Structural and Material Identification of Historic Monuments through AI-based Photogrammetry and Ambient Vibration Testing

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ABSTRACT In practice, assessing the structural integrity of existing structures with complex forms poses a challenge. Although photogrammetry has gained increasing recognition as a versatile and cost-effective technique for obtaining numerical three-dimensional models, it still presents some difficulties in converting the scanned models into exploitable finite element models. This paper specifically focuses on developing a suitable, reliable, and effective procedure for converting images into numerical three-dimensional models for use in the evaluation and assessment of structures. It presents a framework for the structural and material characterization of historic elements with a combined approach using ambient vibration testing. For this purpose, three elements of increasing complexity in a historic site are 3D scanned, converted to finite element models, and updated using experimentally determined natural frequencies. Relying on the shape accuracy obtained by the photogrammetry scans, a genetic algorithm is used to identify the elastic modulus and mass density of the material for the best match of the experimental and numerical frequencies. The integration of photogrammetry, AVT, and AI-based optimization genetic algorithms in this framework provides a robust and reliable approach for characterizing and investigating historic monuments.

Keywords Photogrammetry, Ambient vibration testing, Structural identification, Historic monuments, Genetic algorithm

I. INTRODUCTION

Cultural and historic heritage is generally constituted of a wide variety of elements that vary in size, shape, and material. The management and preservation of such monuments especially in seismic prone regions is of paramount importance, requiring the characterization of material properties and the construction of accurate finite element models for structural assessment and health monitoring. Various techniques, including photogrammetry, laser scanning, ground-penetrating radar, and other methods, are widely employed to generate 3D geometric models that can be converted into finite element models. In 2016, Barrile et al. employed a low-cost technology in which handheld digital cameras were used to create 3D models of historical edifices. Archaeological monuments' remains in Peru were structurally investigated through in-situ non-destructive testing in conjunction with numerical analysis (Aguilar et al. 2015). Other researchers employed a combination of operational modal analysis, laser scanning, and photogrammetry to validate advanced numerical models for historical buildings and multi-body megalithic stones. (Motsa et al. 2020, Sánchez-Aparicio et al. 2014, Diz-Mellado et al. 2021, Korumaz et al. 2017). Recently, Machete et al. (2023), developed an IoT BIM-based solution for real-time monitoring of the central body of a historic palace within the context of structural health monitoring. In line with this current trend of research, the present paper introduces a framework that combines photogrammetry surveying, ambient vibration testing, and artificial intelligence techniques to determine the material properties and modal characteristics of three archaeological elements with increasing complexity, aiming to cross-check the obtained results.

II. DESCRIPTION OF THE ARCHAEOLOGICAL SITE AND THE HISTORIC ELEMENTS

The Tipaza historical site in Algeria, a UNESCO World Heritage Site, preserves the remains of civilizations from the 6th century BC to the 6th century AD, including the Phoenicians, Romans, early Christians, and Byzantines. It spans approximately 60 hectares and comprises two archaeological parks and the Royal Mauritanian Mausoleum. The site features various structures such as an amphitheater, temples, a forum, a basilica, baths, and mosaic artworks, showcasing the innovative use of materials like stone, mortar, mosaic, marble, and wood. This offers insights into ancient construction techniques and design ingenuity. The site has been selected for a study focusing on three architectural elements as shown in Fig. 1:

Column element: The selected column for analysis in this study is characterized by being fixed at its base and possesses a height of 1.35 m. The column's section, is not uniform and measured at a specific height, dimensions of 0.55 m by 0.59 m. This configuration highlights the column's structural stability and integrity, with the fixed base providing a solid foundation. Notably, the column features multiple openings, suggesting the presence of voids within its structure.

Wall element: The chosen wall for analysis in this study is 3.20 m in height. The dimensions of the wall section are 0.45 m in width and 1.50 m in height. It is constructed using some kind of stone and ruble masonry. However, upon examination, it is evident that the wall has experienced significant deterioration. Crumbling sections, and missing portions are notable features of the damaged wall.

Arches: This element is a relatively simple architectural structure composed of four interconnected arches. With a maximum height of 3.50 m and a length of 13 m, the arches command attention within the site. The damaged wall, measuring 5.50 m at its base, provides stability and reinforces the structure. Despite the damaged wall, the arches retain their shape and visual impact.

FIGURE 1. The three chosen structures from the Tipaza (Algeria) archeological site

III. PHOTOGRAMMETRIC SCANNING PROCESS

Generating a 3D model via photogrammetry requires a sizeable collection of accurately captured images depicting the entire target object from fixed distances and consistent angles and with enough overlap (Fig. 2). Repeating this process at multiple distances enhances the dataset's coverage and detail. The specimens were well spaced, allowing us to follow a meticulous procedure to extract as many details as possible from the objects. Numerous photos were taken per object at various angles and elevations, adjusting the camera settings to match the lighting across the entire dataset. Datasets comprising 49 images for the column, 279 images for the wall, and 476 images for the arches were captured and used in the alignment process. These figures achieved an overlap between 60% and 80% for distances ranging from 1m to 10m and average angles of 20° to 30°.

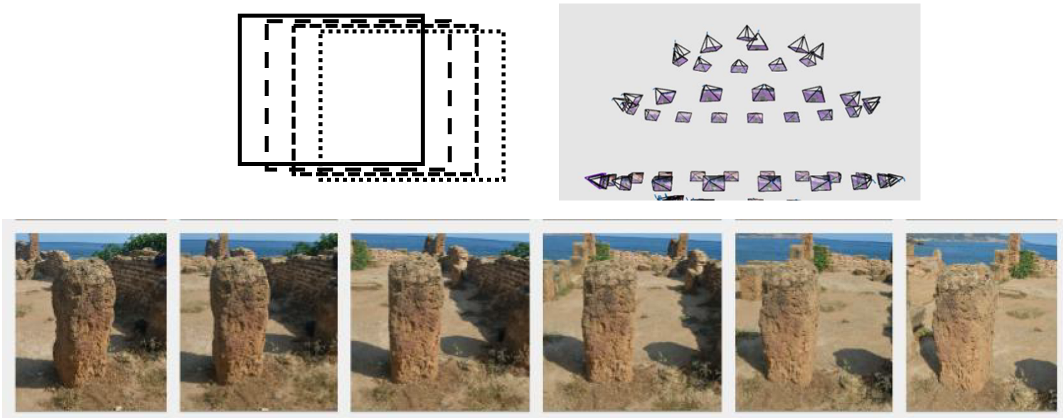


FIGURE 2. **Images overlap and different photography angles**

Image alignment in photogrammetry is the process of aligning multiple images of an object or scene in a common coordinate system. It involves identifying common features in the images and using mathematical algorithms to calculate the necessary geometric transformations. In our case we only used automatic alignment of images in RealityCapture (Reality Capture, 2023) as our photo acquisition was mostly good, but manual intervention must be expected in case of poor data collection or the impossibility of redoing the photography.

FIGURE. 3 **The reconstructed raw model from RealityCapture**

After performing the model calculations and the mesh generation in RealityCapture and exporting the model in the appropriate format (OBJ), it is imported into Houdini (SideFX, 2023). The first processing step involves reducing the polygon count of the mesh, obtained from RealityCapture, to make it suitable for rendering in the Houdini viewport. This is accomplished using the **PolyReduce** node, which allows for the specification of a percentage of polygons to retain in relation to the original count. Photogrammetry may introduce imperfections in the generated mesh, not reflective of the actual object, attributable to factors like inadequate lighting or missing capturing angles, unwanted objects, such as supports or, in the case discussed, the ground, may also be attached to the mesh and need to be eliminated during the processing stage. Performing Boolean operations and cutting on the geometry leaves the model with some gaps and openings that need to be closed in order to create a water-tight mesh. The last step of the processing is to smooth the mesh to eliminate unwanted noise, for that several techniques can be used from direct smoothing which can offer good results, to curvature-based smoothing which is better for regular shapes as it retains the object's features. The scale of the object must be identical to the real version so the analysis can be regarded as accurate, a calibration is then required and to do so only one measurement has to be extracted and injected into the digital version and scaled uniformly. Example of processing the arches is shown in Fig.4.

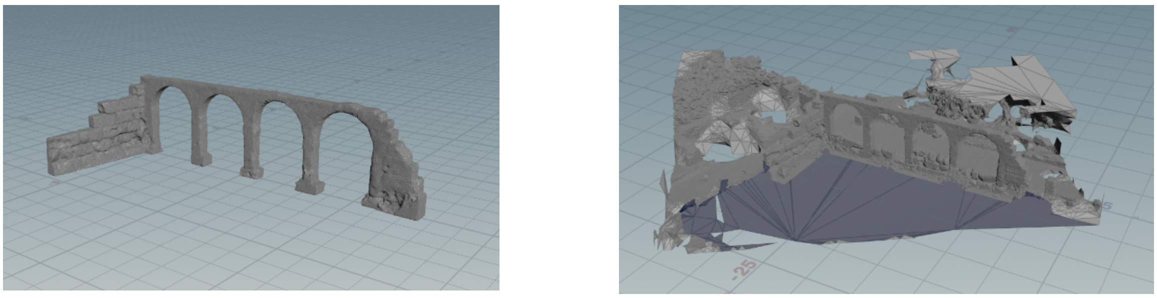


FIGURE 4. **The arches model before (right) and after (left) processing and calibration**

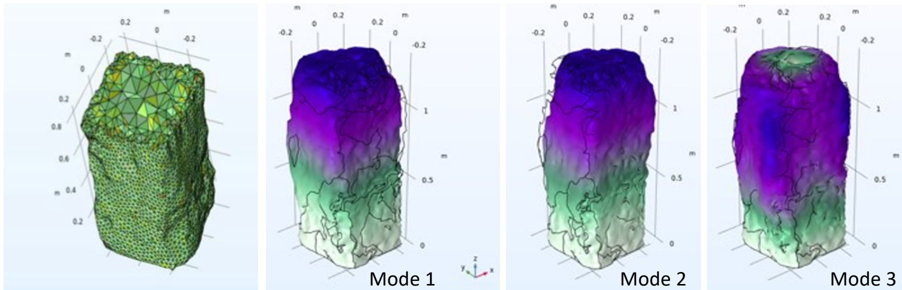
IV. FINITE ELEMENT MODELS GENERATION

After processing, calibrating and exporting the model from Houdini as an stl file, it gets imported into the FE software COMSOL (2012) Multiphysics for analysis, so after creating a 3d component and choosing the solid mechanics physics type, we imported the model from the geometry section.

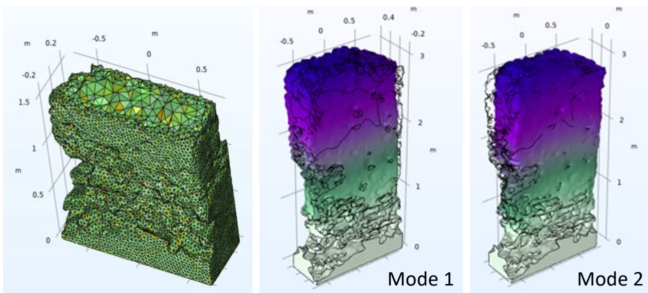
In order to address geometric modifications within COMSOL, it becomes necessary to disregard the existing mesh from Houdini. Consequently, a new surface mesh must be generated within the Mesh section of the component. The **Free Triangular** tool is employed to construct an adaptive triangular mesh featuring a non-uniform distribution. Subsequently, the **Adapt** option is executed to achieve a uniform distribution. To mitigate singularities, the element size can be adjusted, thereby facilitating control over the quantity of generated elements.

The volume mesh is then created based on the surface one with Free Tetrahedral tool. The mesh is composed of adjustable tetrahedral elements with a size node. The volume mesh can then be visualized with a mesh plot and an element filter to inspect it further. At this stage the FE model is ready for further processing, such as imposing boundary conditions, material properties, loading assignment etc.

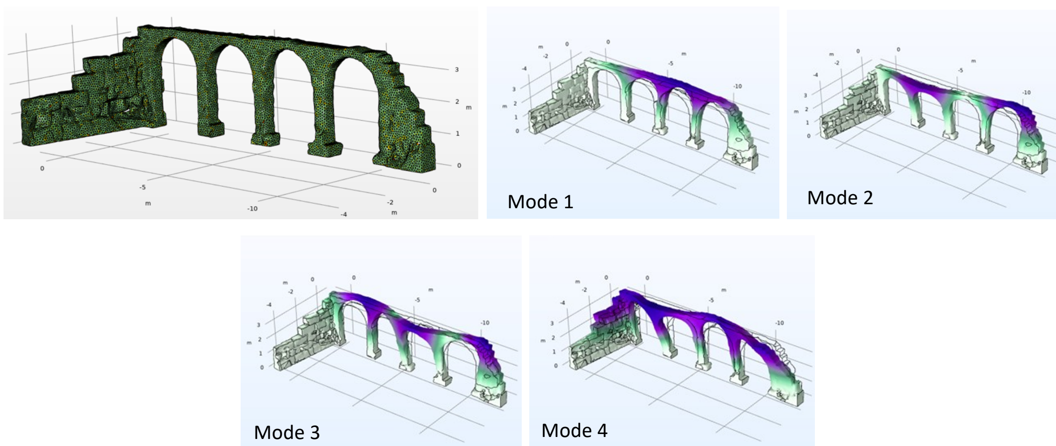
The generated column mesh had 50310 tetrahedral elements and 238302 DoFs, the generated wall mesh had 126283 tetrahedral elements and 599025 DoFs and he generated arches mesh had 107929 tetrahedral elements and 533151 DoFs. The three models will be used in the matching procedure using the genetic algorithm to identify the material properties of the specimens. Preliminary modal analyses were carried out to determine the mode shapes of the specimen (Fig. 5) which will help in optimizing the placement of the sensors for ambient vibration testing.



(a) Column element



(b) Wall element



(c) Arches

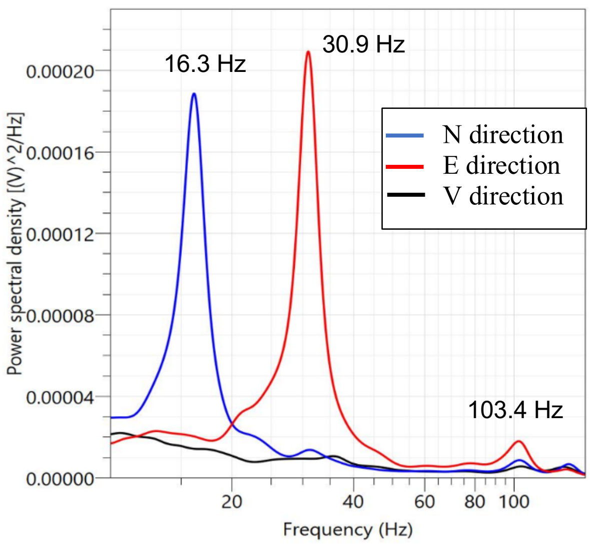
FIGURE 5. Final tetrahedral meshes in COMSOL with preliminary mode shapes

V. AMBIENT VIBRATION TESTING

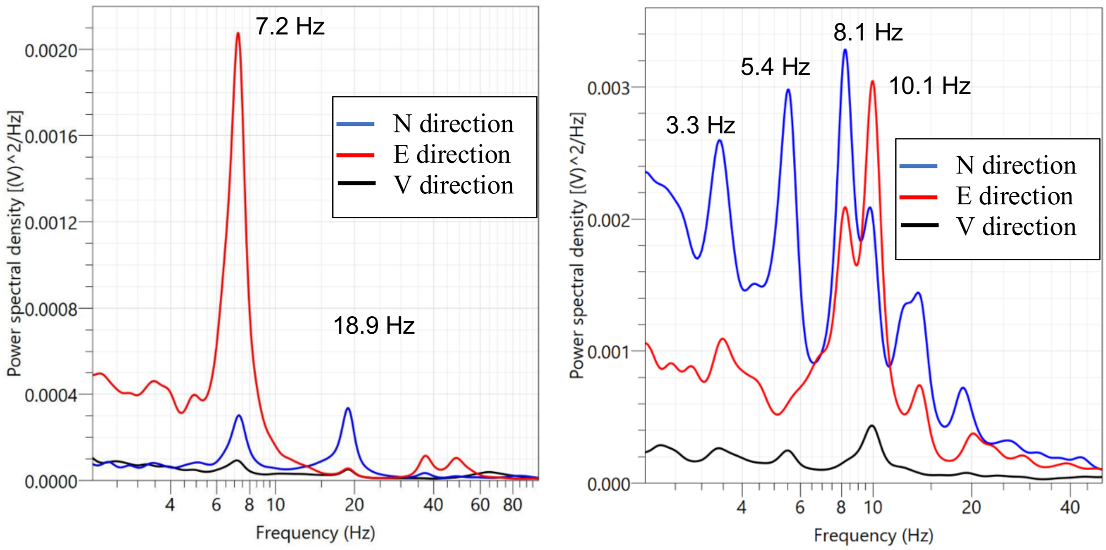
To conduct the AVT test effectively, it is crucial to strategically place the sensors at the measurement points that capture the predominant modes of vibration and align them with the expected direction of dominant vibration signals (Bourahla et al. 2022). In this study, where the structures are simple, the sensors were placed on the top of each structure and oriented to capture the desired horizontal and vertical directions as shown in (Fig. 6).

FIGURE 5. Sensor placement on the structures

The City Shark II data acquisition system was used in conjunction with a three-degree-of-freedom sensor (seismometer) type Lennartz electronic (Le3Dlite), for conducting the AVT survey. The recorded data were processed using the GEOPSY software (Wathelet et al., 2020). Given the specimens' relative rigidity, a 4-minute recording at a 250 Hz sampling rate proved sufficient to generate smooth FRF curves (Fig. 6). Challenges, such as strong winds during recordings, were effectively addressed to maintain reliable and accurate data while minimizing disturbances. The frequencies were identified using the "Peak Picking" method.



(a) Column FRF curves



(b) Wall FRF curves (c) Arches FRF curves

FIGURE 6. The measured FRF curves of the (a) column, (b) the wall and (c) the arches

VI. MODEL MATCHING AND MATERIAL PROPERTIES IDENTIFICATION

The application of photogrammetry enables the creation of highly accurate geometric 3D models, subsequently converted into finite element (FE) models. The second phase involves AVT testing, producing smooth frequency response function (FRF) curves with several pics corresponding to the natural frequencies of the tested specimens. The final stage in the proposed framework involves aligning the numerical modal characteristics with the experimental data. This alignment is achieved using a genetic algorithm to evaluate unknown structural parameters through an optimization process aimed at minimizing the error between observed data and numerical predictions. In this case, two key properties influencing the frequencies, namely Young's modulus and density, were selected for prediction (Fig. 7).

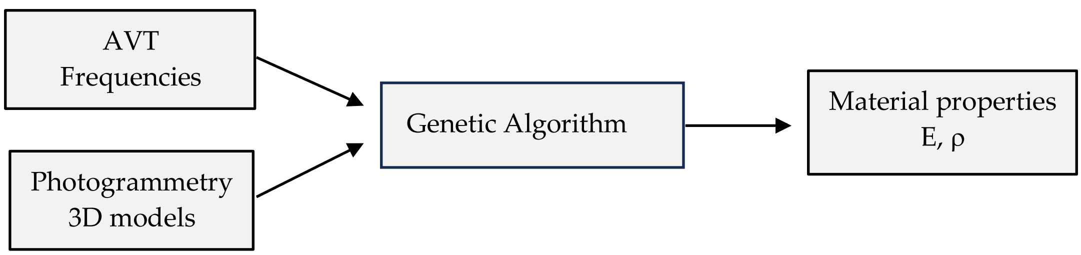


FIGURE 7. Identification framework

The genetic algorithm is initiated with a random population of 40 individuals, each representing a potential solution encoded with random values for Young's modulus and density. The assigned values fall within specified ranges of 1 to 3 GPa and 1400 to 2400 kg/m³, ensuring variability for subsequent evolution and optimization. The interface between COMSOL and the genetic algorithm (GA) is established by means of an API (Application Programming Interface) integrated into the Python code of the GA.

After generating the initial population, the fitness of each individual is assessed using an objective function that measures the disparity between experimental and simulated frequencies, considering mode contribution. Individuals are ranked, identifying those with superior performance for subsequent population improvement. The objective function is determined through the formula of the cumulative error defined as follows:

$$Objective\ Function = \sum_i \alpha_i \left| \frac{f_{num_i} - f_{expi}}{f_{expi}} \right| \quad (1)$$

The coefficients (α_i) represent the weights proportional to the amplitude of relative peaks of the selected number of correlated modes. The sum of all α_i coefficients is equal to 1, i.e.,

$$\sum \alpha_i = 1 \quad (2)$$

Rank-based selection is employed to choose individuals for crossover. A single-point crossover technique is adopted in which a random crossover point is selected along the chromosome, and the genetic material before and after that point is exchanged between two parent individuals. As for the mutation operation, a random mutation approach is used, where a randomly selected gene is modified within an individual.

Several termination criteria are available for the optimization algorithm, including reaching a predefined satisfaction criterion, halting in the absence of improvement for a specified number of generations, or concluding after a predetermined number of generations. In this study, convergence was reached in less than 10 iterations. The best individual, characterized by optimal Young's modulus and density values for historic structures, is identified as the optimal and satisfactory solution for the problem.

VII. RESULTS AND DISCUSSION

Using the genetic algorithm (GA) as part of the optimization process, helps to estimate the Young's modulus (E) and density values for different structural components. Initially, the specimens were chosen in ascending degree of complexity, to explore the performance of the procedure across different level of complexity. The ambient vibration results, however, showed that the simplest specimen which shows a large discrepancy between one of the fundamental numerical and experimental frequencies. The GA results, consisting of the estimated Young's modulus and the material density, for all the specimen including the column when excluding the inconsistent frequencies, are coherent with the material visual appearance of each specimen. Notably, the wall element, constructed with a form of stone rubble masonry, exhibits the lowest density. Meanwhile, the arches, showing noticeable cracks, particularly at the base of the column, demonstrate the lowest average Young's modulus (Table 1.).

TABLE 1. Estimated material properties for each specimen obtained from the GA

	Young's modulus (GPa)	**Density** (Kg/m^3)
Column	1.79	2370
Wall	1.96	1800
Arches	1.17	2150

A significant conclusion drawn from this procedure is its ability to estimate the overall material properties of a structure. While invaluable when seeking global values, it may not accurately reflect the material's properties at a local scale. It is noteworthy that the matched numerical frequencies closely align with the corresponding experimental ones, exhibiting less than a 10% error, except for the column specimen (Table 2).

TABLE 2. Comparison of numerical and experimental frequencies for different specimens

	Mode 1	Mode 2	Mode 3	Mode 4
	Column			
Experimental Frequency (Hz)	-	30.947	103.37	
Simulated Frequency (Hz)	37.110	37.408	101.610	
Error (%)	-	20.88	1.7	
	Wall			
Experimental Frequency (Hz)	7.210	18.88		
Simulated Frequency (Hz)	7.435	19.030		
Error (%)	3.12	0.8		
	Arches			
Experimental Frequency (Hz)	3.334	5.387	8.148	10.104
Simulated Frequency (Hz)	3.588	5.706	8.846	9.3
Error (%)	7.61	5.92	8.57	7.96

VIII. CONCLUSION

Despite the growing acknowledgment of photogrammetry as a flexible and economical method for acquiring numerical three-dimensional models, there are still challenges associated with transforming the scanned models into usable finite element models for structural assessment of existing structures with complex shapes and forms. This study introduces a pragmatic framework that integrates photogrammetry, ambient vibration testing, and artificial intelligence techniques, demonstrated through a case study focused on heritage elements within an archaeological site. The comprehensive process, starting from photo acquisition and progressing through alignment, mesh generation, mesh smoothing, to the transformation into 3D finite element models, is elucidated with specific details related to the analyzed specimen. Subsequent to ambient vibration testing conducted on each specimen, natural frequencies are identified. A genetic algorithm is developed to match numerical and experimental frequencies, in order to determine the material properties in terms of density and Young's modulus. The results obtained align with the visual characteristics of each specimen. It is essential to acknowledge that while this technique proves highly valuable for globally assessing material properties, its ability to predict properties at a local scale may be limited.

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