Identification of the modal properties of an instrumented building

M. Diaferio, D. Foti
Dipartimento di Ingegneria Civile e Ambientale - Politecnico di Bari, Via Orabona 4, 70125 Bari, Italy

N.I. Giannoccaro
Dipartimento di Ingegneria dell’Innovazione, Università del Salento, Via Monteroni 73100 Lecce, Italy

ABSTRACT: Dynamical experimental tests for the structural identification of reinforced cyclopic concrete tower of the Provincial Administration building of Bari, Italy, have been performed for a long period in order to achieve a wide set of data. In this work new experimental data are shown and discussed. Different floors of the tower were simultaneously monitored in such a way to analyse the influence of the external excitation on the tower vibration amplitude. In particular, a very long acquisition (2 hours) during light fires explosions have been carried out. Using the acceleration measurements, the modal parameters of the tower are identified consistently by two different output-only procedures: the first, based on the Enhanced Frequency Domain Decomposition, in the frequency domain; the second, based on the Stochastic Subspace Identification Method, works in the time domain. Considerations about the consistency of the results respect to the different methods and to the choice of the identification parameters are carried out.

1 INTRODUCTION

The tower of the Provincial Administration building of Bari, Italy, dates back to the thirties of the 20th century, and it is about 60 meters tall. It is situated close to the centre of the city, near the seaside; the principal facade is in the North-West direction, that is the dominant wind direction, and it is close to roads with high traffic level. For this reason, the environmental excitations due to wind and traffic are expected to cause non-negligible vibrations of the tower.

The analysis of the vibrations of the tower gives the modal parameters that could describe the dynamic characteristics of this structure.

Many studies regarding the dynamic identification of towers have been developed. In Italy the interest has been especially devoted to the study of the masonry towers of churches, in order to preserve the historical Italian heritage. Some examples include the following tower: “Torrazzo” in Cremona (Binda et al. 2000), the Civic Tower in Vicenza (Valluzzi et al. 2003), the St. Stefano bell-tower in Venice (Lionello et al. 2004). Therefore, most of the research effort in this field is presently focused on integrated methods for assessing tower vulnerability (Sepe et al. 2008), on non-destructive techniques for health monitoring and damage assessment (Gentile and Saisi 2007), or finally on suitable intervention solutions for structural repairing and strengthening (Modena et al. 2002).

Other studies concern the dynamical behaviour of bell towers, realized both in masonry (Bennati et al. 2005a, Bennati et al. 2005b) and in reinforced concrete (Ivorra et al. 2005, Ivorra and Pallarés 2006a, Ivorra et al. 2006b, Foti et al. 2008). In these cases, apart from ambient vibrations, the bells swinging is considered as a forced input on the structure, sometimes causing worrying vibrations (Lepidi et al. 2008)].
Interesting cases in the dynamic study of the behaviour of slender reinforced concrete structures are silos (Dooms et al. 2006) and minarets (Bayraktar et al. 2008).

Anyway, it must be pointed out that no study on towers made with cyclopic concrete exists. In fact, the peculiarity of this material is that the mixture contains concrete and aggregates with big dimensions tied together. A preliminary study has been developed to analyze the behaviour of the tower during the shock event of the collapse of 3 buildings about 1 Km far from the Provincial Administration building (Diaferio et al. 2007). Unfortunately, the resulting signals show a high disturbance and can not be considered for comparison with the present and more detailed acquisition tests. The dynamic behaviour of structures and their natural frequencies, mode shapes and dampings, can be determined by mean of modal testing. It consists in extracting modal information from the dynamic response of a structure and, but not necessary, the corresponding input excitation. The behaviour is defined from a number of natural frequencies and mode shapes, depending on the position of the sensors of the acquisition system. The modal characteristics are then obtained through different methods implemented in the frequency or in the time domain.

All the process to get the dynamic parameters of the structure is known as system identification. It has been applied not only to civil structures such as buildings and bridges, but principally, at the beginning, in the mechanical and aerospace engineering fields.

In the following, to experimentally identify the dynamic characteristics of the tower of the provincial administration building, the Operation Modal Analysis (OMA) (Peeters and De Roeck 2001) method has been applied. In OMA, the structure is excited by an unknown input force (ambient vibrations such as traffic, wind and earthquake loads), and responses of the structure are measured.

In general, these studies involve both analytical and experimental analyzes, to get the possibility to upgrade a finite element model that could describe the real behaviour of the structure.

In this paper new tests have been performed and the results have been discussed; these results have been obtained during a particular event that happens once a year including the explosion of several light fires exactly close to the considered tower. A very long acquisition (2 hours) was carried out and different floors of the tower were simultaneously monitored in such a way to analyze the influence of the external excitation (light fires explosion) on the tower vibration amplitude.

Using the vibration 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, that exploits a frequency representation of the response; the second, based on the Stochastic Subspace Identification Method, that works in the time domain.

Considerations about the consistency of the results respect to the different methods and to the choice of the identification parameters are carried out.

The study of the tower of the Provincial Administration building of Bari is still in progress. In the present paper the results of the analysis obtained utilizing only a part of the recorded oscillations are discussed.

1.1 Description of the tower

The tower has a square plan with a side of about 7.0 m at the base. It is made of massive concrete reinforced with a diffuse and superficial reinforcement and it stands on a foundation slab. The eleven levels of the tower consist of a basement, a mezzanine and nine floors with different interstory heights. From the base to the 5th floor, the tower, excepted the sea-front façade, is surrounded by the building of the provincial administration, from which it emerges for other six levels from 6th to 11th ones, with openings on the facades in the first floor up to the building of the provincial administration and in the upper two floors.
2 ENVIRONMENTAL VIBRATION TESTING

In OMA the structure is excited by an unknown input force (ambient vibrations such as traffic, wind and earthquake loads), and response of the structure is measured. This method has numerous advantages: one is that the experimental instrumentation may be simplified, because no information is needed on the input force. In many cases, in fact, the necessity of an heavy-force excitation becomes very expensive, moreover, the application of this force may be incompatible with the ordinary serviceability conditions and sometimes may cause possible damage to the structure.

Figure 1: Building under analysis.

Figure 2: Reference system. Figure 3: Acquisition board.

In the present case it was analyzed the response data recorded during the local day dedicated to S.Nicola (8th of May), when dozens of thousand people move around the analyzed tower, and, some light fires explosions happened very close to the building.

All the evening (2 hours) of this event was acquired using thirteen SA-107LNC servo-accelerometers by means of an electronic acquisition board (Fig. 3). The servo-accelerometers used are characterized by a high sensitiveness and are therefore good to detect small oscillations such as, for example, those induced by environmental actions.

Figure 4: Positioning of the accelerometers.
All the accelerometers have been installed on the floor level and at 10 cm from the corner (Fig. 2 for example shows the accelerometers numbered as 307 and 308 directed in y and x axis direction respectively). The x-axis direction is chosen parallel to the building surface along the sea-walker (Fig. 1), the y-axis is orthogonal to x-axis, and the z-axis complete the orthogonal reference system.

A more detailed scheme about the accelerometers disposition at different levels is shown in Fig. 4; four different floors were instrumented and they are indicated as P5 (floor 5 at 24.57 m), P7 (floor 7 at 38.20 m), P9 (floor 9 at 49.20 m), P10 (floor 10 at 55.70 m) and their dimensions are depicted in Fig. 4. It is possible to note that all the accelerometers are placed along the same xz-plane of the building. This choice was due to the difficulty of placing at same level other accelerometers at the other side of the building. In fact one side of the internal part of the tower was occupied by a steel staircase and a lift used to get to the terrace visible almost at the top of the tower.

The correspondence of the acquisition channels and the accelerometers labels used in Fig. 4 is shown in Table 1.

<table>
<thead>
<tr>
<th>Accelerometer label</th>
<th>296</th>
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<th>299</th>
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<th>301</th>
<th>302</th>
<th>303</th>
<th>307</th>
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<th>310</th>
<th>311</th>
<th>312</th>
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<tr>
<td>Acquisition Channel</td>
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<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>11</td>
<td>12</td>
<td>13</td>
<td>8</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>Height (z axis) [m]</td>
<td>24.57</td>
<td>24.57</td>
<td>24.57</td>
<td>24.57</td>
<td>24.57</td>
<td>38.2</td>
<td>38.2</td>
<td>38.2</td>
<td>49.20</td>
<td>49.20</td>
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The acquisition frequency has been assumed equal to 400 Hz. The very long acquisition time carried out a very high number of samples. The objective of the analysis was to preliminarily evaluate if something strange could be happened during such a long acquisition. The analysis of the recorded time histories shows that in the examined interval the accelerometers positioned at the 10th floor did not work correctly, so in the following study they have been excluded.

In effect, as it is shown in the Fig. 5, some strange happened regarding some of the 10 channels (channels 4 and 6 i.e.). It has to be considered that the acquisition started at 20.30 of the 10th May; some minutes later several shocks of light fires explosion interested an area very close to the building.

![Figure 5: Acceleration time-histories measured for some SA107LN sensors.](image)

It is evident that the accelerometers, although if referred to different directions, have a similar shape of the amplitude, probably due to the external excitation.

### 2.1 Results of experimental analysis: identification of modal properties

The extraction of the modal parameters from ambient vibration data was carried out by using the OMA software (OMA, 2006). In OMA, the EFDD and the SSI techniques are used to determine the natural frequencies, mode shapes and damping ratios of the building. The EFDD technique is an extension of the Frequency Domain Decomposition (FDD) technique, that is a non-parametric technique based on the singular value decomposition for each frequency line of
the response spectral density matrix (Bayraktar et al. 2008). The singular values are interpreted as a combination of auto-power spectra for a set of Single-Degree of Freedom systems. The physics of the structural system are obtained by looking at the plot, identifying the SDOF functions and picking the peak of each function. The modal parameters are then extracted from the singular values. The SSI technique is a time domain method that works with time data; it identifies a stochastic space model from output-only measurements, than the SDOF normalized autocorrelation functions and finally the frequencies and damping.

In this work, the acquired data are referred to a particular event that happened only once a year and that involves a big amount of people (dozens of thousand) that moves all around the instrumented building. The analysis of the data was carried out dividing the time period in several intervals of 9 minutes each; a statistical analysis was introduced in order to evaluate the repeatability of the identified frequencies in the different intervals and, above all, the effects of the external disturbances. The frequencies identification was carried out considering the consistency of the identified frequencies on the 14 different intervals referred to consecutive time periods. In figures 6 and 7 the experimental results with both the used OMA methods referred to one of the 14 intervals considered are presented; while in table 1 the analysis of the more probable frequencies respect to the time intervals for both the methods are shown.

From table 1 it is possible to note that the two methods give similar results and that there is a good consistency of the selected frequencies for all the time intervals considered during the long acquisition.

![Figure 6](image1.png)

Figure 6: Singular values of 10 signals and average of all signals obtained from the EFDD technique for the interval number 11.

![Figure 7](image2.png)

Figure 7: Stabilization diagram of the estimated state space model obtained from the SSI technique for the interval number 11.
The statistical repeatability of the frequency at about 2.4 Hz, encouraged to use it for calibrating the finite element model. The correspondent experimental mode shape is shown in figure 8 and it seems to have a typical flexional shape in the xz plane. Differently, the frequencies at about 3.8 Hz and 5.7 Hz show a mode shape close to a torsion and flexional mode, respectively.

![Modal Values](image)

Figure 8: The mode shape referred to the frequency of 2.417 Hz for the interval number 11.

3 FINITE ELEMENT MODEL

In order to better determine the Young’s modulus of the cyclopic concrete, two specimens (Fig.9) were extracted from the walls at the 5th and 7th floors. The values are quite different: the first specimen gave $EA=22470$ N/mm², the second gave $EB=20585$ N/mm². That means that the structure and its constitutive material (cyclopic concrete) are very in-homogenous and it is difficult to attribute a unique value to $E$ for a numerical model of the tower.
A preliminary analysis of the tower has been performed on a finite element model obtained using 4-node shell elements. The model has a total of 6678 nodes, 6510 shell elements and 39612 active degrees of freedom. The parameters chosen to upgrade the model are several: the Young’s modulus, the masses and their distribution, the connection with the palace at the low levels. The upgrade of the model, that is still in progress, shows that for a Young’s modulus of 20800 N/mm² and simulating the constraints due to the building situated at the lower floors by an uniform distribution of linear springs of constant 40 KN/m³, the error on the first frequency obtained by OMA is about 15%, while on the third frequency is about 10%. The preliminary results, in the authors’ opinion, encourage the idea that a more detailed model, that is still on study and that utilised 8-node brick elements and a more refined distribution of the masses, will give better results.

4 CONCLUSIONS

In this paper it has been analysed the experimental behaviour of the tower of the Provincial Administration building of Bari made in cyclopic concrete, during a particular event with fire explosions close to the tower.

The novelty of this study lies both in the highly in-homogeneity of the building material, and in the technique used that provides a statistical repeatability analysis applied dividing in several acquisition intervals a very long acquisition concerning all the length of time of the event (2 hours).

The frequency identification was carried out using the classical methods EFDD and SSI of OMA for each of the consecutive acquisition intervals.

The obtained results permit to identify with a good confidence the frequencies of the building; future researches will be focused on the validation of the numerical model.

REFERENCES


Diaferio, M., Foti, D., Sepe, V. 2007. Dynamic Identification of the Tower of the Provincial Administration...


