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Digital Twin Application for Cultural Heritage Structures via Genetic Algorithms

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Abstract

In this paper the actual dynamic behaviour of the civic Clock tower of Rotella, a little village in central Italy heavily damaged by the recent 2016 seismic sequence, is thoroughly investigated by means of a detailed numerical model built and calibrated using the experimental modal properties obtained through Ambient Vibration Tests. The goal is to update the uncertain parameters of the Finite Element Model (elastic moduli, mass densities, constraints, and boundary conditions) to minimize the discrepancy between experimental and numerical dynamic features. Due to the high nonlinear dependency of the objective function of this optimization problem on the afore-mentioned parameters, and the likely possibility to get trapped in local minima, a fully automated Finite Element Model Updating procedure based on genetic algorithms and global optimization is used, leading to the successful estimation of the uncertain parameters of the tower. The results allowed to create a reference digital replica of the current structural condition of the tower and to set the performance standards that will help to optimize the control of the structural integrity over time.

Keywords: masonry towers, structural health monitoring, operational modal analysis, genetic algorithm, model updating, cultural heritage, digital twin, surrogate model.

1 Introduction

The increasing number of seismic events calls for the adoption of special techniques and analysis methods for the prevention of unexpected collapses and irreversible damages of the building stock. In this context, particular attention should be given to constructions of historical and cultural value which are often more prone to experience heavy damages during the quakes due to their peculiar morphological configuration and their centenary state of conservation. The irreparable damages caused to many heritage constructions during the latest events that stroke Central Italy in 2009 and 2016, e.g. the Basilica of St. Mary of Collemaggio in L'Aquila, the Basilica of St. Benedict in Norcia and the civic clock tower of Amatrice [1], [2], just to mention a few, explain why the preservation of these structures has become a hot topic at international level and why an increasing number of researchers continue to direct their interest in the evaluation of the seismic capacity and behaviour of these constructions utilizing Finite Element (FE) models [3], [4] and Machine Learning (ML) techniques [5]–[8]. To study heritage buildings, it is important to have suitable geometrical and material surveys to construct numerical models as close as possible to reality and avoid estimation errors that might lead to wrong behavioural assumptions. However, this information is not always completely available, making necessary the need to resort to inverse methods based on Operational Modal Analysis (OMA) [9]–[12] to extract the dynamic characteristics of the investigated structures and estimate therefrom the unknown physical and mechanical properties. Indeed, OMA can be exploited in combination with FEM to update the uncertain parameters of the numerical models until the predicted dynamic response fits the dynamic behaviour of the building measured experimentally [13]–[15].

The current paper discusses the dynamic identification and the GA-based automatic FE model updating of a historic clock tower located in Rotella, a village of the Marche region in the province of Ascoli Piceno (Figure *1*). The tower is an isolated structure, and it is the only withstanding part of the former Santa Maria della Pietà Church, destroyed by a landslide in 1755. The small village has been stroked by several earthquakes over the centuries and, although it came through unscathed after the Aquila earthquake of 2009, it suffered from serious damages during the Central Italy seismic sequence of 2016-2017, reporting smeared cracks near the openings and in the bell-cell.

Figure 1: Localization of Rotella village inside the Marche region (Central Italy).

2 Methods

The dynamic characterization of the tower was performed by processing output-only vibration data acquired through multiple setups by means of four triaxial Piezo-MEMS accelerometers with 1V/g sensitivity, keeping the top ones as reference sensors in each acquisition (Figure 2). The accelerometers were synchronized by a Sync-HUB connected to a portable station. Each registration lasted 45 minutes. Data were recorded with a sampling rate of 1024 Hz in 8 different measurement points, for a total of 24 nodal processes of nearly 3 million datapoints per channel.

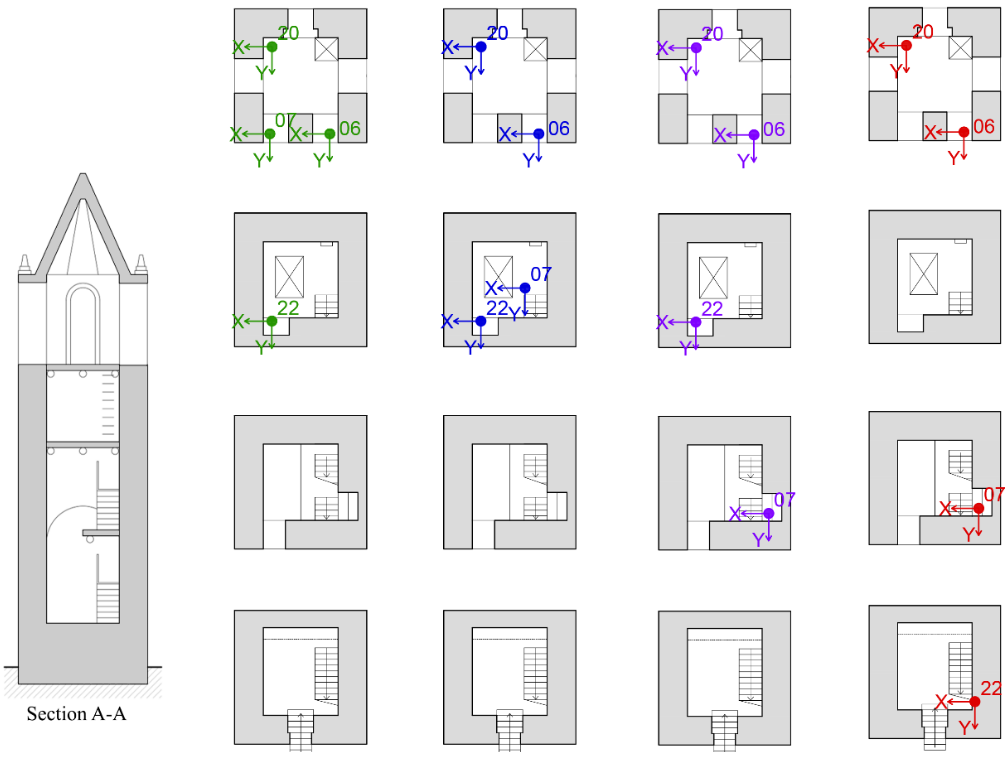


Figure 2: Sensor layouts of the four setups during the dynamic acquisition.

The obtained data was cleaned, decimated, and analysed with the unweighted principal component stochastic subspace identification method (SSI-UPC). This time domain technique permitted to estimate the principal dynamic parameters of the structure, which are summarized in Table 1 [16]–[20]. A visual insight into the mode shapes configuration is also shown in Figure 3.

Mode	f_{exp} (Hz)	Shape Direction
1	2.68	Translation in X Direction
2	2.79	Translation in Y Direction
3	6.97	Rotation around Z axis
4	9.53	Translation in X Direction
5	10.52	Flexural in Y Direction

Table 1: SSI-UPC identified dynamic characteristics.

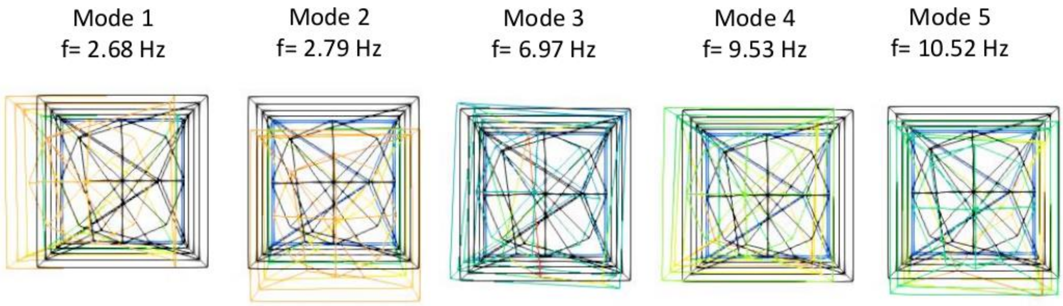


Figure 3: Experimental Mode Shapes of the Rotella identification.

3 Results

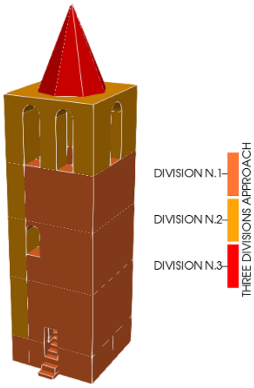
The information collected through in-situ surveys and ambient vibration tests were used to build and calibrate the numerical model (NM) of the tower. The NM, realized in Salome-Meca software© [21], [22], is an accurate representation of the real construction, and accounts for all the geometrical variations and discontinuities of the structure.

The initial values attributed to the uncertain parameters of the model were established according to the Italian Code [23], considering a masonry material made of irregular stone with 19 kN/m3 of density, 0.25 of Poisson's ratio, and 1050 MPa of Young's module. As no visible crack was present, linear elastic parameters were considered for the current condition. The results obtained from the eigenvalue analysis of this preliminary model are reported in Table 2. Considerable differences between numerical and experimental frequencies can be observed.

Mode N.	f_{num} (Hz)	Mass X (%)	Mass Y (%)	$\Delta f_{exp-num}$ (%)
1	2.45	**51.03**	0.07	9.39%
2	2.55	0.07	**49.91**	9.41%
3	6.99	0	0.01	-0.29%
4	9.45	**16.45**	0	0.85%
5	10.36	0	**17.53**	1.54%

Table 2: Numerical frequencies of the preliminary model and comparison with the experimental counterparts.

To improve the NM calibration, a modal-based FE model updating procedure was carried out using a Genetic Algorithm (GA) implemented in Code Aster© software [24], [25]. The corresponding optimal mechanical characteristics were estimated using the eigenfrequencies and modal vectors of the vibration modes experimentally identified (Figure 4).



Division N.	Young Modulus (MPa)	Poisson Ratio (ν)	Mass Density (kg/m³)
1	1402.83	0.449	19
2	682.95	0.207	18
3	1165.01	0.247	18

Figure 4: Sub-division of the Rotella clock tower FE model and corresponding material properties.

The accuracy of the model updating procedure was progressively checked using a very strict objective function that accounted for both frequencies and mode shapes residuals between experimental and numerical results, as well as paying attention to the physical meaningfulness of the updating variables. The results of the calibrated model are shown in Figure 5 and Table 3, where the frequency relative errors and MAC values are also reported to assess the degree of consistency between measured and predicted mode shapes. Overall, a satisfactory agreement is found.

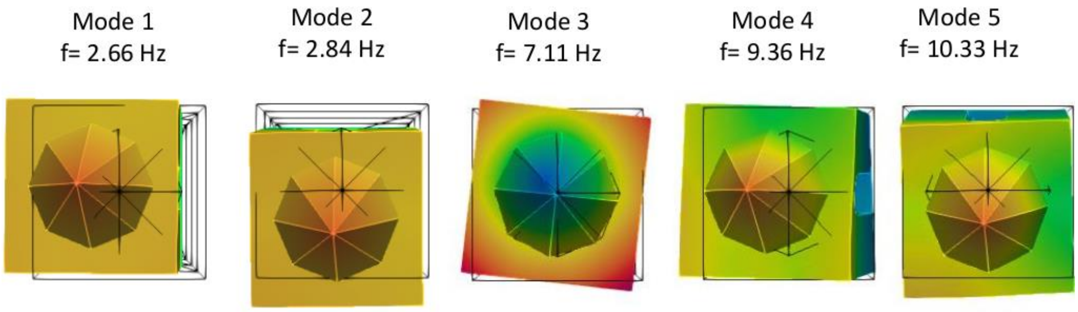


Figure 5: Updated Mode Shapes of the Rotella Numerical model.

Mode	f_{exp}(Hz)	f_{num}(Hz)	Δf (%)	MAC (%)
1	2.68	2.66	-0.75	84
2	2.79	2.84	1.79	84
3	6.97	7.11	2.01	88
4	9.53	9.36	-1.78	89
5	10.52	10.33	-1.81	85

Table 3: Comparison between the experimental and numerical frequencies after the Genetic Algorithms update.

4 Conclusions and Contributions

The paper shows the dynamic identification and model updating with a Genetic Algorithm concerning a case study in the Marche region, Italy. The object of interest is an old, isolated tower in the village of Rotella, a reminder of what once stood there, the church of Santa Maria della Pietà. The church was greatly affected by the 1755 landslide event. The tower was monitored with four accelerometer sensors and its dynamic properties (modal shapes, frequencies, and damping ratio) were identified. The data was utilized to perform a preliminary Finite Element Model updating procedure via a Genetic Algorithm within the Code-Aster© code to minimize the distance between experimental and numerical results. The structure was subdivided into three parts considering the damaged state and degradations observed during the surveys. The results show that the second division has a lower elastic modulus, mainly due to the damaged induced by the recent seismic sequence that affected the Central Italy area in 2016-‘17. It is found that the employed procedure allows to reproduce the actual dynamic behaviour of the real tower in a satisfactory way. Though, in light of the sensitivity of the modal results to the geometrical and material features of the structure, further simulations are required to refine the prediction strategy.

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