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AMBIENT VIBRATION STUDY OF ANCIENT CHADRA HAULY IN UZBEKISTAN SUPPLEMENTED BY MATERIAL TESTING AND LASER SCANNING

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Abstract. *Ancient Chadra Hauly is located in the Khorezm region of Uzbekistan, near the ancient city of Khiva. The building is made of adobe, an earthen material, and this type of construction is widespread in Central Asia. Although most of this type of construction is limited to single-story buildings, this unique monument is a four-story structure. Its geometry was captured using a terrestrial laser scanner, enabling the creation of an accurate 3D digital twin of this heritage building. The laser scanning projects were conducted twice, before and after the recent reconstruction. The monument's geometric details were captured, including anomalies related to its aging. This paper focuses on the next step in the structural health monitoring of this heritage building: an ambient vibration study to measure resonant frequencies of this ancient and unique structure. The study used high-sensitivity accelerometers in combination with a data acquisition system. The ambient vibration study was conducted after reconstruction. Results of mechanical testing of adobe material similar to that used in the construction of this building were used to validate the obtained results. Since the monument's walls are tapered, the variation in wall thickness from the laser scans was used in the validation process.*

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1 INTRODUCTION

Ancient Chadra Hauly (also known as Chodra Havli) served as a summer house for one of the khans of Khorezm. It is located very close to the ancient Itchan Kala, the inner fortress of ancient Khiva. According to its nameplate, this heritage structure was constructed in 1871. It is under state protection and, structurally, it is a four-story building made of earth material, adobe. A few studies have been conducted on the monument [2-4], including assessments of its structural design and condition. The published information was very limited, especially regarding its structural characteristics; therefore, a laser scanning project was undertaken to obtain a precise geometry of the object and create an accurate 3D digital twin of its current condition [1]. The monument was laser-scanned in 2023, right before its minor restoration. A terrestrial laser scanner, Scan Station C10 from Leica Geosystems [5], was used in this phase of the project [1]. All point clouds were stitched in Cyclone [6], and as a result, a precise digital twin of the monument was generated. The point cloud analysis revealed a few anomalies in its current condition. Therefore, it was decided to investigate the structure further by conducting an ambient vibration study. By accomplishing this, the precise geometry of the monument would be complemented by its dynamic performance at very small excitations. This paper discusses the phase related to the ambient vibration study. In the project's next phase, the digital twin will be converted into a comprehensive numerical model that captures the real object's dynamic performance.

The main objective was to collect sufficient measurement data to develop an accurate model of the heritage building, enabling prediction of its structural performance under various loading conditions. To achieve this, a comprehensive approach consisting of several steps was employed. The first step focused on obtaining a precise digital twin of the object's geometry. This was achieved using a terrestrial laser scanner. As a result, the object's geometry was accurately determined and will be reproduced in a numerical model. The second step focused on the object's structural dynamic properties by measuring its resonant frequencies. This was conducted for the case of ambient vibration. These results will be used to calibrate the numerical model's performance under small excitations. The final step focused on material studies of the construction material used for the building. While the previous two steps represent non-destructive methods of structural health monitoring, this step requires collecting samples from the body of the heritage monument. Therefore, as a preparatory step, a study on the optimal sample size was conducted herein. As in the authors' previous studies, the material tests will be conducted up to failure to assess the material's nonlinear performance under high loads. It will enable the measurement of the following critical parameters for finite element modeling: Young's modulus, Poisson's ratio, density, and strength. In addition, the nonlinearity of the material's properties and failure modes can be investigated. For these reasons, this step is very valuable for adequate numerical modeling of the building.

2 STRUCTURAL DESIGN DETAILS FROM POINT CLOUD

2.1 Laser scanning and its major results

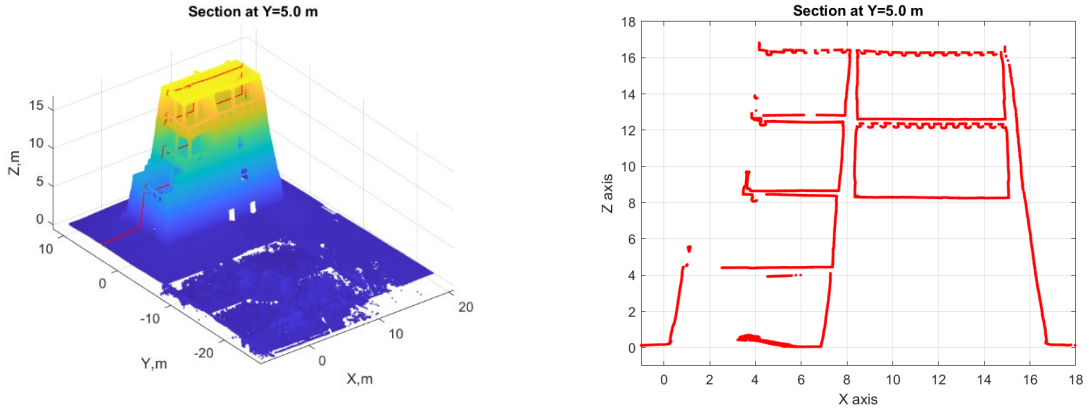
As noted earlier, the monument is constructed as a four-story building, as shown in Figure 1. The photos were taken in the summer of 2024 and show the monument after its minor restoration in 2023.



a) front view b) side view

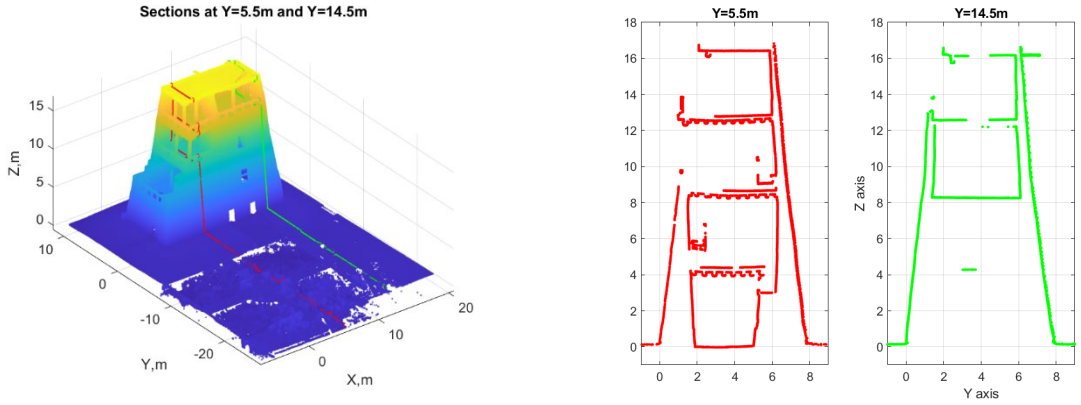
Figure 1: Photos of Chadra Hauli in the summer of 2024.

Figure 2 shows that the presence of walls in the floor plan varies from floor to floor. There are two rooms on the ground floor with very small door openings. Starting from the second floor, the rooms on the front side of the building are constructed as patios. The patio on the second floor has three walls, with no wall on the front. The patios on the third and fourth floors are open on the front and left sides. The second room on the rear of the building was also constructed as a patio on the fourth floor, open to the left. Based on this, it was concluded that the building's construction is quite irregular. In addition, the monument's outer and inner walls are tapered. So, the wall thickness decreases as elevation increases. Based on the point cloud analysis, the wall taper varies with elevation, and this effect is more pronounced in the first two floors. The wall thickness changes by about 0.5 m per floor for the first two floors. This change is smaller for the 3rd and 4th floors and was estimated to be very close to 0.3 m per floor. Figures 2 and 3 show typical longitudinal and transverse cross-sections of the point cloud along and across its length, respectively, demonstrating the monument's structural features. The data reduction of the point cloud is conducted in the Matlab environment [7].



a) Section's outline in the overall point cloud (red line) b) Cross-section (XZ plane)

Figure 2: Typical longitudinal cross-section of the point cloud.



a) Sections' outline in the overall point cloud (red and green lines)

b) Cross-sections (YZ plane)

Figure 3: Typical transverse cross-sections of the point cloud.

3 AMBIENT VIBRATION STUDY

3.1 Ambient vibration study: equipment and configurations

Accelerometers with very high sensitivity, 393B31 from PCB Piezotronics [8], were used in this study. To record the acceleration data, they were integrated with the data acquisition system, E6008U from Pacific Instruments Inc. [9]. The accelerometers were installed on a small rigid fixture at 90 degrees to each other, aligning with the monument's two horizontal principal axes, as shown in Figure 4a. The data acquisition system was located at ground level, as shown in Figure 4b. All accelerometers were connected to the data acquisition system via cables.



a) Accelerometers installed at 90^0 to each other

b) Data acquisition station

Figure 4: Accelerometers' typical installation and data acquisition station on the ground level.

As presented in Figure 5, the accelerometers were installed at two elevations: the ground level and the fourth floor.



a) Accelerometer set on the ground level

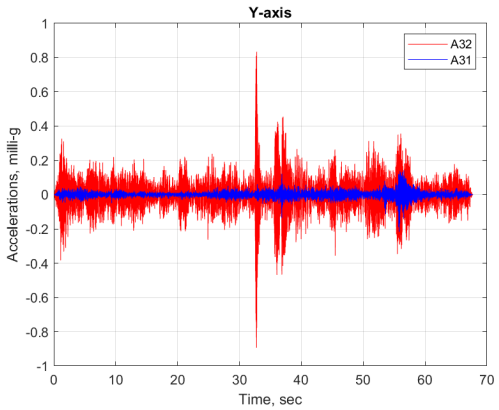


b) Two accelerometer sets on the 4th floor

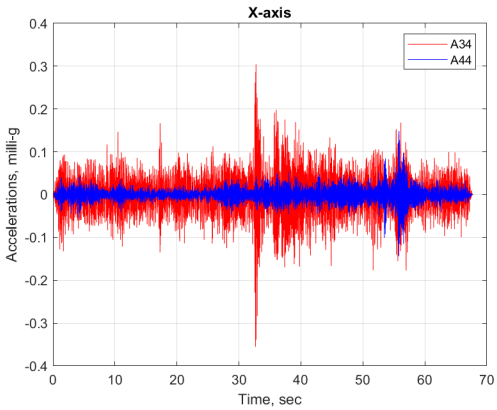
Figure 5: Two elevation levels for the accelerometer installation: the ground and the 4th floor.

3.2 Ambient vibration study: results

Because the accelerometers are highly sensitive, very small accelerations were recorded during the fieldwork. Plots showing the accelerations at the bottom of the building and on the 4th floor in the longitudinal and transverse directions are presented in Figure 6. As the plots show, the ground-level excitation did not exceed 0.2 milli-g. The building's response amplified this vibration level multiple times, and the maximum recorded acceleration on the 4th floor was close to 0.8 milli-g in this data set.



a) Accelerations at ground (A31) vs 4th floor (A32) levels: transverse axis

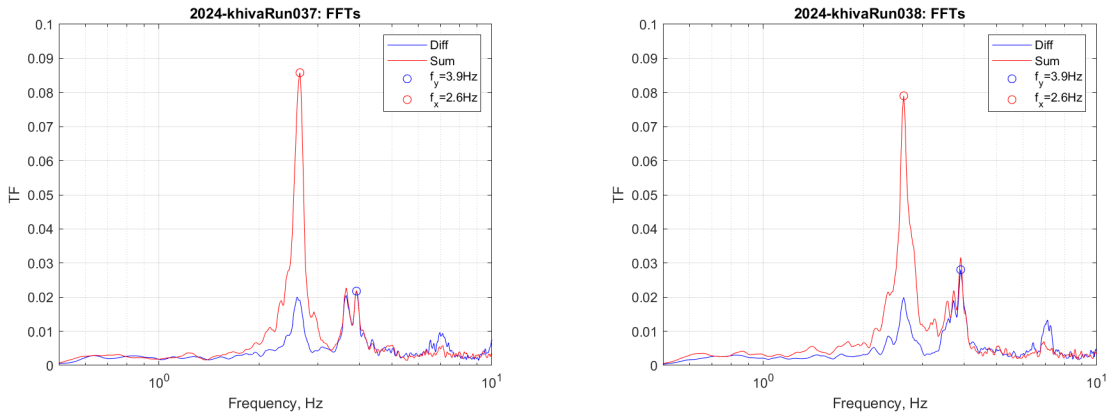


b) Accelerations at ground (A44) vs 4th floor (A34) levels: longitudinal axis

Figure 6: Accelerations at the bottom of the building compared to those on the 4th floor.

A few datasets were recorded, and the results for four of them are discussed herein. The orientation and location of the accelerometers remained the same across these four datasets, and accelerometers A32 and A35 were oriented in the transverse direction on the 4th floor. Hence, the difference between the acceleration data corresponds to the torsional motion of vibration. On the other hand, the sum of the acceleration data collected by these two accelerometers cor-

responds to the transverse vibration mode. The results for the two datasets are shown in Figure 7.



a) Dataset: Run037 b) Dataset: Run038

Figure 7: Typical results: Fast Fourier Transforms (FFTs) (two datasets are shown).

The plots show the Fast Fourier Transforms (FFTs) computed for two vibration modes from the ground- and 4th-floor accelerations. The first mode corresponds to the transverse mode (noted as "Sum" in the plots). The second mode corresponds to the torsional mode (noted as "Diff" in the plots). The plots show that the building's first resonant frequency is close to 2.6 Hz, corresponding to its transverse frequency. The second frequency, 3.9 Hz, is the building's torsional frequency. The results were similar for all four datasets recorded for the same accelerometer configuration.

The obtained resonant frequencies will be used to calibrate the comprehensive finite element model of the monument currently being developed. It is worth noting that the higher vibration modes were challenging to identify because a few unsupported walls were engaged in the building's structural vibration. The future numerical model would be instrumental in this effort to separate wall vibrations from the global modes of vibration.

3.3 Ambient vibration study: discussions

Adobe is a man-made building material made from raw earth, typically sourced from the construction site. Hence, its mechanical characteristics depend on many parameters. These parameters can be as follows: the quality of earth material available for construction, the curing time of the clay before forming it into a wall or a brick, the way the clay was placed into the walls, bonding aggregates added to the earth material (if any), the quality of the craftsmanship work, the curing process after forming the wall, and many others. After construction is complete, the mechanical properties can be affected by moisture [10]. Therefore, there is substantial variability in the mechanical properties of adobe materials used in structures worldwide [11]. The mechanical properties are estimated by testing samples taken from adobe walls or created during construction (which is very rare). Samples can be collected as cubes, prisms, or cylinders, and test results also depend on the shape of the test specimen [12]. For example, based on a comparative analysis of test results for cylinders [13], the Young modulus of adobe material varies by a factor of ten.

Destructive testing, including specimen collection from a monument's body, is not allowed in the case of heritage buildings and structures for obvious reasons. Therefore, an ambient vibration study is one way of estimating the mechanical characteristics of heritage monuments. In the case of heritage structures, it can be the only way. The study results can be used to develop an accurate finite element model of the monument, with structural performance that

closely replicates that measured during the ambient vibration study. The finite element model of Chadra Hauly is under development and will be published in the expanded version of the paper.

4 OPTIMIZATION OF SAMPLE COLLECTION

Although obtaining a permit for sample collection is difficult for a heritage building, it's sometimes possible, especially when a monument is in poor structural condition and requires a rigorous structural assessment. This section focuses on optimizing sample dimensions to maximize useful information while minimizing the sample size.

4.1 Recent cylinder sample tests

To evaluate the mechanical properties of adobe material specific to Uzbekistan, a recent study was conducted [14]. It was focused on three objectives. First, a procedure for collecting cylindrical samples was developed. Second, a procedure for measuring the mechanical properties (Young's modulus, Poisson's ratio, and ultimate strength) of the samples was developed and evaluated on several samples. Third, the results were compared to similar information collected worldwide. To achieve these objectives, samples from two adobe buildings were collected. They were about 60+ years old, and, as such, were not as ancient as the monument studied in this paper. Nevertheless, they were representative buildings of this type of construction in Uzbekistan.

Regarding the first objective of [14], it was concluded that boring samples from adobe walls can be one of the most convenient and reliable methods for sample collection. Figure 8a shows a photo taken during this sample collection procedure [14]. Since adobe material is brittle and not always uniform, the samples can break during the boring procedure, as shown in Figure 8b, a few samples have broken edges.



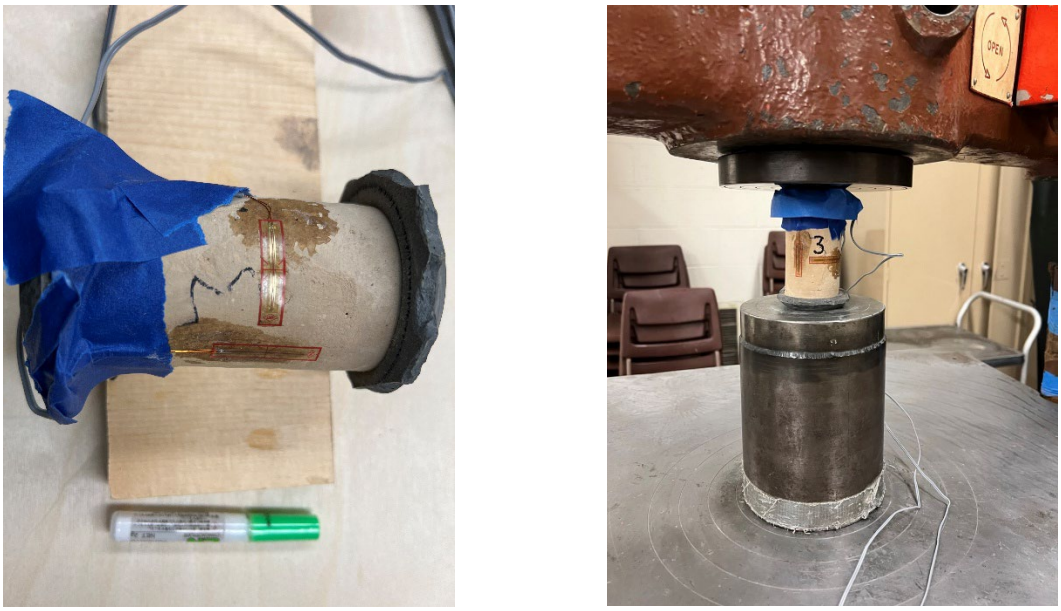
a) Boring procedure [14]



b) Typical samples

Figure 8: Sample collection procedure with typical samples.

To ensure uniform load distribution in compression testing machines, it is recommended to follow the capping procedure commonly used for concrete samples. A sample with caps and a strain gage installed is presented in Figure 9a. A typical photo of the sample during a compression test is presented in Figure 9b.



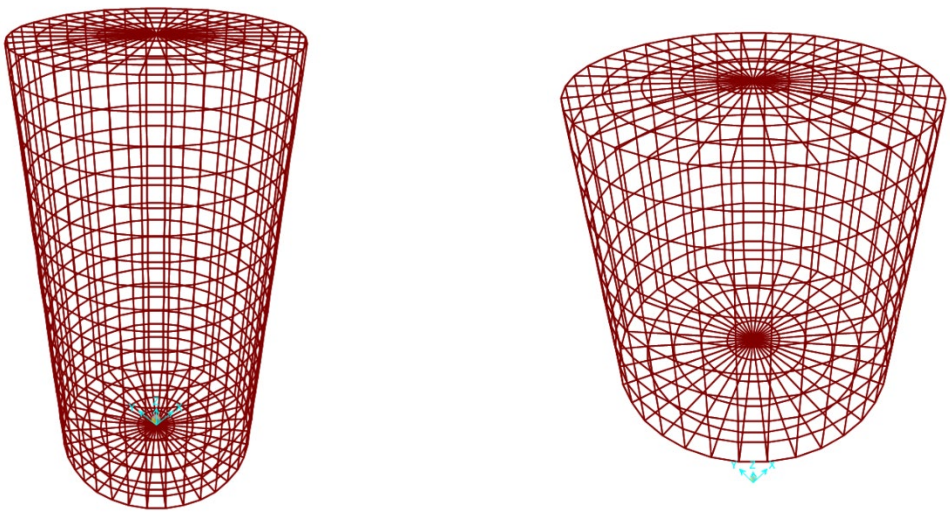
a) Capped sample with strain gages b) Compression test in progress

Figure 9: Fully prepared cylindrical specimen with caps and strain gages in compression testing [14].

4.2 Analysis of sample dimension by finite element modeling

In the recent study, all samples were at least two times longer than their diameter. Since some of the bored cylinders were shorter, with lengths close to one diameter, this section of the paper focuses on how this can affect the quality of the test data. They are called “long” and “short” samples for the purpose of this paper.

To achieve this goal, finite element models of the long and short samples were generated, as shown in Figure 10.

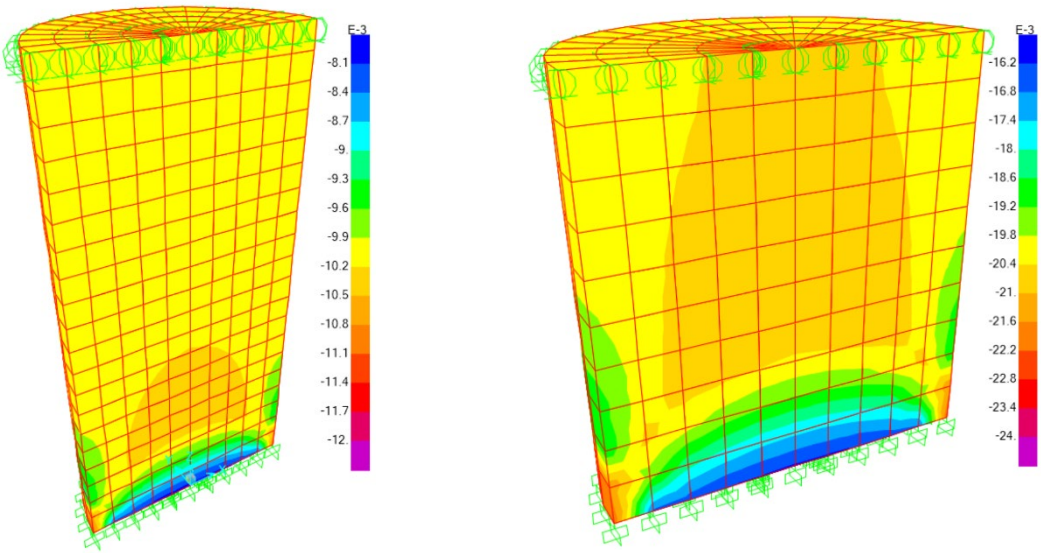


a) Long sample: D50 mm sample 100 mm long b) Short sample: D50 mm sample 50 mm long

Figure 10: Finite element models of Long and Short samples.

Finite element modeling was performed in SAP2000 [15] from Computer and Structures, Inc. Solid elements were used to model the samples.

The models were subjected to compression loading with a force evenly distributed across their top surfaces. The results for the compression strain are presented in Figure 11.



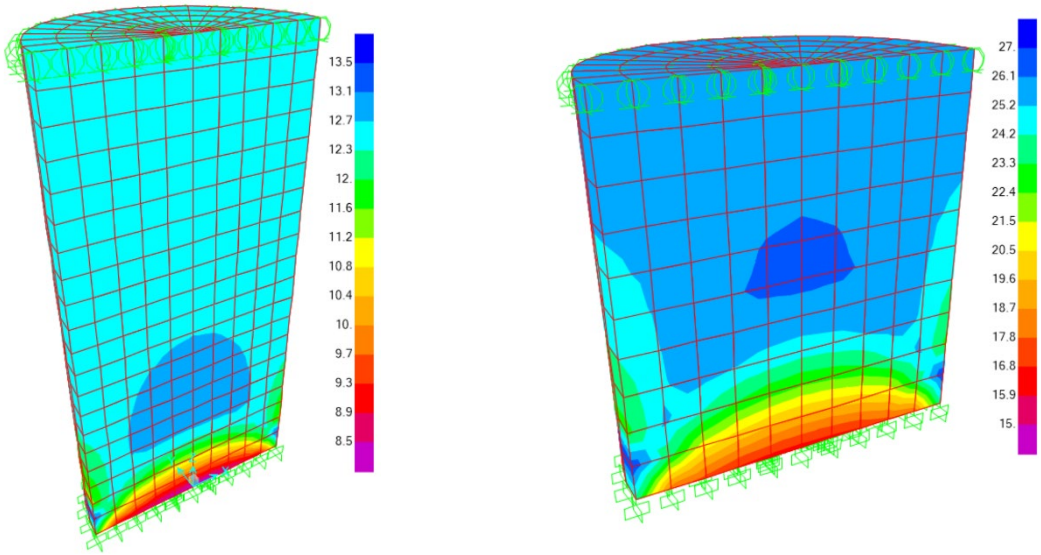
a) Long sample b) Short sample

Figure 11: Compression strain for the long and the short samples.

The material properties measured from Sample No. 6 [14] were used in this modeling. Based on this study, the density was taken as 1,386.8 kg/m^3, the Young's modulus was estimated as 1,258.5 MPa, and the Poisson's ratio was measured as 0.23.

It is worth noting that the results shown in Figure 11 correspond to a uniform displacement of 1 mm on the top surface, while the bottom surface is fixed. For the long specimen, this corresponds to an average compressive strain of 1 percent or $1*10^{-2}$ mm/mm. As shown in Figure 11a, the compression strain is uniform over a large portion of the long sample and is very close to the target value of 1 percent at mid-height. Hence, the strain gage installed at the mid-length (mid-height in the image) would accurately read this uniform strain quote. This is not the case for the short sample as presented in Figure 11b. The compression strain is not uniform and quickly changes in the vicinity of the sample's mid-length. As in the long specimen case, the same 1 mm displacement is applied to the top surface while the bottom surface is fixed, resulting in an average compressive strain of 2 percent. There is a large color gradient indicating rapid variation in strain throughout the sample. Therefore, it is not advisable to test short samples, as the Young's modulus can be measured inaccurately.

Figure 12 shows Von Mises stresses for the long and the short samples. The images show that the stress field is quite different between the two, and the region with a large gradient of stress change extends much deeper in the short sample. Hence, the failure modes and ultimate load capacities can also differ significantly. Therefore, it is not advisable to test short samples.



a) Long sample b) Short sample

Figure 12: Von Mises stresses.

Based on numerical analysis of long and short cylindrical samples, the following conclusions were made. First, the Young's modulus can be measured inaccurately for the short sample, because there is no uniform strain distribution at its mid-length. Second, a short sample can lead to greater variation in ultimate load capacity and failure modes.

Based on the results of this study, it was concluded that long specimens are essential for accurate testing of the mechanical properties of this ancient adobe. The research team is now in the process of obtaining a permit to collect cylindrical samples from the basement of Chadra Hauly.

5 CONCLUSIONS

The analysis of the point cloud collected for Chadra Hauly's structural health monitoring revealed the following facts. The adobe walls of the building have a taper that changes over the elevation. In addition, the number of walls providing lateral resistance to the building changes with the elevation. This led to the conclusion that the building is quite irregular from a structural point of view and, as such, a torsional vibration mode can be among its first resonant frequencies. The latter was confirmed in an ambient vibration study conducted on the monument using highly sensitive accelerometers. The frequencies estimated in the field study will be used to develop a comprehensive finite-element model of the monument.

Based on numerical analysis of long and short cylindrical samples, the following conclusions were made. First, Young's modulus can be measured inaccurately for the short sample, because there is no uniform strain distribution at its mid-length. Second, the short sample can result in greater variation in ultimate load capacity and failure modes.

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