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Dynamic Characterization of the Consistory Building in Comune di Sant'Agapito, Italy: Ambient Vibration Testing, Data Analysis, and Finite Element Validation.

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Abstract.

This research paper presents a comprehensive study on the dynamic behaviour of the consistory building in Comune di Sant'Agapito, Italy, through ambient vibration testing and subsequent data analysis. The consistory building, a significant historical structure, was subjected to an ambient vibration test to capture its natural frequencies and mode shapes. Accelerometers were strategically placed to record the building's response to ambient vibrations. The collected data was then processed using two distinct methods: Fast Fourier Transform (FFT) and Frequency Domain Decomposition (FDD).

FFT and FDD were chosen for their complementary strengths in identifying frequency content and extracting modal parameters, respectively. The differences between the results obtained from FFT and FDD were meticulously analysed to understand the advantages and limitations of each method in the context of historical buildings.

To validate the experimental findings, a finite element model (FEM) of the consistory building is developed to simulate its dynamic response. The FEM results were compared with the experimental data to assess the accuracy of the model and the reliability of the FFT and FDD methods.

This study not only contributes to the understanding of the consistory building's dynamic characteristics but also demonstrates the efficacy of combining ambient vibration testing, advanced data processing techniques, and finite element modelling.

Keywords: Modal Analysis, Fast Fourier Transform, Frequency Domain Decomposition, Finite Element Modelling, Ambient Vibration test.

1 Introduction

The preservation and seismic assessment of historical buildings are critical for maintaining cultural heritage and ensuring public safety. One such structure, the consistory building in Comune di Sant'Agapito, Italy, stands as a testament to architectural heritage and historical significance. Understanding its dynamic behavior [1] under various environmental influences is paramount for devising effective preservation strategies. This research paper presents a comprehensive study on the dynamic behavior of the consistory building through ambient vibration testing and subsequent data analysis, employing advanced techniques to gain deeper insights into its structural characteristics.



Fig. 1. Consistory building in Comune di Sant'Agapito [2].

Ambient vibration testing (AVT) [3] has emerged as a non-invasive method for assessing the dynamic properties of structures [4], particularly valuable for historical buildings where traditional testing methods might be detrimental. This method is preferred for historical structures due to its non-destructive nature. Studies [5] have shown that AVT provides reliable data for structural identification and damage assessment. In this study, accelerometers were strategically placed throughout the consistory building to record its response to ambient vibrations. The data collected from these tests were analyzed using two distinct methods: Fast Fourier Transform (FFT) and Frequency Domain Decomposition (FDD) [6]. Each method brings unique strengths; FFT [7] is adept at identifying frequency content, while FDD [8] excels in extracting modal parameters. FFT is particularly useful in the initial stages of data analysis for its efficiency in handling large datasets. However, while FFT is effective in identifying frequency peaks, it has limitations in extracting modal parameters, such as damping ratios and mode shapes. On the other hand, Frequency Domain Decomposition (FDD) excels in extracting mode shapes and damping ratios, providing a more comprehensive understanding of the dynamic behavior of structures. By leveraging both techniques, we aim to provide a thorough analysis of the building's natural frequencies and mode shapes.

To ensure the robustness of our findings, a finite element model (FEM) [9] of the consistory building was developed. This model simulates the building's dynamic response

and serves as a benchmark to validate the experimental results obtained from FFT and FDD. By comparing the FEM results with the experimental data, we assess the accuracy of the model and the reliability of the data processing methods.

The integration of AVT, FFT, FDD, and FEM represents a comprehensive approach to structural analysis. Each method contributes uniquely to understanding a building's dynamic characteristics. AVT provides non-invasive data collection; FFT offers initial frequency content analysis; FDD extracts detailed modal parameters; and FEM simulates dynamic response for validation purposes. This multi-faceted approach has been successfully applied in various studies [10], demonstrating its efficacy in preserving and assessing historical buildings.

The outcomes of this study extend beyond mere academic interest. They offer practical implications for the preservation and seismic assessment of historical buildings [11]. By demonstrating the efficacy of combining ambient vibration testing [12], advanced data processing techniques, and finite element modeling, this research provides valuable insights that can inform future conservation efforts and policy making.

2 Methodology

The methodology for this research is designed to comprehensively assess the dynamic behaviour of the consistory building in Comune di Sant'Agapito, Italy, as stated in the introduction section above. The steps involved in this methodology are the following.

2.1 Description of the Consistory Building

The building's geometry, construction materials, and existing conditions are assessed to inform the subsequent steps in the methodology. The Consistory building of the Comune di Sant'Agapito, Italy, is a notable landmark that blends historical significance with architectural charm. This building serves as the administrative heart of the municipality, hosting various governmental functions and public services.

Architecturally, the Consistory building reflects traditional Italian design, characterized by its elegant façade, symmetrical layout, and use of local materials. The structure likely showcases classic elements such as arched windows, terracotta roof tiles, and ornate detailing that hint at its historical roots. The building's size and stature make it a prominent feature within the town, symbolizing the local governance and community spirit.

Constructed using local materials such as stone, brick, concrete and wood, the building is designed to withstand the local climate and integrate seamlessly with its surroundings.The structural framework incorporates load-bearing walls and a reinforced concrete skeleton of beams and columns that support the upper floors and roof.

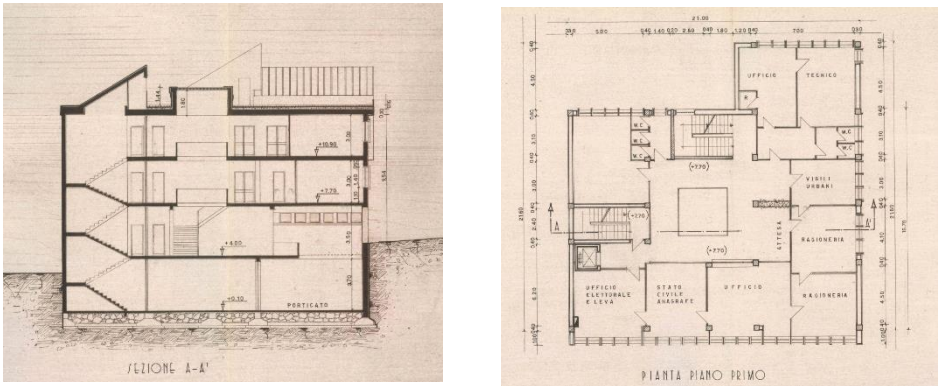


Fig. 2. Construction drawings of the building. Source: Comune di Sant' Agapito.

2.2 Ambient Vibration Testing (AVT)

AVT was selected for its non-destructive nature, which is crucial for historical buildings [13]. The ambient accelerometer system in question is part of an advanced monitoring sensor network designed for precise and autonomous operation in various environments. This network integrates seven highly sophisticated accelerometric triaxial Force Balance sensors. Each of these sensors is meticulously engineered to capture and measure three-dimensional accelerations with exceptional accuracy.

The system boasts an impressive dynamic range of 90 dB, which allows it to detect and accurately measure a wide spectrum of acceleration magnitudes, from very subtle vibrations to more intense movements. This makes it suitable for a variety of applications, from environmental monitoring to structural health assessments.



Fig. 3. Environmental accelerometers employed in this Ambien Vibration testing.

To ensure high-resolution data collection, the sensors have been programmed to operate with a sampling frequency of 250 samples per second. This high sampling rate ensures that even rapid changes in acceleration are captured, providing detailed and granular data for analysis.

In addition to its accelerometric capabilities, the system is equipped with a built-in Global Navigation Satellite System (GNSS) receiver. This feature provides precise geolocation information, enabling the integration of spatial data with acceleration measurements. This is particularly useful for applications requiring accurate positioning, such as seismic monitoring or infrastructure health diagnostics.

For data transmission, the system utilizes Wi-Fi connectivity. This wireless data transfer capability allows for real-time data streaming and remote monitoring, reducing the need for physical intervention and enabling more flexible deployment in diverse environments.

The accelerometer system is also designed with practical portability and autonomy in mind. It can operate on battery power for up to 30 hours, ensuring sustained monitoring without the need for constant recharging or external power sources. The compact dimensions of 18x18x10 cm and a weight of 3 kg make it relatively easy to transport and deploy, even in challenging or remote locations.

2.3 Data Analysis using FFT and FDD

The recorded data were processed using two distinct methods: Fast Fourier Transform (FFT) and Frequency Domain Decomposition (FDD).

Fast Fourier Transform (FFT) was applied to transform the time-domain data into the frequency domain. This method allowed for the identification of the building's natural frequencies by examining the peaks in the frequency spectrum [14]. The steps included preprocessing of raw data to remove noise and ensure signal clarity, the application of FFT to the preprocessed data and identification of dominant frequency peaks corresponding to the building's natural frequencies. The FFT of a signal x(t) is defined as Eq. (1):

$$X(f) = \int_{-\infty}^{\infty} x(t) e^{-i2\pi f t}\, dt \quad (1)$$

On the other hand, Frequency Domain Decomposition (FDD) was employed to extract more detailed modal parameters [15]. The FDD process involved estimating the spectral density matrices from the vibration data, decomposing the spectral density matrices (through the Singular Value Decomposition) to identify the modal characteristics, and in further analysis extracting mode shapes and damping ratios for the identified frequencies.

The Power Spectral Density (PSD) matrix G(ω) can be obtained as Eq. (2):

$$G(\omega) = H(\omega)H^*(\omega) \quad (2)$$

where H(ω) is the Frequency Response Function (FRF) matrix, and H*(ω) is its conjugate transpose.

Singular Value Decomposition (SVD)**:** The PSD matrix G(ω) is decomposed using SVD to isolate the contribution of each mode. The SVD of G(ω) is given by Eq. (3):

$$G(\omega) = U(\omega)\Sigma(\omega)U^*(\omega) \quad (3)$$

Where U(ω) is the matrix of singular vectors and Σ(ω) is the diagonal matrix of singular values.

The dominant singular values in Σ(ω) correspond to the building's natural frequencies, and the associated singular vectors in U(ω) represent the mode shapes. The damping ratios can be estimated from the width of the peaks in the PSD.

2.4 Finite Element Modeling (FEM)

To validate the experimental findings, a finite element model (FEM) of the consistory building has been developed. The FEM was created using detailed geometric and material properties of the building provided by the Consistory' authorities. Structural elements were modelled to replicate the actual construction as closely as possible [16]. The model was subjected to dynamic analysis to simulate the building's response to ambient vibrations. The simulated data were then compared with the experimental results obtained from FFT and FDD.

The equation of motion for the FEM is given by Eq. (4):

$$M\ddot{u}(t) + C\dot{u}(t) + Ku(t) = F(t) \quad (4)$$

where:

- M is the mass matrix,
- C is the damping matrix,
- K is the stiffness matrix,
- u(t) is the displacement vector,
- F(t) is the external force vector.

The FEM results were compared with the experimental data to assess the accuracy of the model. Discrepancies were analyzed, and the model was calibrated to improve its reliability. This iterative process ensured that the FEM accurately represented the building's dynamic behavior [17].

3 Data Analysis

In this data analysis section are presented the experimental results obtained with the ambient vibration testing performed during 18th May of 2024. The different sensor configurations deployed, and building orientation, are presented in Fig. 4 below:

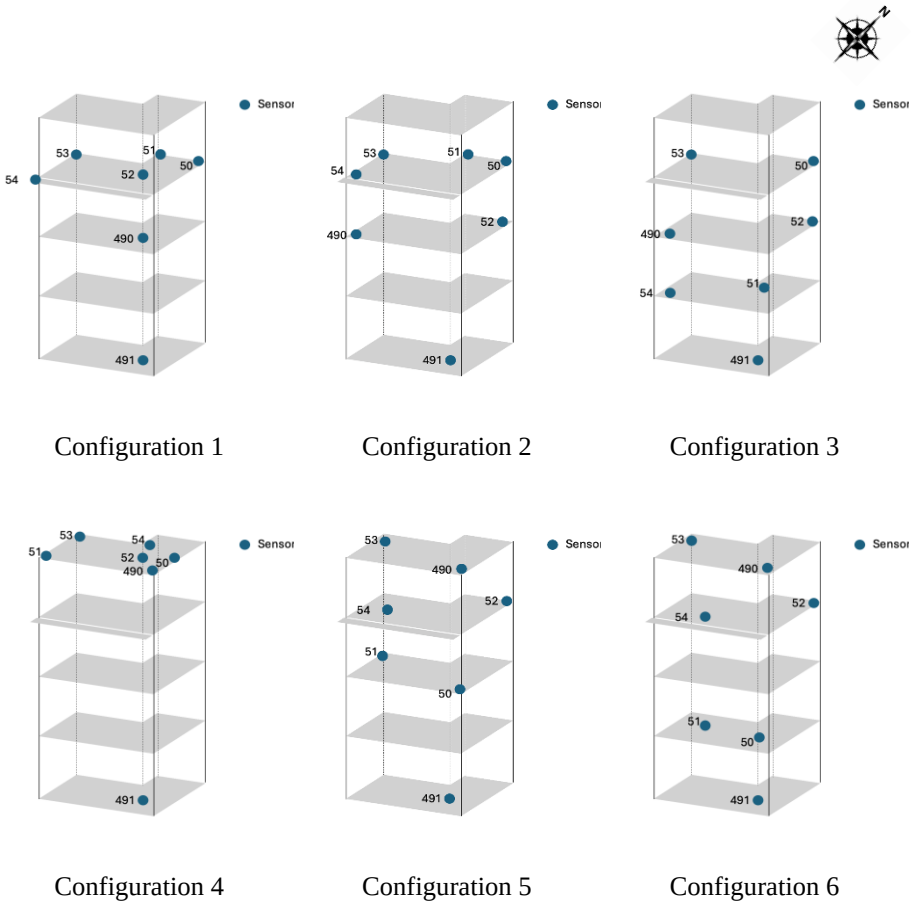


Fig. 4. Ambient Vibration Testing configurations employed. Own source.

3.1 Fast Fourier Transform (FFT)

To obtain the Fast Fourier Transform, it is compiled the time registers obtained, for each sensor configuration deployed, and for each axis of the sensors, and applied the FFT to the time domain. Acceleration unit from registers obtained by sensors is $^{m}/_{s^2}$. Concerning the FFT calculation, it has been calculated the number of discrete samples used in FFT (N), impacting frequency resolution (f_s) and range [18]. The choice of FFT points should balance the desired frequency resolution and computational efficiency, often influenced by the nature of the signal and the specific requirements of the analysis. Using a value of 16.384, the frequency resolution obtained in Eq. (4):

$$\Delta f = \frac{f_s}{N} = \frac{250\ Hz}{16.384} = 0{,}015\ Hz \quad (4)$$

A higher number of FFT points (N) results in a finer frequency resolution, allowing more precise identification of frequency components. With the value chosen, and according to the captured natural frequencies (from FDD, FEM, FFT), this frequency resolution can assure a proper result.

Focusing the analysis on the configuration 1 (according to Fig. 4), the acceleration time register combined in North axis direction is as Fig. 5:

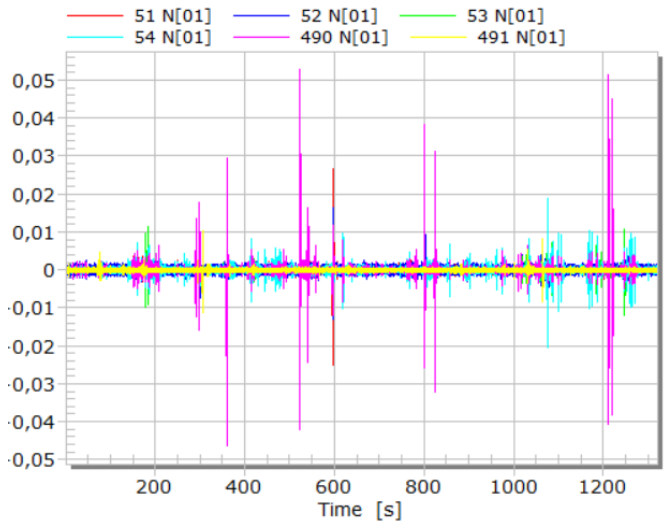


Fig. 5. Ambient Vibration Testing time register. Configuration 1, North direction axis.

Applying FFT to the time register, results are presented in Fig. 6:

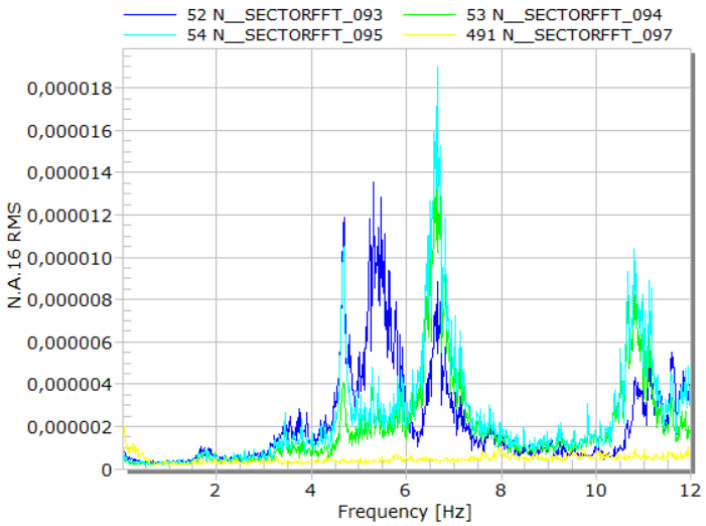


Fig. 6. Fast Fourier Transform results. Configuration 1, North direction axis.

Identified natural frequency peaks are, from the range 0 – 12 Hz, 4.68 Hz, 5.31 Hz, 6.65 Hz and 11.15 Hz. It can be noted how the natural frequency corresponding to 6.65 Hz is the most excited during this configuration, corresponding to sensors placed in the third floor (52N, 53N, 54N). With respect with sensor 491N, in this configuration is placed on the ground floor, not capturing any excitation (as expected). In the next Fig. 7, the East axis time registers are analysed:

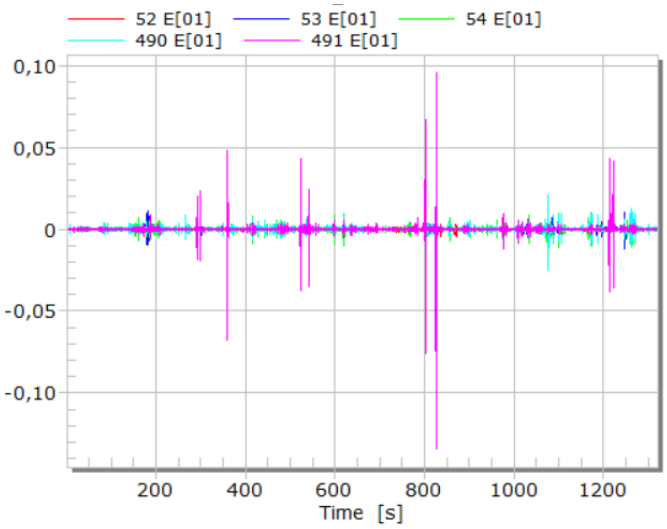


Fig. 7. Ambient Vibration Testing time register. Configuration 1, East direction axis.

Applying FFT to the time register, results are presented in Fig. 8:

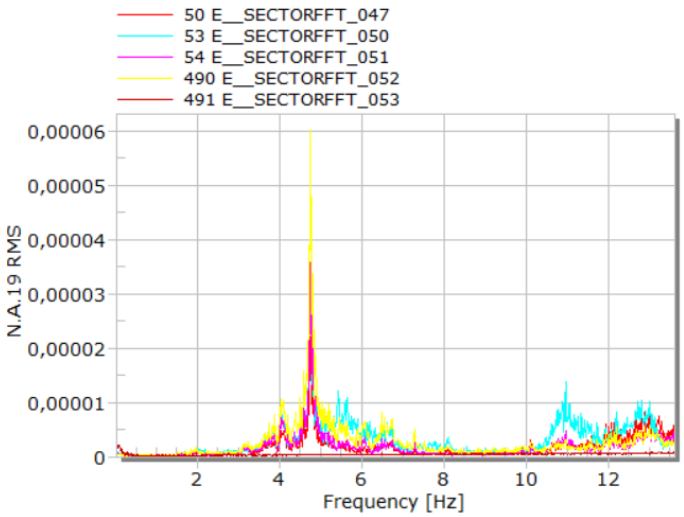


Fig. 8. Fast Fourier Transform results. Configuration 1, East direction axis.

Identified natural frequency peaks are, from the range 0 – 12 Hz, 4.74 Hz, 5.43 Hz, 6.75 Hz, 10.97 Hz and 12.67 Hz. It can be noted how the natural frequency corresponding to 4.74 Hz is the most excited during this configuration, corresponding to sensors almost all the sensors placed except 491E, the one placed in the floor. The rest of the natural frequencies noted are excited, but in a minor degree.

From an initial analysis, it can be deducted that lateral and torsional mode shapes are being captured with this configuration, being a clear lateral mode shape the first mode corresponding to the 4.74 Hz due to its high excitation degree in one direction. In the comparative analysis section, it will be presented the correlation and identification of these experimental natural frequencies with the structural global mode shapes, combining the different results obtained.

3.2 Frequency Domain Decomposition (FDD)

In this section are presented the results using FDD technique, following same considerations as the previous section using FFT. In this case, it is processed the same time registers as previous section. Results for N and E axis directions are presented in Fig. 9:

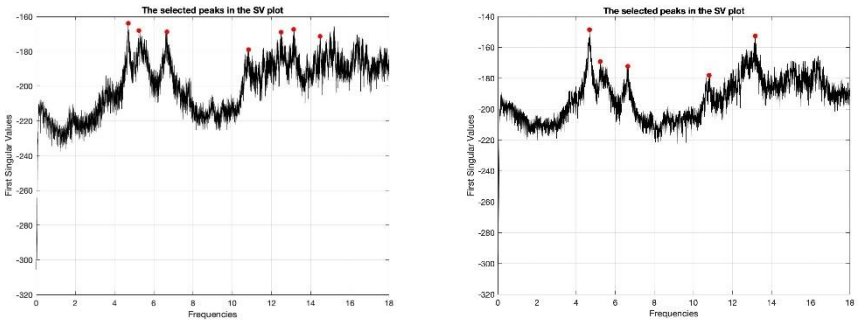


Fig. 9. Frequency Domain Decomposition results. Left: Configuration 1, North direction axis. Right: Configuration 1, East direction axis.

In this case, frequency analysis range is from 0 to 18 Hz. Results obtained for North axis are 4.69 Hz, 5.24 Hz, 6.67 Hz, 10.83 Hz, 12.49 Hz, 13.14 Hz and 14.48 Hz. Results obtained for East axis are 4.69 Hz, 5.24 Hz, 6.64 Hz, 10.80 Hz, and 13.14 Hz.

The initial considerations of these results are that dynamic behavior findings processing FDD are more detailed than in the FFT case. These results will be compared in detail, also together with the FEM modal analysis results, in the Comparative Analysis section of this document.

4 Finite Element Modelling

This chapter details the development, validation, and application of the finite element model (FEM) used to simulate the dynamic behaviour of the consistory building in Comune di Sant'Agapito, Italy. The software used for this analysis is ANSYS 2023 R2 [19].

4.1 Model Development

The first step in developing the FEM involves creating a detailed geometric representation of the consistory building. The geometric model includes all significant structural elements such as walls, floors, and roof. The dimensions and shapes are obtained from architectural drawings and on-site measurements. Historical masonry materials typically exhibit lower stiffness and higher damping than modern construction materials, which must be accounted for in the model [20]. The designed building is shown in Fig. 10:

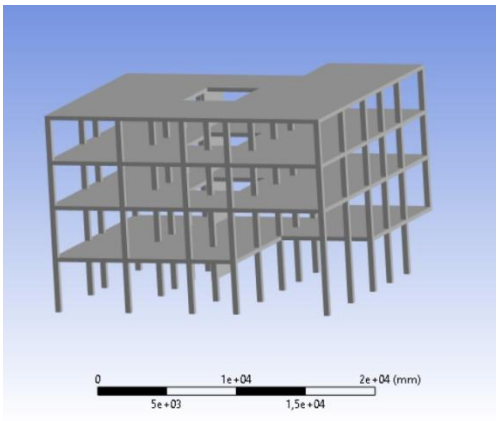


Fig. 10. FEM geometry 3D view of the Consistory building.

The geometric model is discretized into finite elements. The choice of element type for this model has been 3D solid elements, using a finer mesh in areas expected to have high stress gradients, while a coarser mesh suffices for less critical regions.

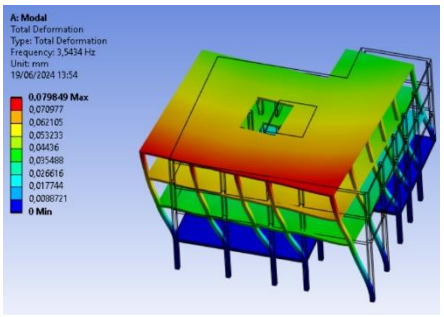
Appropriate boundary conditions are applied to the model to replicate the actual constraints on the building. In this case, the foundations of the building columns are fixed, and the buried structural elements on the east / west and south façade are restricted as well to represent the effect of the soil that confines those sides of the building (in this case is the ground floor). A more accurate structural model would be possible to obtain if ballast coefficient [21] of the surrounding soils could be obtained, to represent this boundary condition as an elastic support using that coefficient.

4.2 Modal Analysis

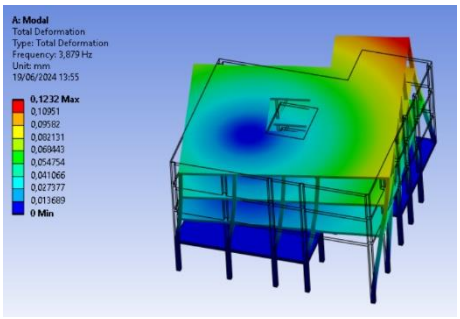
To extract the building's natural frequencies and mode shapes, a modal analysis is performed. This involves solving the eigenvalue problem in Eq. (5):

$$(K - \omega^2 M)\phi = 0 \tag{5}$$

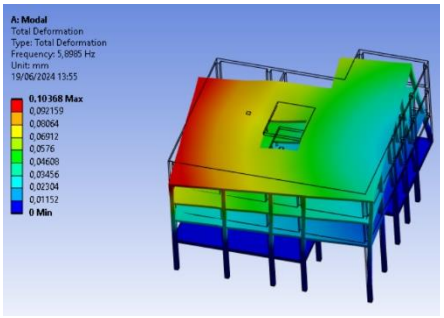
The solution to this equation provides the natural frequencies and corresponding mode shapes, which are compared with the experimental results from FFT and FDD to validate the model. Results are shown in the next Fig. 11:



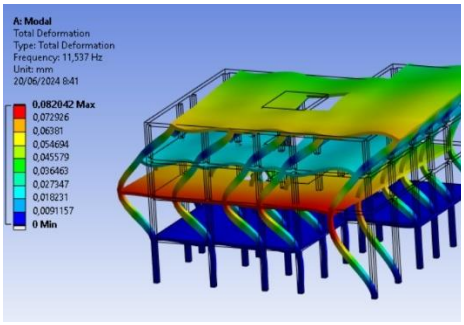
Mode 1: Lateral + Torsional mode. 3.54 Hz.



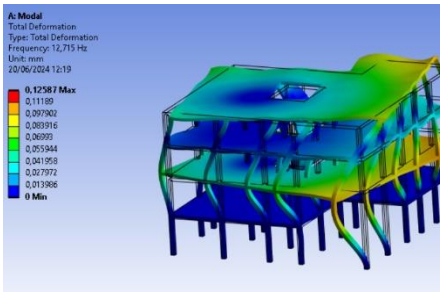
Mode 2: Torsional mode. 3.87 Hz.



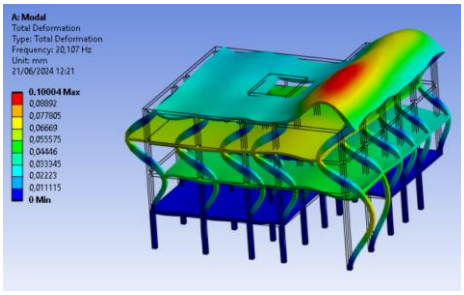
Mode 3: Torsional mode. 5.89 Hz.



Mode 4: 2º degree lateral bending mode. 11.53 Hz.



Mode 5: 2º degree torsional mode. 12.71 Hz.



Mode 6: 3º degree lateral bending mode. 20,10 Hz.

Fig. 11. FEM modal analysis mode shapes.

4.3 Dynamic Response Analysis

Once obtained the mode shapes with the FEM model, it is now analysed the Modal Participation Factor calculation, obtained through the software employed for the analysis. This analysis will provide an important insight and understanding about the most relevant mode shapes present in the structure and supports the experimental identification as the mode shapes with a bigger ratio of effective mass mobilized are the most visible and remarkable during the peak detection in the FFT and FDD results. The Newmark-beta method or other numerical integration techniques are typically used for this purpose [22]. The results obtained are presented in Fig. 12 for the North axis direction, and Fig. 13 for the East axis direction:

MODE	FREQUENCY	PERIOD	PARTIC.FACTOR	RATIO	EFFECTIVE MASS	CUMULATIVE MASS FRACTION	RATIO EFF.MASS TO TOTAL MASS
1	3.54345	0.28221	2.6899	0.156262	7.23553	0.164432E-01	0.123945E-01
2	3.87899	0.25780	-9.0750	0.527184	82.3550	0.203600	0.141075
3	5.89846	0.16954	17.214	1.000000	296.323	0.877011	0.507602
4	11.5371	0.86677E-01	0.50979	0.029615	0.259890	0.877602	0.445192E-03
5	12.7147	0.78649E-01	2.4448	0.142026	5.97725	0.891186	0.102391E-01
6	20.1070	0.49734E-01	0.15666	0.009101	0.245415E-01	0.891242	0.420397E-04
7	20.2964	0.49270E-01	-0.43293	0.025150	0.187429	0.891667	0.321067E-03
8	21.2650	0.47026E-01	6.8354	0.397081	46.7223	0.997847	0.800355E-01
9	21.3793	0.46774E-01	-0.40777	0.023688	0.166276	0.998225	0.284831E-03
10	21.8407	0.45786E-01	0.88389	0.051347	0.781265	1.00000	0.133831E-02
sum					440.032		0.753777

Fig. 12. Modal Participation Factor results for North axis direction.

MODE	FREQUENCY	PERIOD	PARTIC.FACTOR	RATIO	EFFECTIVE MASS	CUMULATIVE MASS FRACTION	RATIO EFF.MASS TO TOTAL MASS
1	3.54345	0.28221	19.280	1.000000	371.712	0.836232	0.636744
2	3.87899	0.25780	6.3674	0.330261	40.5435	0.927442	0.694513E-01
3	5.89846	0.16954	0.37894	0.019655	0.143598	0.927765	0.245985E-03
4	11.5371	0.86677E-01	5.1450	0.266858	26.4707	0.987315	0.453445E-01
5	12.7147	0.78649E-01	-1.5008	0.077841	2.25227	0.992382	0.385815E-02
6	20.1070	0.49734E-01	-1.6865	0.087476	2.84437	0.998781	0.487241E-02
7	20.2964	0.49270E-01	0.65978	0.034221	0.435307	0.999760	0.745684E-03
8	21.2650	0.47026E-01	0.21652	0.011230	0.468812E-01	0.999866	0.803077E-04
9	21.3793	0.46774E-01	0.24033	0.012465	0.577580E-01	0.999996	0.989397E-04
10	21.8407	0.45786E-01	0.43030E-01	0.002232	0.185157E-02	1.00000	0.317174E-05
sum					444.508		0.761444

Fig. 13. Modal Participation Factor results for East axis direction.

5 Comparative Analysis

Once obtained the results for experimental and analytical modal analysis, it is summarized the results to compare and detect strengths and limitations for each technique in identifying dynamic behaviour of historical buildings, dividing the analysis in two main aspects:

1. **FFT vs. FDD**: The natural frequencies, mode shapes, and damping ratios obtained from the FFT and FDD methods are compared with the FEM results to evaluate their accuracy and reliability [23].
2. **Experimental vs. FEM Results**: The overall consistency between the experimental data and FEM results is assessed to validate the efficacy of the

integrated approach [24] combining AVT, advanced data processing techniques, and computational modeling [25].

As quantitative comparation technique, the following aspects are considered:

1. **Natural frequencies**: The natural frequencies identified by FFT and FDD are compared to ensure consistency and accuracy.
2. **Mode shapes**: The mode shapes extracted from FEM are visualized and compared with the experimental natural frequencies obtained, supported by the modal participation factor obtained from the FEM (using the ratio of the Effective Mass / Total Mass).

Then, results are summarized in Table 1:

Table 1. Comparative analysis summary of FFT, FDD, FEM and MPC (Modal Participation factor).

	FFT (Hz)		**FDD (Hz)**		**FEM (Hz)**	**EM / TM**	
	N	E	N	E	Global	N	E
1º mode shape: Lateral bending E + Torsional	4.68	4.69	4.69	4.69	3.54	0.012	0.63
2º mode: Torsional	5.31	5.43	5.24	5.24	3.87	0.14	0.069
3º mode: Torsional	6.65	6.75	6.67	6.67	5.89	0.50	0.0024
4º mode: Lateral bending 2º degree E	-	10.83	10.83	10.83	11.53	0.004	0.045
5º mode: Torsional 2º degree	11.15	12.67	12.4	13.14	12.71	0.01	0.0038

6 Results & conclusions

The results & conclusions section presents the findings from the ambient vibration testing (AVT), the application of Fast Fourier Transform (FFT) and Frequency Domain Decomposition (FDD) methods, and the finite element model (FEM) analysis.

From table 1 results, combining the different analysis techniques the results obtained for each mode shape are as follow:

- 1º Mode shape: FFT and FDD values match perfectly. According to the FEM model, it is a highly lateral bending mode on the East direction of the building, with a slight torsional component. This theory is reinforced through the 0.63

value of the Effective Mass / Total Mass ratio, as well as can be observed in the Fig. 8 as this mode is highly excited in East direction in comparation with the other torsional modes. This theory is supported analysing the values of Eff. Mass / Total Mass ratio for the other mode shapes.

- 2º - 3º Mode shape: It is identified as a Torsional mode. Again, despite small variations, FFT and FDD values, are matching. A more compensated values between N-E axis of the Eff. Mass / Total Mass demonstrate this torsional behaviour; similar insights can be proven for the third mode but providing a stronger North axis movement in this torsion than the second mode.
- 4º Mode Shape: This mode is identified as a lateral bending of the building of second degree, as some floors are not involved in displacements. This motion can be detected as from FFT registers, sensors not placed on the floors that comprises movement do not register any type of natural frequency.
- 5º Mode Shape and the following: For these mode shapes, which increase the bending or torsional degrees of complexity, the modal participation factors start to appear very low, so these types of mode shapes are considered out of the scope of this research.

With these results exposed, the conclusions are as follows:

- The natural frequencies identified by both FFT and FDD were consistent, but FDD provided more detailed natural frequencies content. FDD proved to be a more comprehensive method for modal parameter extraction in buildings, while FFT can provide a detailed insight for each sensor or configuration applied separately.
- The centre of stiffness and the centre of mass of the floors may not coincide, so the building tends to twist. In addition to its geometric asymmetry, there is an asymmetry in the boundary conditions (building partially surrounded by the ground) that also contributes to the torsional behaviour.
- Experimental vs. FEM Results: The behavior of the finite element model is consistent with that identified experimentally, but the model exhibits lower stiffness (lower eigenfrequency values), probably because the actual modulus of elasticity of concrete is higher than the theoretical one, as well as the usual higher flexibility of finite element models with respect to real structures. Future work can be done to update a finite element model using advanced computational techniques or to update the current model with the result of non-destructive testing (if feasible).
- It is to be noted the importance of the Eff. Mass / Total Mass ratio, and in this paper, it has been demonstrated how this type of indicators can help to match analytical and experimental data, providing a strong support on the dynamic behavior understanding of the structures.

This study has presented a comprehensive analysis of the dynamic behavior of the consistory building in Comune di Sant'Agapito, Italy, using ambient vibration testing (AVT), advanced data processing techniques (FFT and FDD), and finite element modeling (FEM). The findings have significant implications for the preservation and

seismic assessment of historical buildings. The integrated approach of using AVT, FFT, FDD, and FEM provides a robust framework for understanding the dynamic behaviour of such structures, which is crucial for their conservation and safety assessment.

Future research can build upon this study by exploring more advanced modelling techniques, incorporating detailed material characterization, and extending the analysis to other historical buildings. The methodology and findings of this study offer valuable insights for similar applications in structural health monitoring and preservation of cultural heritage.

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