and standardization [43], and BIM's fundamental assumptions about regularity and homogeneity [1,40] require high-diligence cloud-to-FEM heuristics [15,39,41–44].

In this study, we used HBIM procedures and techniques to virtualize the Apollo Temple in Delphi, and within the model, we performed FEM analysis to test its structural stability. BIM in the heritage sector can have many benefits, including interoperability, ease of data access, and collaboration [20].

A survey is a constantly evolving field of investigation and heavily depends on the object's dimensions [45]. Traditionally, they included tape measurements, but nowadays, they encompass a plethora of instrumentation, from UAV drones [11,46] and terrestrial laser scanners to iPhones embedded with LiDAR scanners.

A survey classification system adopted by Barber et al. [45] includes three discrete methods listed below:

1. Topometric: These survey methods are traditional, usually based on the triangulation principle. They are typically applied to buildings of small dimensions since their accuracy is limited. The maximum accuracy is around 5–10 cm for a scale of 1:50.
2. Topographic: These methods are around 100 years old and are typically used for big buildings. The accuracy is around 1–1.5 cm for a scale of 1:50.
3. Photogrammetric: These methods are based on taking several photos of the building from predetermined positions and later stitching all of those pictures together. The resulting pictures are geo-referenced with high accuracy. Results can be visualized on coordinates and maps or directly on 3D models.
4. Laser scanner-based methods: Laser scanners capture both shape and texture. They operate quickly, are often contactless, and have high resolution and accuracy. Results are stored on a point cloud and can be processed to obtain 3D models. Laser scanners dominate the industry since they can scan practically anything, as long as it lies on their detection beam.

In summary, HBIM enriched with structural predictions like the ones coming from FEM analysis can be defined as structural-HBIM and can be used for strength and stability evaluations of the monument. Further steps could be introducing real-life measurements from structural health monitoring systems, adequate model adaptation, and updated predictions, leading to a heritage digital twin [37,47].

1.2. Historical Background

The Temple of Apollo at Delphi is located on Mount Parnassos in Central Greece and occupies a remote but central location relative to Greek settlements. The temple's heightened position on the mountain signifies the prominence of Apollo and the sanctuary itself (see Figure 1). It is an imposing temple of the Doric order whose existence is woven throughout the site's turbulent history and endured numerous incarnations before settling into the ruinous state we find today, dating back to the 4th c. B.C. [14].

Figure 1. The Apollo Temple in Delphi.

The temple was built in 330 B.C. by Spintharos from Corinth, Xenodoros, and Agathon, whereas Praxias and Androsthene created the decorations and sculptures. The building is a peristyle temple with six columns on the short side and 15 on the long side, and it is made of limestone [48]. The temple was the Delphic Sanctuary's principal building, with hosted gods, statues, and offerings. On its wall were engraved the words "Known thyself" and "Meden Agan," as well as the letter "E," which remains uninterpreted to date [49].

The Temple of Apollo's remnants exhibits six prominent Doric columns, with an additional two that have collapsed and are barely discernible. The lower section of the temple's capital, known as the crepidoma, comprises three distinct levels in a staircase-like arrangement. This configuration serves to separate the sanctuary from the surrounding ground and offers support to the vertical columns. The upper portion of the temple is absent, with only a single column retaining its capital out of the original six. Regarding the geometry of the columns, the columns are made from heavy stone blocks of porous stone and limestone [50] overlapped with mortarless connections. Today, the joints can easily be identified due to the severe environmental degradation of the porous material. The columns are about 10.60 m high and have a base diameter of 1.5 m, diminishing with height and forming a conical frustum. Each column is composed of multiple drums spanning about 77 cm each, thus allowing for a quick estimate of the height of each column in the scene. The diameter at the base of each column is computed to be 1.5 m, yielding a height-to-diameter ratio (slenderness) of 7.0. The diameter then diminishes to approximately 40 cm at the top. The crepidoma spans 58.18 m in length and 21.64 m in width and consists of monolithic stones [50].

1.3. Research Aims and Objectives

The aim of this work is twofold: to produce and validate a 3D model of the Apollo Temple that complies with state-of-the-art finite element analysis standards and to further elicit the available scientific knowledge regarding a site of utmost importance to the heritage sector. The Temple of Apollo at Delphi has gained much attention in the past. Liritzis et al. used specimens from this site to test the validity of thermoluminescence as a methodology for dating edifices of antiquity [51]. In a different approach, 3D modeling was deployed as an auxiliary tool for demonstrating lighting regimes throughout the year inside the temple [52]. More recently, the origin and composition of the stones used in the Apollo Temple have also been exhaustively investigated to shed some light on how ancient Greeks chose their resources [50]. The available documentation regarding this particular site [50–52], combined with the most recent advances in mesh segmentation that now reaches stone-level accuracy [53] and FEM modeling [39], has now allowed for a plethora of new possibilities that could significantly benefit the heritage and conservation sector. To this end, this paper seeks to enrich experts' knowledge regarding this monument and demonstrate FEM's potential in seismic vulnerability [6] and damage assessment in a multidisciplinary and integrated manner [7].

Last but not least, FEM modeling entails some rigorous [2] complexity, which could jeopardize HBIM modeling in the first place [1]. Another novelty of this paper is that it was conducted with another work that targeted mesh segmentation automation for FEM applications [44]. Therefore, the results disclosed herein could provide a reference for validating the automated decimation performance under different structural analysis techniques, and, finally, recommendations and good practices for archaeology can be derived.

2. Materials and Methods

2.1. 3D Scanning

One of the first steps in heritage conservation is surveying the artifact [1,15]. In order to obtain a geometrically accurate 3D model of the Apollo Temple with realistic textures, terrestrial 3D laser scanning, and aerial photogrammetry were combined [14]. Specifically, the deployed instrumentation comprised a Faro X130 3D scanner and a Phantom Four RTK UAV, which captured 930 high-resolution images in total [14]. These data-fusion techniques produce point cloud data with remarkable speed and accuracy but require [54] quite delicate post-processing (Allen et al., 2003). Dense-image matching was utilized via the Reality Capture commercial package. Then, in the last step, a high-resolution TLS-generated point cloud was merged with a high-definition mesh from Reality Capture to produce the final model of the Temple of Apollo (see Figure 2) [14].

2.2. 3D Modeling for FEM Analysis

Three-dimensional modeling and stone-by-stone segmentation from point clouds can be performed in several ways, which have been extensively researched [1,44,53]. State-of-the-art approaches nowadays range from semi-automating recurrent label transmission using object-oriented programming integrated with commercial BIM architectural packages [55] to deep learning semantization utilizing either well-established methods in the field of computer vision, convolutional neural networks [53,56,57], or high-efficiency voxel-based feature engineering [58].

Semantic segmentation, as per architectural, engineering, construction, and facility management requirements [59], remains an open subject with no one-size-fits-all resolution yet [57]. It extends beyond the scope of this manuscript, but current literature reveals that most researchers now consolidate towards a common pipeline for converting existing CH monuments to FEM-compatible configurations [15,39–43,60,61]. Scan-to-FEM workflows, with some slight variations [41,44], are initiated from the 3D texturing of the asset, also known as the digital twin [37], then render a dense point cloud [41], and either re-mesh directly for FEM or transit from BIM to FEM [32].

Once the point cloud optimization process is finalized, the meshing algorithm can accurately rewrap the functional and structural properties of the modeled entity [60]. To date, this high-fidelity and high-resolution mesh is only meant for rendering and visualization and cannot be directly imported into most modern FEM packages [15]. FEM-compliant mesh must be a non-manifold rigid solid with no overlapping surfaces, self-intersections, or open faces/edges [6,32]. This mesh incompatibility issue is a rather common pitfall in the FEM community and, if not treated carefully, results in a fragmentation of too many intermediate steps, data formats, and third-party plugins or software [15,39,42].

Figure 2. 3D mesh model of the Apollo Temple in Delphi.

In the case of simple and regular shapes, a common method for mesh simplification, inclined to FEM applications, is the use of 2D drawings for extruding the 3D model geometry [3,6–9]. Of course, these polygon reduction schemes will always infer a representation accuracy drop, which is, to some extent, anticipated in FEM modeling. On the other hand, most sophisticated state-of-the-art implementations entail machine learning and even deep learning for class recognition and primitive extraction [62] that reach the stone level [53,57,59]. Contemporary research focuses on a shape-agnostic point cloud-driven segmentation [63] that facilitates primitive extraction, thus allowing for more comprehensive analysis, such as [59,64] or DEM [12].

For the Apollo case study, the high-resolution SfM-rendered model established the ground truth for the CAD 2D-to-3D conversion. The temple was decomposed into sections, and different layers were assigned to each floor. The bedrock supporting the naos crepidoma was also considered a multi-block structure, and the ramp was considered a different part of the structure. Multi-drum dry-stone columns were created using the Loft command within the AutoCAD environment. For the sake of simplicity, the drums were set to be concentric, and no gaps were assigned between each block.

The methods used to model the basement are fairly standard and include the following:

- Increase point cloud density, adjusting the Level-of-Detail and the Point Size commands—this step is crucial since it affects the visibility of the point cloud and, therefore, the denser the points, the more precise the modeling.
- Drawing on floorplans, using the Polyline command to trace building elements on the horizontal plane and extruding the volumes along the Z-axis.
- Particular attention was paid to eliminating voids since FEM analysis expects watertight meshes, and there could be no gaps between the blocks of the dry-stone columns. The resulting simplified CAD-crafted 3D model (see Figures 3 and 4), devoid of its high LoD, could then be imported to FEM packages [10].

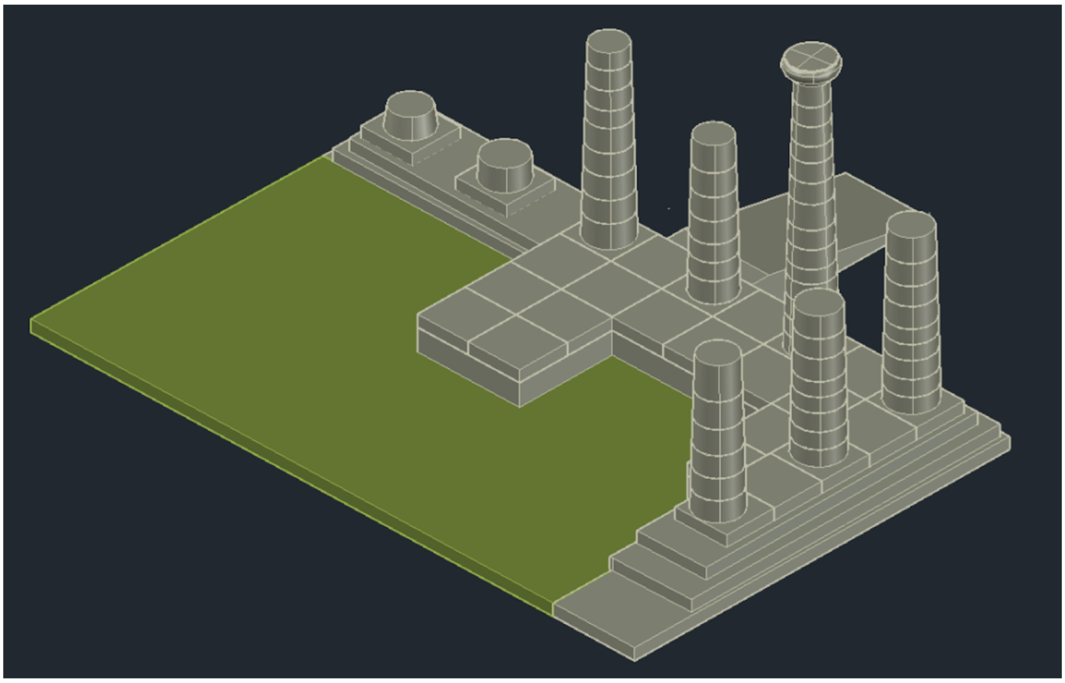

Figure 3. CAD model with stone-by-stone segmentation.

Figure 4. Comparison of CAD model with initial 3D point cloud.

2.3. FEM Analysis

FEM entails three domains: energy methods, approximation theory, and CAD. FEM assumes that all building elements (called finite elements) are spatially constrained (i.e., finite) and perfectly aligned to each other; between those, there are junctions called nodes. This method helps simplify more complex problems to several easier ones—which can be easily solved using automatic calculators such as specific software.

In this case study, ANSYS v. 17.0 FEM was used, which is organized as follows:

- Phase 1: problem definition—we chose structural analysis to solve static problems, whereas modal analysis was used to perform dynamic analysis;
- Phase 2: geometry input;
- Phase 3: material definition;
- Phase 4: mesh creation;
- Phase 5: input of active loads and bearing structure;
- Phase 6: resolution;
- Phase 7: presentation of results.

2.3.1. Material Definition

The Apollo Temple, which consists of six columns, each composed of multiple blocks in a dry-stone formation standing on the inner part of the cella (see Figure 5), is made of limestone transported from the nearby quarry of Profitis Ilias, about 5 km from the temple [50]. The mechanical properties of the model were selected according to the petrological findings in the available literature [5,10], and the values adopted are as follows:

$$E = 40 \text{ GPa} \tag{1}$$

$$\nu = 0.20 \tag{2}$$

$$p = 2.7 \text{ ton/m}^3 \tag{3}$$

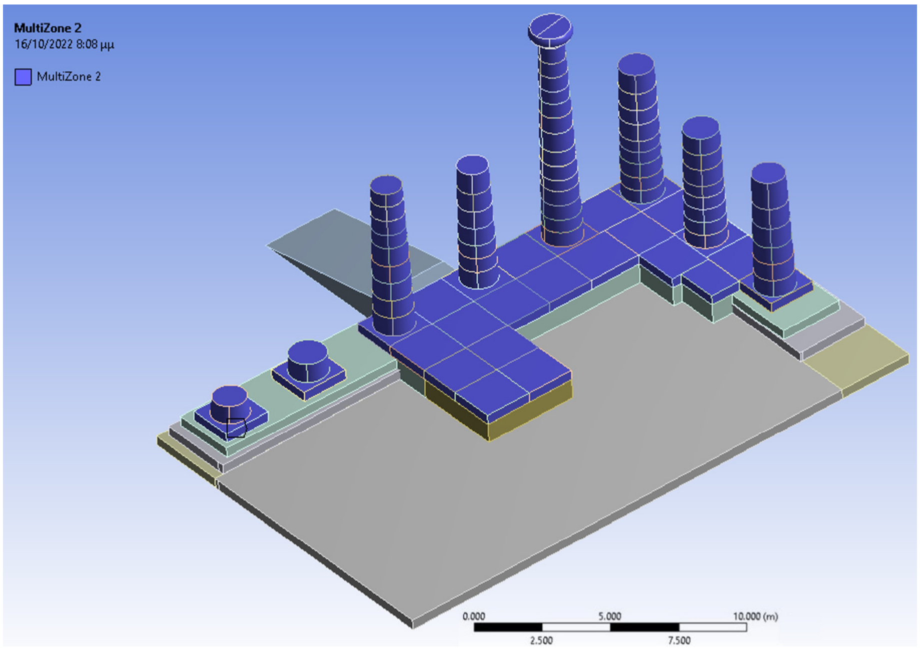

Figure 5. Manually traced AutoCAD model depicting the final configuration of the Apollo Temple.

Elastic modulus (Equation (1)), Poisson ratio (Equation (2)), and material density (Equation (3)) matched Panagouli and Christodoulou's assumptions [9]. The assumed values were carefully selected to coincide with most of those assigned by other researchers investigating similar structural typologies with FEM [3,5,9,10,12].

2.3.2. Meshing

As soon as the CAD model was ready, water-tightening of the model was carried out with the MultiZone command, which resulted in a total of 84 rigid bodies, 13,148 elements, and 80,263 nodes. This method eliminates gaps between discrete bodies and ensures perfect alignment (see Figures 3 and 4). Finally, mesh retopology was utilized by invoking the Hex Dominate Method function, which is embedded in Ansys and iteratively converts polygon mesh to a solid tetrahedron mesh. Here another constraint was added to limit each element to 400 mm.

The mechanical behavior was approximated at each node using the displacement of the structure's degrees of freedom (DOF). In general, the higher the number of elements, the better the accuracy of the textured geometry [20]. Nonetheless, the overwhelming complexity of these faithful models may jeopardize the rest of the processing [32]. In this case, an acceptable compromise was found, and the final mesh comprised 13,148 elements and 80,263 nodes.

The mesh model comprised 84 parts (called bodies), which were interconnected thanks to ANSYS's Automatic Connection command.

However, the Hex Dominate Method utilized in order to recombine tetrahedra into hexahedra for generating high-quality meshes suitable for finite element calculations [65] was applied in the parts where MultiZone failed to converge, such as the elements on the top of the column. Therefore, retopology finally consumed the mesh, resulting in volumes similar to cubes.

3. Results

FEM was performed on both static and dynamic conditions. Specifically, we sought distribution and displacement information for static stress, whereas for dynamic conditions, vibration information and, specifically, eigenmodes and eigenvalues, were calculated.

FEM analysis yielded interesting results regarding stress distribution on the temple in static conditions. As expected, the maximum stress values were found at the bases of the columns, whereas the maximum displacements were identified on top of the columns (Figure 6).

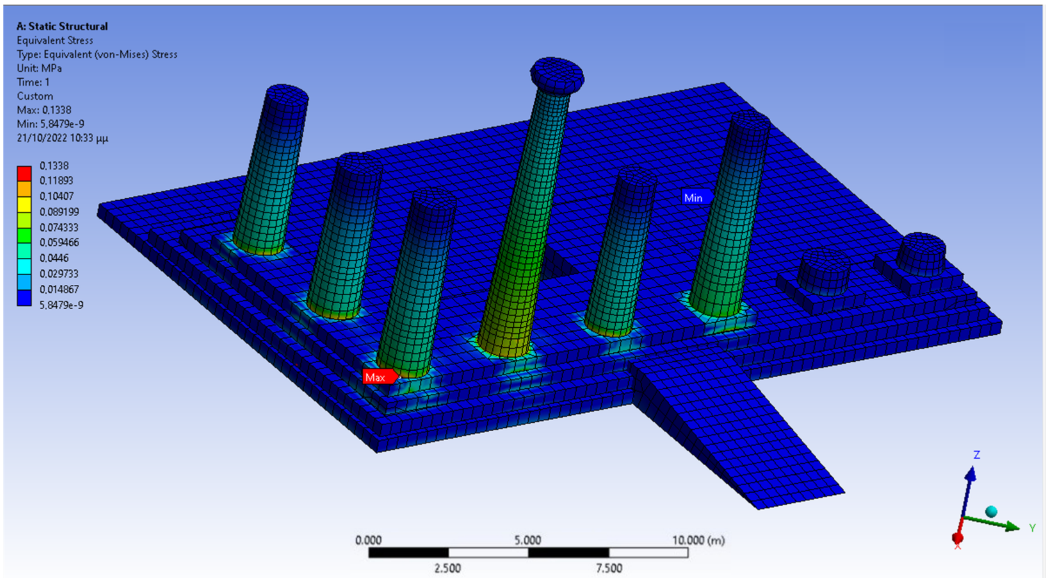

Figure 6. Static structural analysis—equivalent stress.

Regarding dynamics, vibration information was sought. It is pivotal to have vibration information—specifically, eigenmodes and eigenvalues—especially for seismic protection to avoid resonance between seismic input and the structure's dynamic characteristics. In this case, catastrophic results, extensive damage, and even collapse are expected.

For the Delphi case study, these vibrations were calculated. Since different columns have different sizes and consequently, different eigenvalues, a given earthquake may affect some of them and leave other without any vibrations.

Modal analysis (see Figures 7–14) highlighted different behaviors for different frequencies. Specifically, eight different frequencies were calculated on the same column.

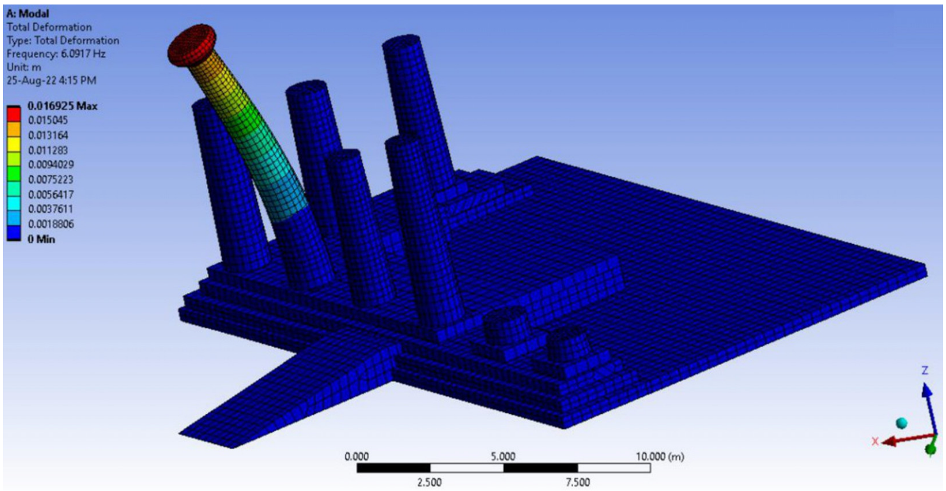

Figure 7. First vibration mode, 6.0917 Hz.

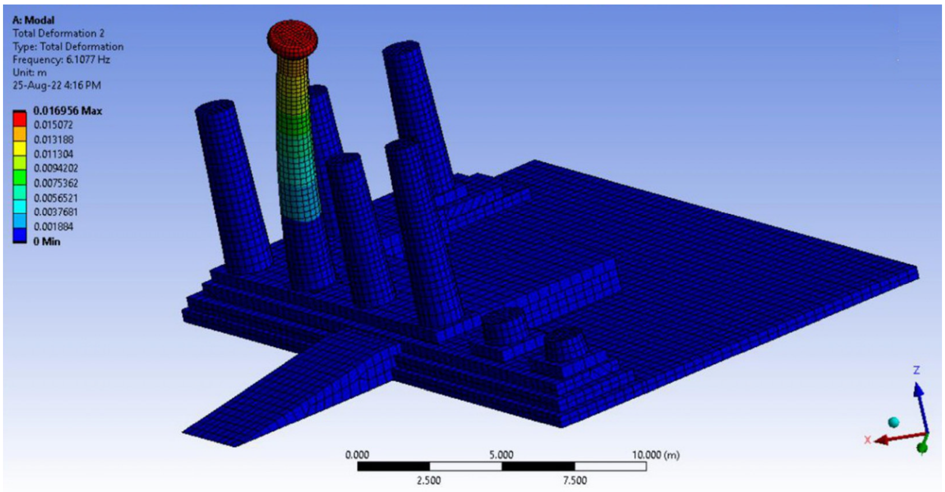

Figure 8. Second vibration mode, 6.1077 Hz.

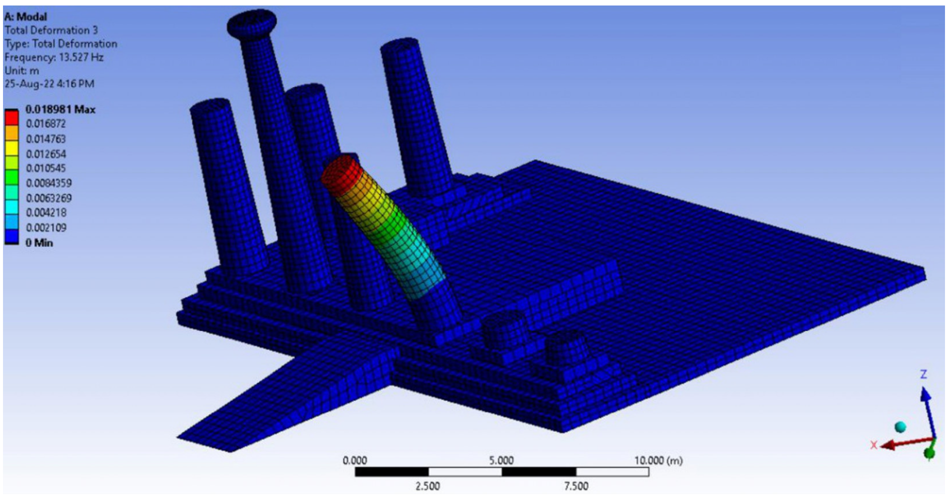

Figure 9. Third vibration mode, 13.527 Hz.

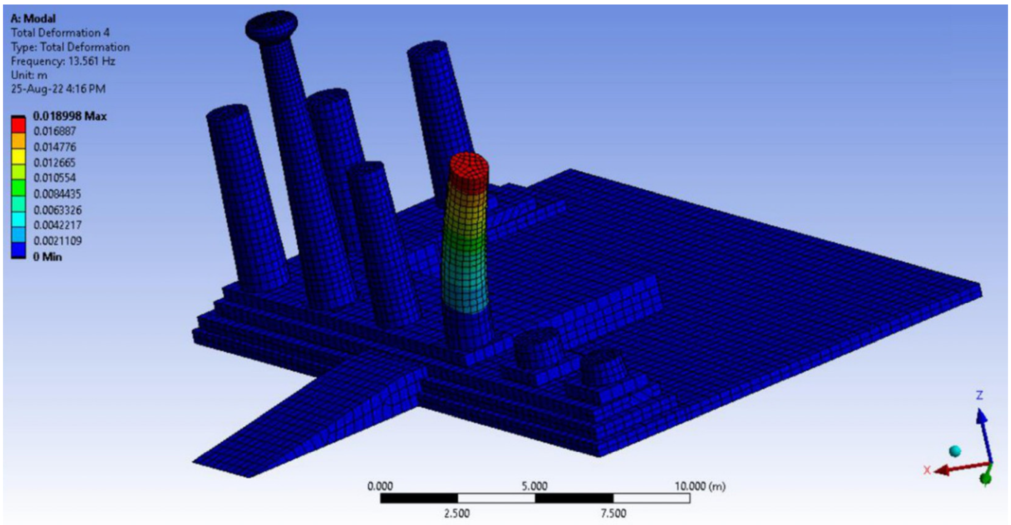

Figure 10. Fourth vibration mode, 13.561 Hz.

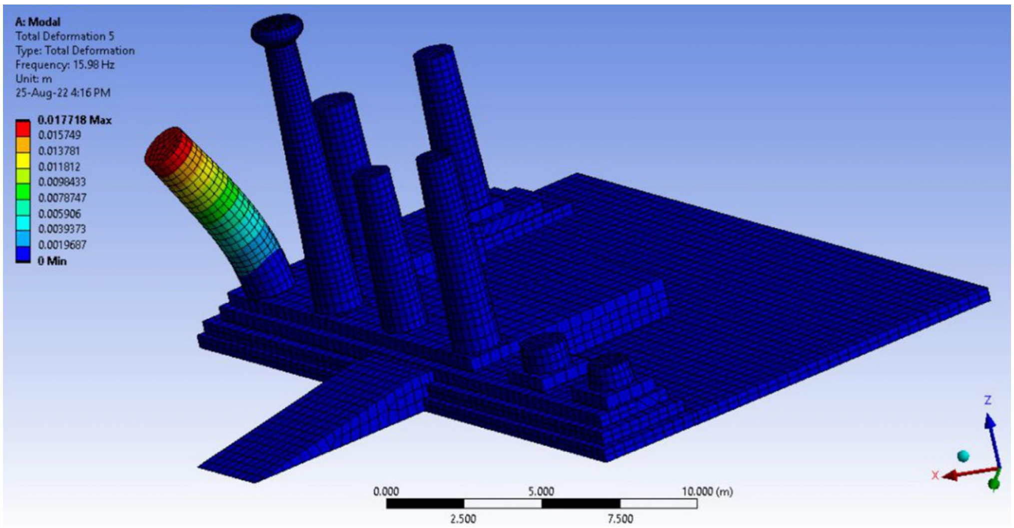

Figure 11. Fifth vibration mode, 15.98 Hz.

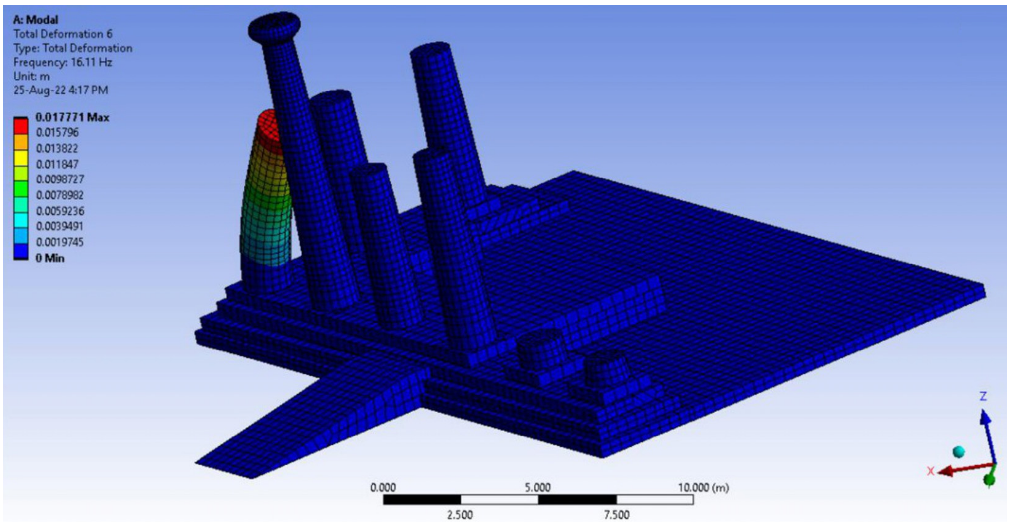

Figure 12. Sixth vibration mode, 16.11 Hz.

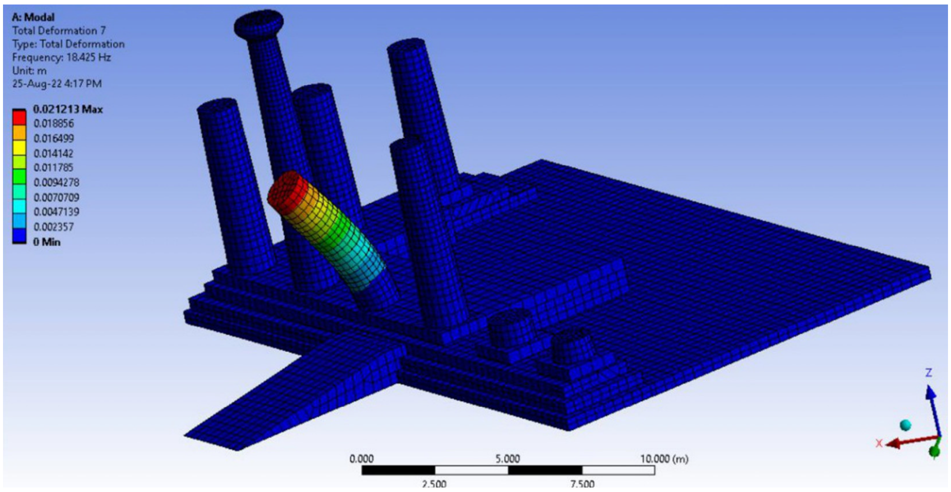

Figure 13. Seventh vibration mode, 18.425 Hz.

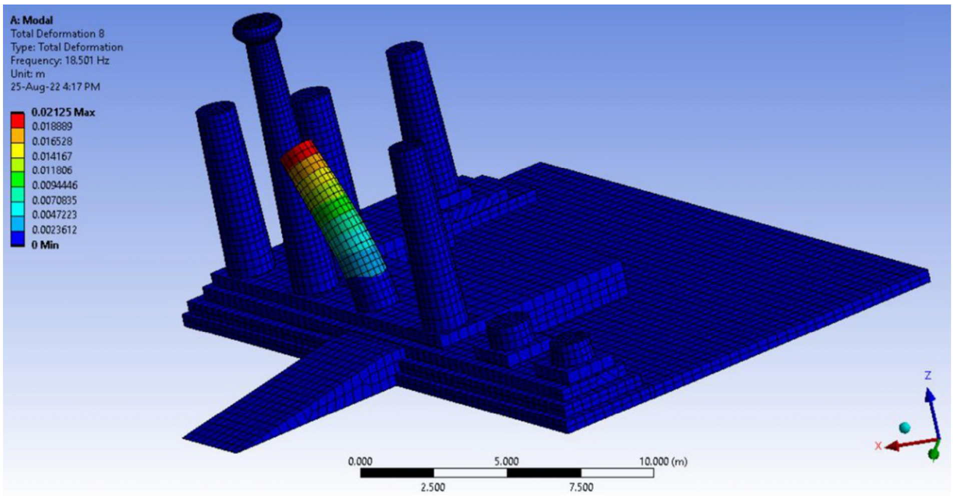

Figure 14. Eighth vibration mode, 18.501Hz.

Modal analysis is critical to avoiding catastrophic consequences; additionally, it can support further dynamic analysis, such as response spectrum analysis and time-step modeling.

4. Discussion and Conclusions

This study focused on modeling methods and FEM analysis for cultural heritage, using the Apollo Temple in Delphi as a case study. Based on the presented findings, the following conclusions and recommendations can be drawn:

1. Modeling on point clouds has significant positive effects on precision, accuracy, and time compared to more traditional methods;
2. A balance between representation accuracy and computational speed was pursued, and the results proved to be acceptable;
3. During FEM analysis, using software commands (herein, ANSYS) was extremely beneficial, as voids were avoided and analysis could be properly performed;
4. Stress analysis for static loading produced results as expected and was used for the final check of the model;
5. Dynamic analysis demonstrated the vulnerability against earthquakes and the prevalence of horizontal vibration modes, as analyzed with eight modes;
6. Advance computational tools equipped with predictive non-linear dynamic analyses are essential for the seismic vulnerability of complex structural typologies [66].

Finite element analyses have been extensively used to model multi-drum free-standing columns, typical representatives of ancient Greek antiquity [3,5,9,10]. To date, complexity in the scan-to-BIM reversed engineering workflow still undermines HBIM and FEM integration in various applications [1,2]. However, structural analysis is a critical part of asset management and can provide useful insights to improve the maintenance and restoration of these indispensable assets in an integrated and multidisciplinary fashion [4,6,7]. Future work could thoroughly compare the FEM results disclosed here against those from a fully automated mesh segmentation algorithm [44]. As mentioned, another novelty of this research paper is the ongoing multidisciplinary approach for scan-to-FEM automation, for which some promising results regarding colonnades have already been published. Another future consideration is a non-linear analysis, which is expected in this kind of structural typology [4,5,7,10] and should be regarded as the most robust tool for seismic vulnerability analysis of global models [66]. Last but not least, the importance of linear and, non-linear analysis of block-type masonry structures should be emphasized. The BIM-to-FEM methods developed within this work provide more accurate models that facilitate this task [33,66]. Future research will be focused on this topic.

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