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EXTENDED ABSTRACTS

On the vulnerability of an irregular reinforced concrete bell tower

Diaferio, Mariella[1]; Foti, Dora[2]; Giannoccaro, Nicola Ivan[3]; Ivorra, Salvador[4]; Notarangelo, Giovanni[5]; Vitti, Michele[6];

ABSTRACT

In the present paper the bell tower of the church of Santa Maria Assunta of Lamadacqua in Noci (Bari, Italy) realized by reinforced concrete septa is studied regarding its vulnerability. The bell tower has a total height of about 14m, and is characterized by an unusual cross section, which is composed by three slender septa, which are connected in correspondence of the cantered axis, realizing a kind of star shape. A Finite Element (FE) model validated by an experimental dynamical analysis has permitted to get considerations about the tower vulnerability, on the basis of the following retrofitting for making the structure safe.

Keywords: reinforced concrete structures, slender structures, Operational modal analysis, finite element model.

1. INTRODUCTION

In literature many studies are available on the dynamic identification of masonry structure, however very few studies are devoted to the analysis of reinforced concrete buildings by means of dynamic tests.

In the present paper the bell tower of the church of Santa Maria Assunta of Lamadacqua in Noci (Bari, Italy) realized by reinforced concrete septa has been considered as a case study to define its vulnerability before and after restoring interventions [REF IOMAC].

Bell towers are typically high, slender structures, usually adjacent to churches and city halls (belfries) or free-standing near eminent civic and religious buildings (campanili). They represent important urbanistic emergences characterizing the whole Italian countryside; they usually constitute a rich cultural heritage, for their historical and architectural value.

However, bell towers present a certain slenderness which stresses their flexibility, exposing them to high dynamical risk. Even if collapses are often justified by extraordinary loading events, in aging masonry towers danger may arise even during common service conditions, due either to the progressive deterioration of particular structural elements or to the gradual decay of the material

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properties. Therefore, most research effort in this field is presently focused on integrated methods for assessing tower vulnerability [1,2], on non-destructive health monitoring techniques [3], or on suitable intervention solutions for structural repair and strengthening [4].

Thanks to the possibilities offered by current technologies and materials, modern bell towers are often characterized by audacious and spectacular architectural designs, calling for structural solutions driven by the search for extreme lightness and slenderness. Despite the modern towers' vulnerability against natural excitations tending to be lower with respect to aging traditional masonry structures, the trend towards increasing flexibility should call the attention of structural designers to the high dynamical risk related to the service conditions, that is to the effects of the complex dynamical action caused by swinging bells.

To better understand the modal behavior or dynamic characteristics of bell towers, Structural Health Monitoring (SHM) techniques enable engineers to understand the real dynamic characteristics of buildings [REF]. In these techniques, vibration data recorded under ambient conditions or during seismic events are processed in time or frequency domain and consequently actual dynamic characteristics such as modal frequencies, shapes and modal damping ratios are obtained. Therefore, in recent times SHM is adopted to update a Finite Element Model (FEM) of the structure based on the parameters obtained from vibration-based identifications in order to minimize the uncertainties in the model itself [REF].

Modal testing is one of the most popular and effective techniques for studying the behavior of structures and, in particular, of slender ones. Various methods, including both time and frequency domain based, are available for extracting modal information from the dynamic response of a structure and the corresponding input excitation. The process of establishing the dynamic characteristics of a system from an experimental model is known as system identification [5, REF]. Modal testing has been implemented on many different types of civil engineering structures.

In modal testing, the Operational Modal Analysis (OMA) method is able to experimentally identify the dynamic characteristics of a structure [6, REF]. In OMA the structure is excited by an unknown input force (ambient vibrations such as traffic, wind, and seismic loads) and responses of the structure are measured. Therefore, the system identification techniques through ambient vibration measurements have become very attractive. In this case, though, only the response data due to the ambient vibrations are measurable while actual loading conditions are unknown.

The methods defined above have been utilized to identify and to model update the bell tower of Lamadacqua, one of the few campanili in reinforced concrete.

The church of Lamadacqua and its bell tower are realized in the countryside, in an area, which is subjected to winds of high intensity, thus, the church and its bell tower have been interested by a significant degradation of the structural materials.

The structure has undergone degradation phenomena caused mainly by exogenous phenomena, such as wind and atmospheric phenomena. Therefore, a series of interventions for the recovery and the structural reinforcement have been designed and realized.

The behaviour of the structure to environmental vibrations has been experimentally monitored in-situ before using special accelerometers positioned on the bell tower and on the spiers. The acquired data were used to dynamically identify the structure and calibrate the FE model of the bell tower, taking into account that the geometry of the bell tower is non-conventional.

2. DESCRIPTION OF THE TOWER

The Church of Santa Maria Assunta has been realized with aload-bearing structure in soft stone ashlars (tufa) masonry with a thickness of 75 cm and with a single face. The bell tower was designed by Plinio Marconi and completed in 1963. The bell tower has a total height of about 14m, and is characterized by an unusual cross section, which is composed by three slender septa, which are connected in correspondence of the centered axis, realizing a kind of star shape. Moreover, the transversal section of the tower varies along the height: starting from the height of about 12,5 m the septa reduce to 4 spiers, similar to cantilever beams, characterized by high slenderness. On the top of the spiers, metal struts connect the lateral spiers to the central one and support three bells (Fig. 1). The tower is near the masonry church but not structurally connected to this one.

Figure 1. *Church and bell tower of Santa Maria Assunta of Lamadacqua in Noci (Bari, Italy).*

The roof is pitched and made in reinforced concrete (r.c.) with a double strut scheme. The bell tower to the left of the building, instead, is a structure entirely in r.c. with section septa varying from bottom to top. In the space between the church and the bell tower there is a small room in load-bearing masonry and a horizontal floor in r.c. simply leaning on the main structures (Figure 1).

From a careful visual inspection, it was possible to outline the conservative state of the structure. The structure has undergone degradation phenomena mainly caused by exogenous phenomena, such as wind and atmospheric phenomena. The conformation of the spiers similar to a cantilever beam and the unobstructed area on which the structure stands means that the wind's kinetic action causes particularly critical bending moment stresses at the base, with tensile stresses too high for concrete. Degradation phenomena are noted, such as diffuse cracks in correspondence of the cover plates, total and partial expulsions of them, oxidation of the reinforcing rods. Therefore, a series of interventions for the recovery and the structural reinforcement have been designed.

From the point of view of structural modelling, the walls are of the bell tower, the sail and the veil positioned on the front entrance of the church are in reinforced concrete with mediocre mechanical characteristics.

The situation of the structure before the intervention is depicted in Figure 2 (front view and lateral view) where the profiles of the damage are highlighted in red.

a) front view b) lateral view

Figure 2. *Damages observed on the r.c. structures on the Church of Santa Maria Assunta bell tower (pre-intervention)*

The bell tower is affected by cracks and injuries partly caused by problems of capillary rising and, in part, by the scarce mechanical characteristics of the materials utilised. In this regard, the detailed survey of degradation and instability was able to confirm the important cracks patterns. In particular, the shape of the cracks on the three spiers of the bell tower is caused by a concomitance of actions and reactions to which the structure is subject (Figure 3). In particular, the exogenous degradation, that is the alteration of the characteristics of the materials constituting the structure, was caused by external agents such as wind. The area in which the structure rises, in fact, can be considered without obstacles and this causes an increase in the kinetic pressure that the wind exerts on the structures it meets. Moreover, in the case of a cantilever structure, the action of the wind causes particularly critical bending moment stresses at the base with tensile stresses to which the concrete is not able to resist. Among the three spiers at the top of the bell tower, the one adjacent to the remaining part of the structure is damaged to a lesser degree; this could be caused by the holding reaction that the remaining structure exerts on it, with a consequent reduction of the tensile stresses.

Figure 3. *Detail of damages observed on the r.c. structures on the Church of Santa Maria Assunta bell tower.*

The intervention provided a set of works designed to operate a structural reinforcement of the bell tower as localized reinforcement on an existing building in accordance with Chap. 8.4.3, DM 14.01.2008 [22]. Of course, the intervention on the existing construction must improve the constructive regularity, resistance and ductility, so that it intervenes more intensely, for example, on the more resistant structural elements or on the mechanisms of collapse in order to transform them from fragile to ductile.

3. DESCRIPTION OF THE EXPERIMENTAL TEST CAMPAIGN AND RESULTS

3.1. The experimental tests before retrofitting

On 22th January 2018 while the structure was made safe by means of coatings and scaffoldings were placed for repairing the structure (as shown in Fig. 4), the first experimental campaign was carried out. The tower was instrumented with seventeen 393B31 uniaxial piezo-accelerometers with a sensitivity of 10.000 mV/g, placed at three different levels on the tower. The accelerometers were connected to a centralized data acquisition system National Instruments DAQ model NI 9232 mounted on a NI cDAQ-9188 Chasis CompactDAQ. To guarantee the recordings in two perfectly orthogonal directions in each acquisition point, a cubic metallic device has been utilized as shown in Fig. 5. Due to the situation, several blocks containing the accelerometers were only placed on the pillars where it was possible.

Figure 4. *Details of coatings and scaffoldings before the retrofitting intervention.*

Figure 5. *Details of the blocks placement and accelerometers connection*

Some consecutive ambient tests have been developed with a duration of 10 min each. All tests have been developed with a sampling frequency of 1024 Hz. Regarding the environmental tests, the aim was to perform a statistical analysis on the repeatability of the identified modal parameters. The location of the sensors have been selected to detect accelerations in the North-South direction, similarly to those in the orthogonal direction (Figure 6). At each level they are applied in two opposite points of the structure and they provide together the oscillations in both directions; in this way they also allow to study the possible torsional motion of the structure. To analyse the structure's main modes and frequencies, four environmental noise recordings were carried out named Test1, Test2, Test3 and Test 4 respectively.

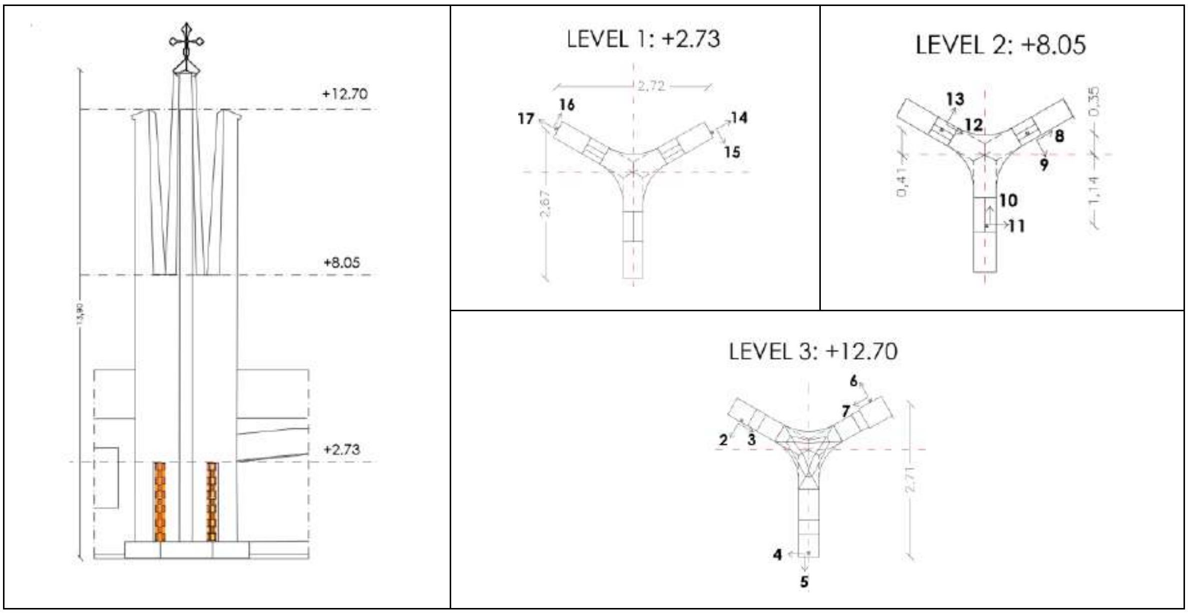


Figure 6. *General design on the tower. Accelerometer location*

The analysis of the data acquired in the 1st experimental test campaign for determining the dynamic behavior of the bell tower was carried by mean of Operational Modal Analysis techniques using Artemis Modal software [23]. For the OMA analysis, the bell tower structure geometry was simplified as showed in Figure 7 with 16 nodes (for nodes for each level) indicated with points in Figure 7; moreover, the location and orientation of each accelerometer and its direction is also showed and the considered xyz reference system.

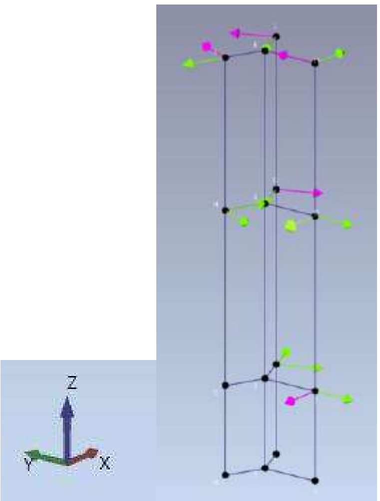


Figure 7. *Model for OMA analysis*

3.2. The OMA results

The dynamical identification has been carried out by using the classical OMA methods for all the four test. In Fig.8 is shown the diagram obtained with the Stochastic Subspace identification (SSI) with Unweighted Principal Component (UPC) [31], applied to the data of Test 1 with a frequency range [0-17 Hz], 4096 bit of resolution and 5 channels of analysis corresponding to the accelerometers indicated with pink arrows in Fig.7.

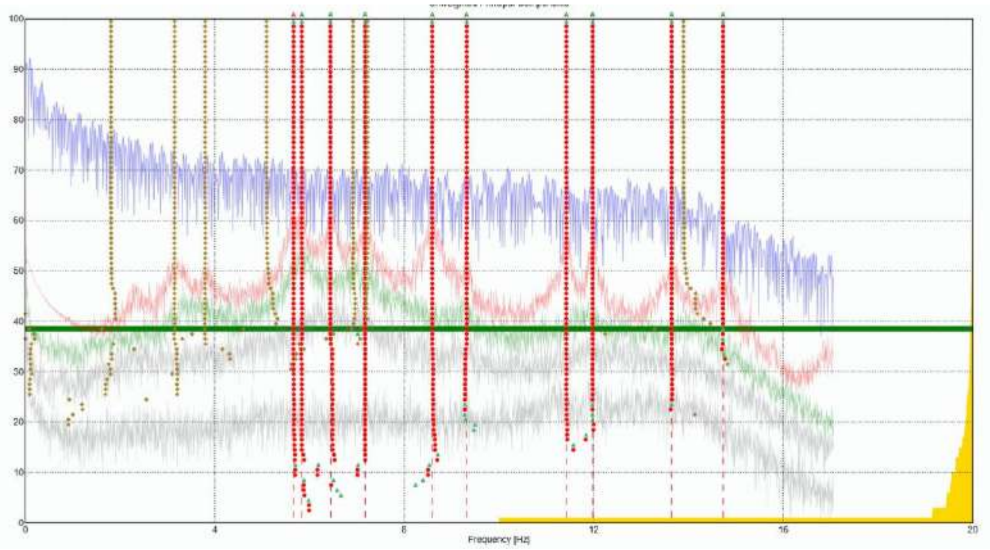


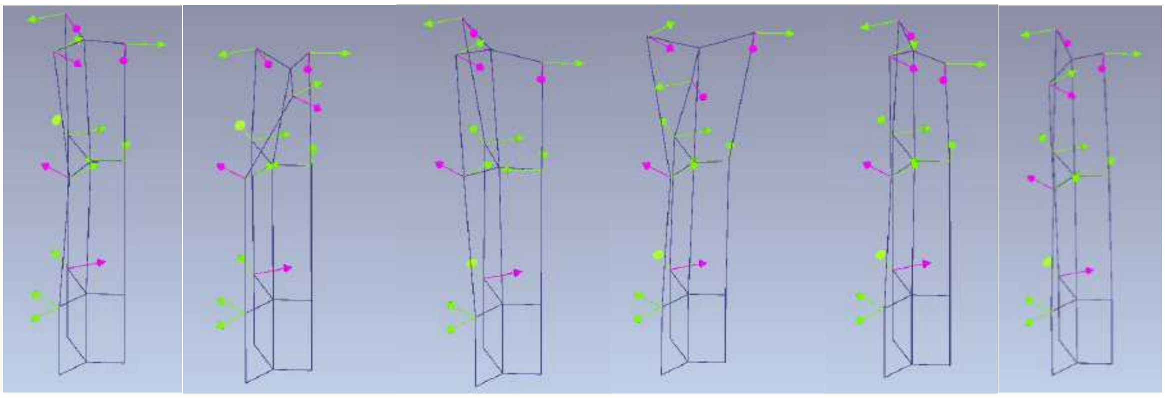
Figure 8. *SSI results for Test 1*

As clearly depicted in Fig.8, several frequencies may be clearly estimated from the experimental data. In Table 1, the first six identified frequencies and the corresponding damping (%) for the 4 considered tests in order to have an idea of the repeatability of the results. It is evident from Table 1 and Fig.8 the excellent repeatability of the identification results that make the authors extremely confident about the values of the first 6 identified frequencies. Also the values of damping, that usually is a very unstable parameter, increase the conviction of the goodness of the obtained results and the identified frequencies constitute a modal sign of the structure.

Table 1. The first 6 identified frequencies from the experimental campaign of 22th January 2018

Frequency number	**Test 1**		**Test 2**		**Test 3**		**Test 4**	
	Frequency [Hz]	**Damping [%]**	**Frequency [Hz]**	**Damping [%]**	**Frequency [Hz]**	**Damping [%]**	**Frequency [Hz]**	**Damping [%]**
1	5.67	1.85	5.64	1.42	5.62	1.63	5.67	1.49
2	5.84	1.10	5.82	1.12	5.81	1.36	5.86	1.02
3	6.45	1.43	6.46	1.47	6.48	1.83	6.48	1.28
4	7.17	1.72	7.11	1.49	7.16	2.2	7.18	1.22
5	8.59	0.97	8.58	1.17	8.59	1.01	8.71	0.73
6	9.31	0.35	9.31	0.24	9.32	0.40	9.31	0.35

About the characterization of the modes related to the identified frequencies, considering the state of the tower and the particular shape , the modes have been depicted without introducing slave nodes equation apart the joint connection of the nodes at level 0 with the ground. This assumption is justified by the damage pattern which shows the degradation of the connections at the top of the spiers. The modes are shown in Fig. 9, they demonstrate the complexity of the geometry of the structure and the existence of local modes.



a)1st mode b) 2nd mode c) 3rd mode d) 4th mode e) 5th mode f) 6th mode

Figure 9. *Identified modes corresponding to the first 6 frequencies*

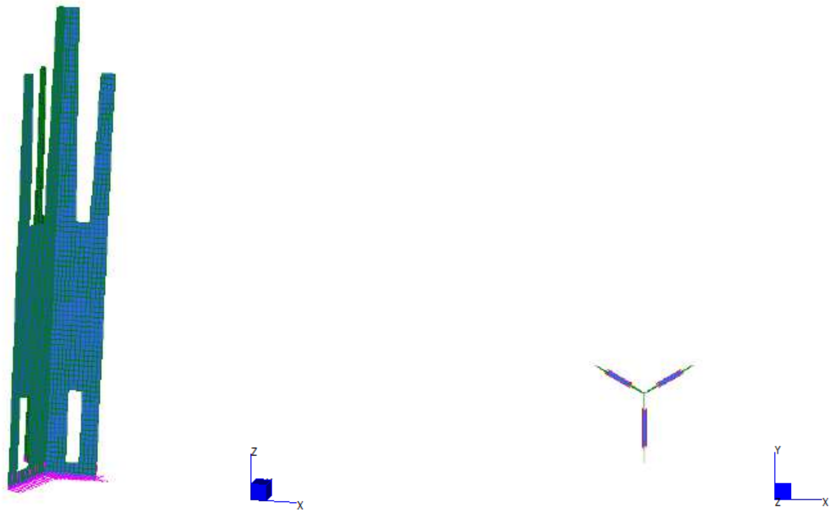
The analysis of the mode shapes may be performed considering the specific spiers most solicited from each mode, finding also a suitable tool of comparison with the realized FE model.

4. Model

A numerical model of the bell tower has been defined by means of Straus software [24], which operates in the framework of the finite element method.

The septa of the bell tower have been modelled by 2853 QUAD4 elements which are four-node shell elements, while regarding the mechanical properties of the reinforced concrete has been assumed the elastic modulus equal to 23237 MPa, the Poisson's ratio equal to 0,2 and the density equal to 2500 kg/m3.

As a first step of the analysis, it has been assumed that the church and the bell tower do not interacted each other, in accordance with the documents, and that the bell tower was fixed at the base. In Fig. 10 the numerical model is shown.



(a) (b)

Figure 10. Finite element model of the bell tower of Santa Maria Assunta of Lamadacqua in Noci (Bari, Italy):

a) 3D view; b) plan view.

In Table 2 the first 5 frequency values of the finite element model and the percentage differences with the experimental ones are listed .

Table 2. Frequency values of the FE model and percentage differences between the numerical and experimental frequencies.

Mode #	Frequency [Hz]	Difference [%]
1	5.47	3.50
2	6,17	5.65
3	6.21	3.70
4	7.89	10.04
5	8.20	4.50

The In fig. 11 the first five natural modes of the structure are shown, it can be verified that due to the absence of connections at the top, the first modes are local modes which involve mainly the spiers. The mode shapes are quite similar to the experimental ones, thus to reduce the differences between the numerical and experimental frequency values, a updating procedure is needed. In detail, a more refined model may be obtained by varying the concrete elastic modulus. It must be underlined that as a first step it has been assumed a low value for the concrete elastic modulus as in several parts of the structure the concrete was interested by deterioration. However, in some parts of the bell tower the concrete is in better conditions. This circumstance may be modelled by assume g two different values of the elastic modulus for describing the different level of concrete degradation. Moreover, an analysis of the influence of the church on the response will be investigated.

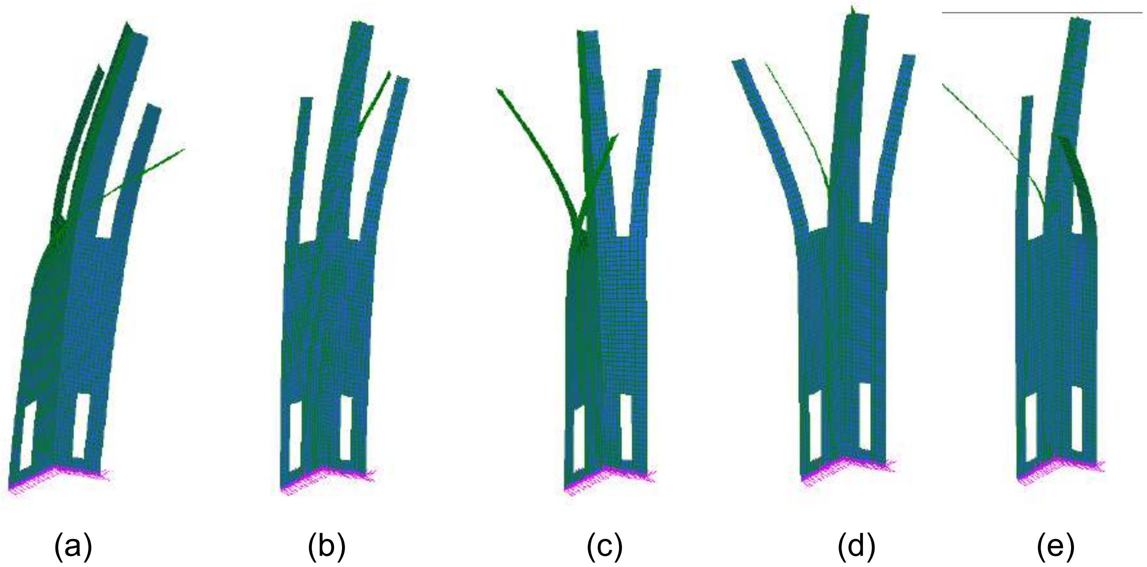


Figure 11. First five natural modes of the finite element model of the bell tower of Santa Maria Assunta of Lamadacqua in Noci (Bari, Italy).

5. CONCLUSIONS

The paper deals with the preliminary analysis of the bell tower of Santa Maria Assunta of Lamadacqua in Noci (Bari, Italy). The structure was interested by a high level of degradation and retrofitting interventions were needed. In order to achieve information regarding the main problems of the structure and to design the interventions, the analysis of the available documentation, a visual and geometrical survey of the damage pattern, a finite element model and ambient vibrations tests have been performed. The experimental results confirm the existence of local modes which mainly involve the spiers. The comparison between the numerical model results and the experimental ones confirm the existence of local modes which may be responsible of the damage pattern at the top, and that must be inhibited in order to improve the structural behaviour. Even if the experimental and the numerical mode shapes are quite similar, the next step of the research will be the update of the numerical model in order to match the experimental frequencies. The final step of the research will be the estimation of the behaviour of the bell tower after the retrofitting interventions through dynamic tests.

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