IDENTIFICATION OF THE MODAL PROPERTIES OF A SQUAT HISTORIC TOWER FOR THE TUNING OF A FE MODEL

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ABSTRACT

This work describes the modalities of non-destructive tests performed on the clock tower of Trani Castle (Bari, Italy) by using accelerometers installed in different points of the structure. The acquired data have been analysed to identify the modal parameters of the structure that may be used for the calibration of a Finite Element (FE) model. After a description of the investigated structure, the paper gives full details about the experimental set-ups, the operational modal analysis of the recorded data, and the defined FE model. The particular squat structure of the clock tower has suggested to make not only the traditional monitoring under only environmental actions, but also forced tests by mean of a vibrodine ad-hoc designed and realized.

Keywords: non-destructive tests, operational modal analysis, environmental vibrations, high sensitivity accelerometer, microwave remote sensing.

1. INTRODUCTION

During the last decades, a great attention has been devoted to the necessity of defining detailed model of important building heritage that may be utilized for the evaluation of their vulnerability and/or the design of possible interventions. The possibility of validating such models has been increased by different types of non-destructive analysis methods; in this sense, the dynamical tests have acquired a great importance in the recent studies. These tests are based on the consideration that the modal parameters of a structure are strictly dependent on its geometrical and mechanical characteristics. Thus, the analysis of the structural vibrations allows the evaluation of these characteristics by means of minimization techniques that proceeds reducing the difference between the identified experimental frequencies and the numerical ones evaluated through the FE (Finite Element) model (i.e. [1-7]).
Trani castle is one of the most important among those erected by Holy Roman Emperor Frederick II. It is placed just a short distance from the Cathedral of Trani and its location on the edge of town and the height of the towers allowed to guard the entrance of the port and the access roads to the village. Originally had a simple and functional quadrangular enhanced layout with four square towers of the same height. The clock tower of the castle (about 9 meters tall and with a square side of about 3.90 meters), in limestone, was added to the main entrance on the west side in the XIX century; it was built on the principal entrance of the Castle and supported by a barrel vault reinforced with an arch.

In this work an extensive experimental analysis aimed to identify the structural modal parameters has been performed using the data obtained from environmental vibration and forced vibrations, moreover, a Finite Element (FE) model has been realized for preliminarily comparing its dynamic behavior with the experimental data. For identifying the dynamic behavior of the historical buildings, the data are usually recorded by mean of a series of accelerometers installed in specific points of the structure. The recorded data will be then used for the Operational Modal Analysis (OMA) (i.e. [1-11]), which is utilized to get the real values of the modal parameters of the tower. Slender structures such as towers are particularly suitable to this type of investigation, because if they are subjected to vibrations even of low intensity, generally produce very clear signals. On the other side, the analyzed clock tower can be considered a squat building and for this type of structures may be necessary a forced excitation (examples of squat structures or forced excitation in [12-13]) for obtaining enough dynamic information. At this proposal an ad-hoc realized vibrodine has been used for forcing the structure to oscillate. In this paper the equipment and the experimental set up that has been used for in-situ dynamic identification tests are described and an extensive analysis about the effects of the vibrodine on the vibrations of the tower is presented completing the preliminary analysis shown in [14-15]. Using the acquired acceleration measurements, the modal parameters of the tower are identified consistently by two different output-only procedures: the first, based on the Complex Mode Identification Function, exploits a frequency representation of the response; the second, based on the Stochastic Subspace Identification Method, works in the time domain. All the experimental tests have been analyzed and the frequencies of the structure have been identified; moreover useful indication on the use of the vibrodine will complete this contribute together with the presentation of the FE model.

2. EXPERIMENTAL DYNAMIC IDENTIFICATION

2.1. Description of the Trani castle clock tower

The clock tower here considered is built on the principal entrance of Trani Castle and it is supported by a barrel vault reinforced with an arch. It is about 7.0 m tall and about 4.0 x 4.0 m. It consists of three parts: the base, the clock and the hut realized for housing a small bell. The clock tower structure consists in masonry walls in Apulian tufa (with a variable thickness of about 75 cm), covered with Trani stone, of about 25 cm thick. The clock part, of equal size of the base, is a cubic element that has, on each facade, a division in different parts. On the main facade there is the face of the clock, in perfect line with it while the other side has a lower-level openings. On the last level, in perfect proportion with the underlying layers, there is a hut which has a small bronze bell that, at the time when the castle functioned as prison, indicated the changing of the guard. Each level is defined by a cornice; the one which separates the first from the second level is rounded and has no protrusion; the frame on which is set the hut is convex and presents a higher protrusion.
2.2. Monitoring setup

The monitoring system consists of several elements properly connected: the acquisition units or piezoelectric accelerometers with a sensitivity of about 10 V/g; the data acquisition system or DAQs positioned at each of the monitored level; the laptop with an acquisition software; the cables that connect all elements to each other.

In the specific case, the tower has been instrumented with 23 high sensitivity seismic accelerometers ICP PCB 393B31. The accelerometers were placed on four different levels on the four lateral sides of the tower: 8 accelerometer at the four corners of the surface over the clock, 6 accelerometers at three corners at the intermediate level, 6 at the three corners at the lower level part of the clock tower, and 1 accelerometer at the basis as a reference sensor. Finally, two accelerometer were placed on the superior arch for monitoring the oscillation of the upper part, probably the most significant local modes for stability analysis. In figure 2a) a detailed description of the position of the 23 accelerometers on the tower is shown. Appropriate rectangular blocks where the accelerometers were inserted with screws, were used for ensuring the orthogonality of each couple of accelerometers applied in the same point (in figure 2b).

The environmental tests (four consecutive acquisitions) were carried out on 23th January 2014 by recordings of 15 minutes with a frequency of 1024 Hz; the data sampling frequency has been subsequently reduced to 128 Hz and also normalized for eliminating the offset for the analyzed data of the accelerometers.
The particular structure of the tower that may be considered a squat building suggested the possibility of using forced excitation for obtaining enough dynamic information. A special equipment, an electro-hydraulic shaker (called vibrodine) has been designed and realized in order to force the structure. The following day (24th of January 2014) the vibrodine exciter was moved with a special transport from the laboratory of the Politecnico of Bari to the tower of Trani and then, with big efforts, placed on the main entrance of the Tower (figure 3).

Figure 3. The transport and placement of the vibrodine exciter at the entrance of the clock tower

The forced tests were carried out on 24th January 2014 not placing the vibrodine in contact with the tower, but only placing it on the underlying floor at the entrance of the Castle (figure 4). The vibrodine was controlled for vibrating at a defined frequency with a constant amplitude; the accumulator was charged by an electric motor.

Figure 4. The vibrodine exciter placed on the floor

Experimental forced tests were carried out considering a frequency oscillation of 3 Hz, 9 Hz, 16 Hz, 18 Hz and 20 Hz. The length of these tests has been influenced by the limited power of the accumulator; the tests have a length of about 1 minute, decreasing with the increasing of the frequency. Other forced tests were carried out maintaining the electric motor on for charging the accumulator and increasing the test length; but the uncontrolled effect of the motor has influenced the forcing oscillating action of the vibrodine.

3. IDENTIFICATION RESULTS

A preliminary analysis conducted on the time histories of the accelerometers [14] permitted to demonstrate, considering the data of three environmental tests of the accelerometers aligned in the frontal side at different levels including the superior arch and orthogonal to the main entrance and indicated as positions A, B, C and D in figure 5, that:

- the repeatability of the oscillations for the three different tests is very good
- the different amplitude of the oscillations for the 4 considered measured points in all the tests; the peak to peak value of the oscillations in position A is the maximum and it decreases continuously in position B, C and D (lower part of the turret). This consideration ensures a registered environmental oscillation of the superior part of the tower and of the arch nevertheless the very stocky profile of the building; the peak to peak values are consistent with the accelerometers sensitivities ensuring the correctness of the used experimental setup.

![Picture of a building with points A, B, C, D marked]

**Figure 5.** Preliminary analysis on the accelerometers placed on four different levels.

Subsequently further tests were carried out considering the effect of the vibrodine: Figure 6 shows the time histories of a test in which the excitation has been applied with the same amplitude and with a changing frequency. The vibrodine frequency was changed from 1 Hz to 15 Hz with a step of 2 Hz manually modified every about 2 minutes. The final 80 seconds of acquisition have been done switching off the motor in order to evaluate the influence of the motor on the oscillations in the considered positions; it is evident that there is a brusque diminution of the oscillations.

![Graphs showing time histories of vibrodine tests]

**Figure 6.** Forced tests with vibrodine and motor on related to the positions A, B, C, D

From figure 6, it is evident that the vibrodine amplifies the oscillations in all the positions (with a factor of 5-10 times with respect to the environmental oscillations) nevertheless it is placed in the base entrance without a direct contact with the tower structure. A relevant amplitude is observed in all the positions when the vibrodine frequency reaches to the values of 9, 11, 13 and 15 Hz. Considering the last 80 seconds of figure 6 when the pump motor is off, it is clear that the dominant effect of the oscillation is due to the pump motor. This preliminary analysis convinced to use the vibrodine with only the accumulator power (motor switched off), in order to excite the structure avoiding the vibrations of the motor.
The analysis has been very useful for arranging further tests with the possibility of acquiring data only related to the vibrodine forcing action and not influenced by the pump motor effects. Short tests were carried out using only the accumulator energy as forcing action. But the accumulator autonomy was very short and also depending by the frequency; for a frequency of 3 Hz the accumulator has 110 seconds of autonomy, but it decreases to about 50 seconds for 9 Hz, to about 25 seconds for 18 Hz and to only 15 seconds of autonomy for 20 Hz. In figure 7 the plots of the tests in positions A, B, C and D are shown; it is evident that the amplitude varies in accordance with the frequency variation of the vibrodine; in all the positions the maximum amplitude is achieved with a frequency of 18-20 Hz, letting us consider that this value could be considered close to a frequency of the building. The results here obtained are interesting because they demonstrate the applicability of the vibrodine for forcing the structure also if applied not directly in contact with the tower.

A specific software (ARTeMIS) [15] was used for the extraction of the modal parameters. Two different OMA methods were used for each analysis: the Enhanced Frequency Do-main Decomposition (EFDD) in the frequency domain and the Stochastic Subspace Identification (SSI) using Unweighthed Principal Components (UPC) in the time. In Figure 8 is presented the plot of the two methods applied to two environmental acquisitions and in Table 1 are summarized the identification results for all the environmental tests. In the examined tests, the identification of the frequency values has been successfully completed and the identified frequency values are almost the same for the two procedures and for all the examined tests.
Table 1. Mean values and standard deviation of the identified mode shapes for the environmental tests.

<table>
<thead>
<tr>
<th>Mode number</th>
<th>EFDD method</th>
<th>SSI method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean value</td>
<td>Standard deviation</td>
</tr>
<tr>
<td></td>
<td>[Hz]</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>7.52</td>
<td>0.009</td>
</tr>
<tr>
<td>2</td>
<td>10.31</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>13.03</td>
<td>0.6</td>
</tr>
<tr>
<td>4</td>
<td>16.85</td>
<td>0.178</td>
</tr>
<tr>
<td>5</td>
<td>21.78</td>
<td>0.47</td>
</tr>
<tr>
<td>6</td>
<td>26.37</td>
<td>0.28</td>
</tr>
</tbody>
</table>

The identification results for the four considered environmental tests are very satisfying; the first six frequencies may be estimated with a good repeatability between the two methods and between the different tests. There is to underline that the EFDD method is less adapt in this case of very noisy data to identify the frequencies for all the considered tests; for the second mode, only in one test it was possible with EFDD method to estimate it.

The same identification methods have also been applied for the forced tests acting only for the effect of the accumulator: some plots of the most accurate technique (the SSI technique) for the forced tests are shown in figure 9.

![Figure 9: Forced tests identification with SSI: a) forcing frequency 3 Hz b) forcing frequency 9 Hz c) forcing frequency 18 Hz d) forcing frequency 20 Hz](image)

From the identification results plotted in figure 10, it is evident that the effect of the vibrodina forcing is that of creating a number of additional frequencies almost uniformly spaced in the frequency domain. The estimated frequencies appear interrupting the regularity of the frequency added by the vibrodina. It is evident, for example, that the first frequency (around 7.5 Hz), breaks the uniform distribution of the frequencies of the test in figure 10 d) that has a regular step of about 4 Hz. The repetition step of the forced frequencies seems to be around 0.8 Hz for the test with forcing frequency of 3 Hz, 1 Hz for the test with forcing frequency of 9 Hz, 2 Hz for the test with forcing frequency of 18 Hz and, finally, 4 Hz for the test with forcing frequency of 20 Hz. This very interesting aspect will be further investigated in the future. Anyway, there is to consider that the forced tests have a narrow duration due to the limited power of the accumulator and so, the identification techniques may be subjected to errors.
The good results of the identification applying both the techniques of all the environmental tests, confirmed by the presence of the same frequencies also in the forced tests, has permitted to complete the OMA considering the corresponding mode shapes. In figure 10 a plot of the mode shapes referred to the environmental test 1 is shown. It may be clearly noted that the first and second frequencies are identified as the first couple of flexional modes along respectively on the y and x axis. The third mode is the second flexional mode along the x axis, the fourth is a mixed mode (flexional and torsional), the fifth frequency is a pure torsional mode and the sixth is a local mode referred to the superior arch.

![Figure 10: Mode shapes related to the first six identified frequencies](image)

### 4. FE MODEL

The objective of the present research is to define a detailed Finite Element (FE) model of the clock tower that is able to estimate its dynamic behavior and that will be the starting point for a vulnerability evaluation of the structure. Consequently, a three dimensional FE model of the tower has been defined by means of the Straus Software package [16].

In detail, the geometrical dimensions have been imposed on the basis of the performed geometrical survey. The tower has been modelled by means of 2147 plate elements with 8 nodes (QUAD8) that can better describe the behavior of thick plates like the ones here considered (Fig.11). The tower has been considered fully fixed at the base, this assumption has been made considering that the tower was built in a different period respect to the castle; moreover, the high difference between the stiffness of the tower and the castle one makes reasonable the assumption that the dynamic response of the clock tower will be ruled by “local” modes, i.e. the ones strictly connected to the tower itself.

The clock tower is characterised by a single rigid floor located at the top, under which a vault is positioned, this one has been modelled by means of 308 8-nodes plates while the roof has been described by means of a rigid link.

The tower is composed by two levels divided by a floor realised by electro welded gratin, consequently no internal constraints have been considered between the two levels.

The walls at each level are characterised by two layers: the internal one made by tufa masonry, and the external one made by Trani stone; however, as the ground penetrating radar tests has shown, the two layers can be considered perfectly connected and consequently the wall has been modelled as an homogenous wall whose mechanical characteristics have been chosen as weighted average of the properties related to each layer.

The wall thickness at the first level diminishes from the base up to the second level with different dimensions on the north and south facades respect to the ones of the east and west facades. In order to take into account this thickness variations, the first level has been subdivided in five horizontal layers each one characterised by a different thickness (in fig.1 the different thicknesses are highlighted by
different colours of the mesh). The total thickness of the walls at the second level is 0.725m on the north and south facades, and 0.725 on the east and west facades. Consequently, on the basis of the aforementioned assumptions, 14 different transversal section of the plates have been introduced, that in figure 1 correspond to different colours of the mesh.

As a first step of the analysis, the elastic modulus of the plates has been assumed equal to 1155 MPa, while the density equal to 1840Kg/m$^3$. In Table 2 the first five natural frequencies of the FE model are shown together with the characteristics of the corresponding mode shape.

<table>
<thead>
<tr>
<th>Mode number</th>
<th>Numerical frequency [Hz]</th>
<th>Mode shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.97</td>
<td>I bending mode in the arch plane</td>
</tr>
<tr>
<td>2</td>
<td>6.07</td>
<td>I bending mode out of the arch plane</td>
</tr>
<tr>
<td>3</td>
<td>11.83</td>
<td>Bending of the arch</td>
</tr>
<tr>
<td>4</td>
<td>13.03</td>
<td>Torsional mode</td>
</tr>
<tr>
<td>5</td>
<td>18.03</td>
<td>II bending mode in the arch plane</td>
</tr>
</tbody>
</table>

Comparing the FE model results with the identified frequencies, it is evident that an important updating procedure will be necessary for matching the identified mode shapes by tuning opportunely the elastic modulus and the density of the plates at the different levels of the tower.

5. CONCLUSIONS

The study focuses on the evaluation of modal parameters of the historical clock tower of the Trani Castle through the application of accelerometers and on the following utilization of these data for defining a detailed FE model that describes the actual behavior of the structure.

The dynamic tests were performed in operational conditions and also by using a forcing vibrodine. The extraction of modal parameters from ambient vibration data was carried out using OMA techniques both in frequency and time domain. The obtained results are reasonable and encourage about the accuracy of the modal estimation and of the updated FE model of the tower.
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