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Mechanical Models in Structural Engineering

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Mechanical Models in Structural Engineering

Polytechnic School of Alicante

23rd – 25th October 2019

Universitat d'Alacant
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HEALTH MONITORING THROUGH A TUNED FE MODEL OF A MEDIEVAL TOWER PLACED IN A LANDSLIDE AREA

Diaferio, Mariella[1]; Foti, Dora[2]; Giannoccaro, Nicola Ivan[3]; Ivorra, Salvador[4]

ABSTRACT

The present paper deals with the analysis of the dynamic behaviour of a medieval tower placed in a landslide area. All the available documents have been analysed, a geometrical survey was performed and a visual inspection, in order to verify the actual conditions of the tower with respect to the effects of the landslide and the degradation of the structural materials, was conducted too. Interesting conclusions have been obtained about the integrity state of the tower and the proposed procedure could be generalized to predict the behaviour of the tower under other kinds of unexpected environmental events.

Keywords: Operational Modal Analysis, historical building, health monitoring, finite element model.

1. INTRODUCTION

Among the buildings belonging to the architectural heritage, masonry structures represent its main part. One of the most important characteristics of the masonry structures is their low ductility, which can lead to a rather fragile global behaviour; as a consequence, masonry structures are particularly vulnerable to dynamic actions. Of course, the evaluation of their vulnerability is an important information and many researchers devoted their studies to this aspect. Mainly these studies proceed by the definition of a reliable numerical model of the structure in order to carry out a subsequent evaluation of its vulnerability and the definition of possible retrofitting interventions, if required [1-5].

In the present research the interest is centred on the medieval town of Craco, located on a hill not far from the city of Matera, in the South of Italy; Craco is now considered a phantom town due to different landslides, which affect the settlement of the town. Now there is no active landslide, but they can easily be reactivated, as demonstrated by the events that of the years 1962 and 1991, which led to the necessary evacuation of the inhabitants of Craco.

All buildings suffered high collapse phenomena except the medieval tower of Craco [6], which is the only building that still stand. In fact, the tower is built on a rocky ridge, but all around the landslide has dragged many buildings. The structure, of Normand origin, was built for defensive aims. Therefore, it was built on the highest point of the hill. Around it then, the town was built; that is now the historical

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center of Craco. The scenario that presents itself nowadays is that of a village completely abandoned due to damage to houses and buildings caused by serious landslides developed in the South-Western part between 1959 and 1972 [7].

The Normand tower of Craco, instead, suffered minor damages caused by the landslide (Fig. 1). It was realised by masonry walls without any floors, the roof can be considered as rigid. Inside the tower during the 1949, a reinforced concrete tank was realised.

For all described above, and for its peculiarity of presenting two structures one inside the other, it has been chosen as case-study for defining a numerical model which will be well utilized to design and obtain information on possible structural interventions on it.

Figure 1. *Medieval tower at the upper area of Craco (Matera, Italy).*

In fact, the present paper proposes, through modal analysis and visual inspection, to evaluate the real behaviour of the Norman tower and to determine the effective stability of the structure in relation to a possible evolution of the landslide. Due to the uncertainties related to the properties of the material and the characteristics of the structural elements that make up the tower (i.e. the size and type of material of the structural walls, the presence of a tank inside the tower, a possible degree of connection of the part lower tower and adjacent structures, etc.), the complete definition of a numerical model that is able to estimate the structural behaviour of the tower is not easy to be reconstructed.

It was necessary to use non-destructive techniques due to the instable situation governing the area, and to the historic character of the tower under exam. The dynamic tests, in fact, have been performed under the actions induced by wind, as the whole city of Craco is evacuated. The experimental campaign made use of 16 piezoelectric accelerometers installed at different levels of the tower. The accelerometers data have been elaborated with techniques of Operation Modal Analysis (OMA) [7-10], in order to extract the real frequencies and the mode shapes of the structure.

Moreover, the analysis was carried out by a Finite Element numerical modelling defined by means of Strauss software [11]. A simulation has been developed of a possible vertical yielding of a part of the foundation closed to the landslide face. In this way it was possible to estimate how the structure would react if the landslide affects the foundation ground.

Slender structures such as towers are very suitable to this type of experimental investigation [12-14], like explained in the Italian Code [15], because, if subjected to low vibrations, generally they produce very clear signals. Sometimes, on the contrary, difficulties arise due to the geometry of old masonry towers and buildings, which are often not accessible to the upper levels [16]. However, monitoring these levels is preferable as the response vibrations are clearer and stronger.

This technique, which uses non-destructive tests to obtain information on the behavior of buildings, is therefore very useful for those buildings that have a cultural value such as the case study of the medieval tower of Craco [17, 18].

The paper has been divided in four parts. In the first a thorough investigation was conducted from the geomorphological and geological point of view of the area of Craco, with the aim of determining the main causes of the collapses suffered by the historic center; in particular, to define the reasons according to which the tower is one of the few structures remaining unharmed following landslides. Subsequently, in the second part, the method used for the dynamic tests of the tower is described, with reference to the type of instrumentation used and to the setting of the experimental test plan. In the third part, instead, the passages and the choices that have determined the realization of the 3D numerical model with finite elements are described, which, as already mentioned, is essential to understand the real behavior of the structure. The preliminary FE model of the tower was developed based on the data obtained from the visual inspection and from the archive research - definition of the tower dimensions and the type of structural and non-structural materials that make it up - which allow to acquire an appropriate knowledge of the mechanical characteristics of these materials. Finally, the data obtained from the test campaign will then be compared, in the fourth part, with the previous dynamic characteristics evaluated by means of the FE model so as to be able to achieve a possible update of the model to obtain closer values of the first natural frequencies. This will be useful to have a model of the tower even closer to reality, on which further studies can be carried out on the behavior of the structure in relation to the evolution of the landslide, in order to safeguard the tower from structural damage caused by landslides or other types of events that may compromise its stability.

2. PRELIMINARY ANALYSIS FOR LANDSLIDE RISK IN CRACO AREA

Craco (Matera, Italy) is located in a hilly area comprised between the rivers Agri and Cavone, which, further to the East, flow into the Gulf of Taranto.

The ancient inhabited center rises on the top of a hilly ridge that reaches the maximum elevation of 390 m.s.l.m. and extends in the direction NO-SE between the incisions of the Salandrella torrents to the North-East and Bruscata to the South-West. The landscape, typical of the clayey hills of the Matera area, is characterized by modest and isolated hills (*calanchi*), on the peaks of which the oldest inhabited areas of the area are found.

There are numerous mass movements that affect the whole area, but the particular development they take along the South-western slope of Craco is evident. This accentuated landslide appears to be closely related to the presence of a large movement, which can be traced back to a Deep Gravitative Slope Deformation. The continuous reactivations of this landslide complex along the slope, which from Craco degrades towards the Bruscata stream, have always threatened the stability of the town until it reaches the drastic decision of abandonment. In fact, the ancient country is currently uninhabited by virtue of laws that have required its evacuation, following the progressive deterioration of the conditions of stability in the area.

The propensity for landslides derives from the lithological composition and the geomorphological structure of the area. The upper part is made up of conglomerates, interspersed with sand, erodible and very permeable; while the underlying layers are mainly composed of relatively permeable sandy clay, which forms the bed of the water table. The swelling and plasticity of the clay on the contact surface causes the conglomerates and rubble to slide downstream in decay, triggering landslides.

The rapid evolution of landslides reactivated between the sixties and the seventies of the twentieth century, which caused collapses and large structural movements, is at the origin of two evacuation orders: the first in 1962 and the second in 1991 with the transfer of the inhabitants mostly towards the nearby valley.

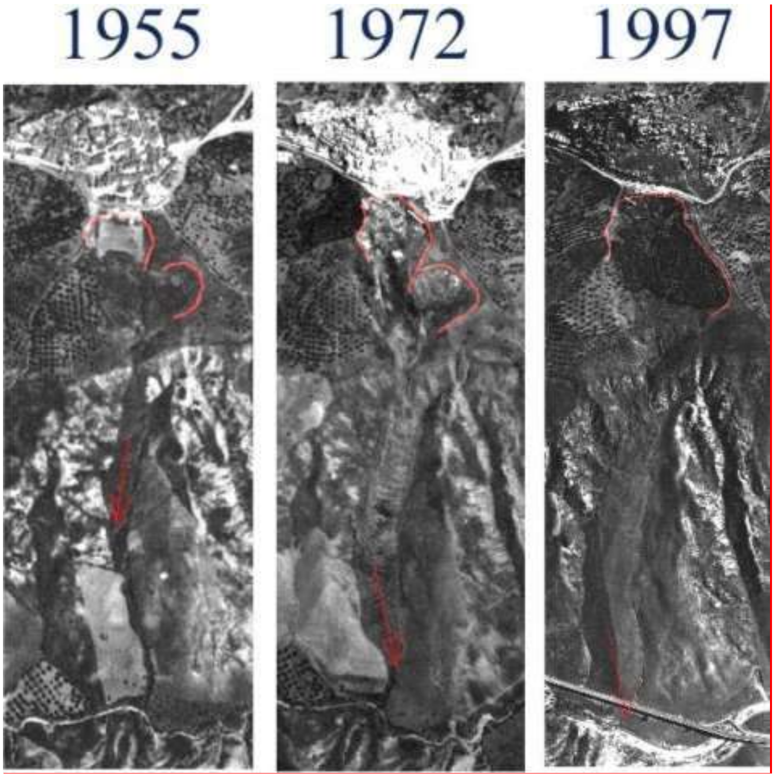


Figure 2. *Landslide in the historic center in three different years; in red the detachment niches are highlighted and the arrows indicate the progress of the casting.*

Based on the multi-temporal geomorphological analysis, currently all major landslides can be classified as quiescent, i.e. forms of instability that can be reactivated in the presence of triggering factors.

As it is possible to note from the historical analysis of the failures (Figure 2), the landslide of the historical center, also currently quiescent, shows, in its evolution, the typical characters of a retrogressive and multi-directional phenomenon, as the main landslide crown has progressively shifted towards the top of the ridge (about 50 m between 1955 and 1972) affecting ever larger areas of the ancient town, while the second crown has progressed towards the North-East; today the two areas form a single large basin. The retrogressivity character, related to the distribution of landslide activity, is also attributable to the other large quiescent landslides in the area, in fact the historical evidence collected during the reactivation of the main landslide, report observations regarding the areas of attraction of the two large lateral niches, which over time have damaged ever higher portions of inhabited areas. Furthermore, from the direct observations made during the survey campaigns, stress fractures have been identified, both inside the town and along the road SS. 103, in correspondence with the schools and especially near the convent, where recent fractures are observed due to the disruptions present in the northern slope, below the roadside.

The Norman tower, object of study, is one of the few structures remained unharmed by the effects of the landslide, until today (Figure 3). The building, dating back to medieval times, rises in the highest part of the hill on which the town stands, and the historic center was built around it.

Figure 3. *The Normand tower of Craco.*

The defensive character of the tower is underlined by its robust appearance and by a quadrangular structure in compact masonry of 11x11 m size, with an architrave opening on the east side at the first level which allows access and arched openings on the second level (12.5 m), one for each side, with the exception of the one facing North. Cracks arranged in three rows at the height of the crown (triangular in the lower rows and quadrangular in the third row) mark the horizontal closure placed at 20 m from the ground level; while the basement has a truncated pyramid shape.

From the relief of the thickness of the wall (about 2.15 m at the base and about 1.70 m in the upper part) and from the visual inspection of the two sides, external and internal, it is assumed a two-pitch masonry with a sand-interposed core. Externally the masonry base consists of a set of irregular river stones and shows conditions of advanced decay; the upper part of the tower, apparently in good condition, consists of sandstones of varying sizes, with the exception of the cantons where cut stone blocks prevail, used for the double rings of the arched openings.

The presence of a reinforced concrete tank inside the tower built in 1949, supposes some interactions even if it is not connected at all with the masonry walls of the tower, especially during the vibrations of the tower. Also, by considering the uncertainties related to the properties of the material and a possible degree of connection of the lower part tower and the adjacent structures, it is clear that a numerical model that is able to estimate the structural behavior of the tower cannot be easily defined.

3. THE DYNAMIC MONITORING OF THE NORMAND TOWER OF CRACO

The geometrical survey and the visual inspection have been followed by the monitoring phase. The experimental study consisted in ambient vibration tests and recordings of acceleration time-histories in specific points of the tower.

3.1. Test setup and acquisition system

The monitoring system consists of several elements properly connected:

1) acquisitions units: piezoelectric accelerometers, PCB 393B31 with a sensitivity of 1000 mV/g and frequency range [0.1-200] Hz. Appropriate rectangular blocks were designed and realized in order to ensure the perfect orthogonality of the accelerometers in each point of application, directly applied to the masonry: the accelerometers were inserted with screws on the threads realized on the perpendicular faces of the blocks (Fig. 4a),

2) data acquisition system (DAQ): The control units consist in acquisitions modules, each one is divided into 3 channels; for each DAQ two modules were used, so overall there are 6 channels (Fig. 4b)

3) co-axial cables with low impedance and with a length variable from 4.0 m to 15.0 m;

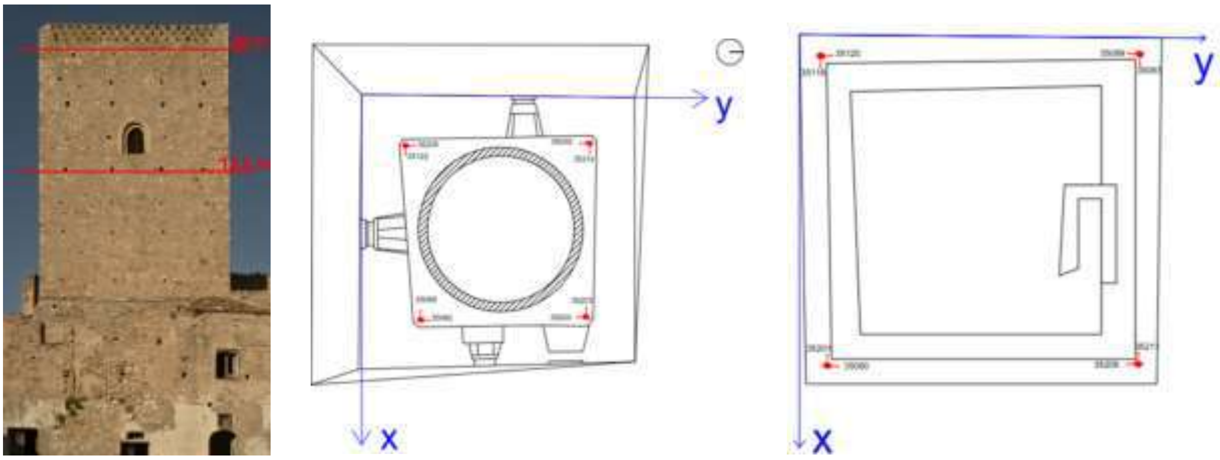
4) a laptop where an opportune code based on Labview software is installed.

The piezoelectric accelerometers have been installed on two levels, first level and second level respectively at 12.5 and 20 meters, the only ones accessible from a narrow staircase (Fig. 5a). The difficulty to install more accelerometers at other levels was principally due to the presence of the r.c. cistern inside the tower. Figs. 5b and 5c show the plan view at a quote of 12.5 m and 20 meters (terrace level), respectively, the position of the accelerometers, their code and orientation (red arrows) with respect to a xy reference system and to the magnetic north (line in the circle). It is possible to notice the presence of the cistern inside the tower, very close to the structural walls. Totally 16 accelerometers (8 for level) have been used for the experimental setup and their symbol and coordinates are synthetized in Table I; the accelerometers on the terrace have been placed 1 meter over the ground.

The experimental tests have been carried out on 4 June 2014 considering four consecutive repetitions of 15 minutes in environmental conditions, for evaluating the repeatability of the phenomenon, with a sampling frequency of 1028 Hz, acquiring the samples of the 16 synchronized acquisition channels.

a) b

Figure 4. *a) connection of piezoelectric accelerometers; b) acquisition modules (DAQ).*



a) b) c)

Figure 5. *a) levels of acquisition; b) plan view and accelerometers placed at 12.5 m c) plan view and accelerometers placed at 20 m*

Table 1. Accelerometers coordinates and direction

Symbol	**Accelerometer coordinates and direction**			
	x [cm]	**y [cm]**	**z[cm]**	**Direction**
35205	200	176	1250	y
35122	200	176	1250	x
35035	187	911	1250	-y
35212	187	911	1250	x
35203	885	900	1250	-x
35204	885	900	1250	-y
35098	900	235	1250	-x
35092	900	235	1250	y
35211	1110	1150	2100	-x
35208	1110	1150	2100	-y
35090	1120	96	2100	y
35201	1120	96	2100	-x
35119	72	72	2100	x
35120	72	72	2100	y
35089	57	1157	2100	-y
35083	57	1157	2100	x

3.2. Analysis of the environmental data

The four experimental tests, from now identified as Test 1, Test 2, Test 3, Test 4, have been preliminary analyzed by checking the time histories of the 16 accelerometers in order to identify their eventual uncorrected working and anomalies. After a preliminary check the accelerometers indicated with 35211 and 35208, placed at the second level, gave strange time histories due, probably to external phenomenon or interferences, and the corresponding data have not be considered in analysis. The acquisition sampling frequency is 1028 Hz for a total time of 15 minutes, so for the post processing an undersampling of 8 times has been introduced getting an effective sampling frequency of 128 Hz.

In Figs 6-7 some examples of time histories of the accelerometers placed in the corresponding points at first and second level, along x axis (Fig.6) and y axis (Fig.7), respectively, for the Test 3. There is to consider that the y axis is multiplied per 10 between the plots at first and second level (range respectively ± 10^{-3} g and ±0.01 g), so there is an order of magnitude between the oscillation at first or second level.

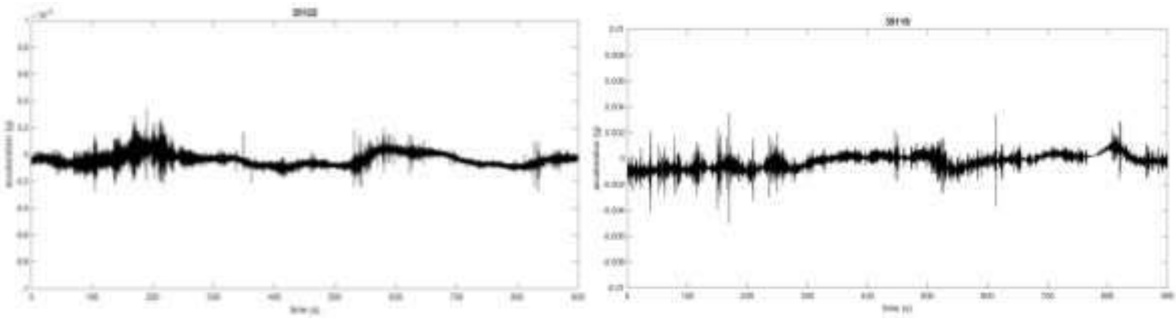


Figure 6. *Test 3 x axis: a) Time histories of 35122 (first level); b) Time histories of 35119 (second level)*

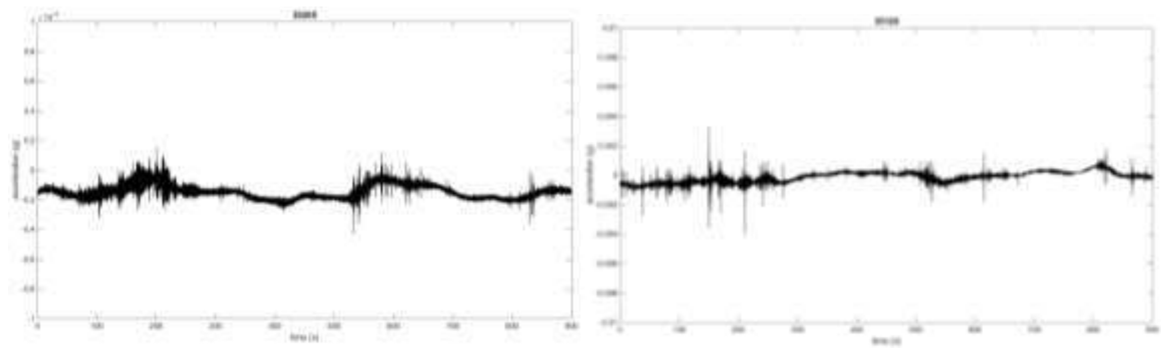


Figure 7. *Test 3 y axis: a) Time histories of 35205 (first level); b) Time histories of 35120 (second level)*

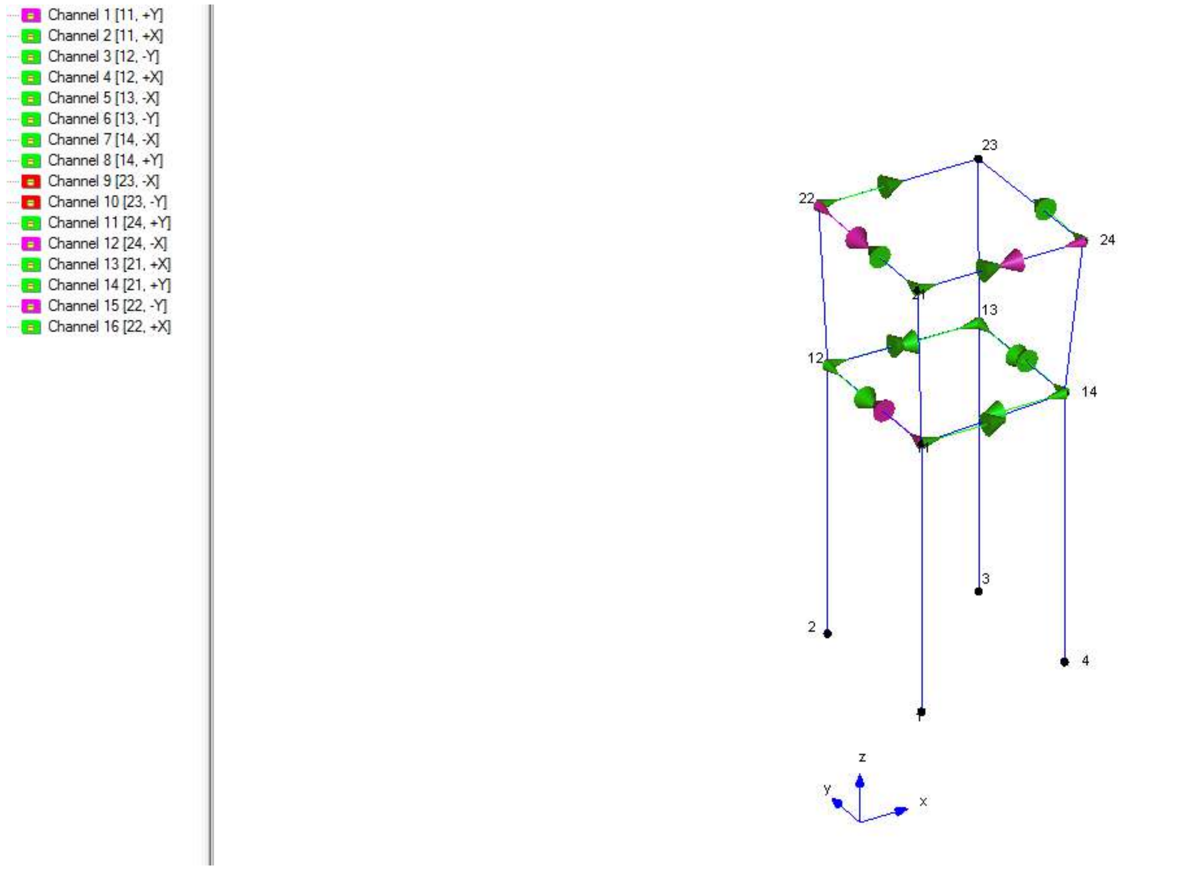


Figure 8. *Artemis model of the tower*

The specific software ARTeMIS [19] was used for the preliminary extraction of the modal parameters. Two different OMA methods were used for each analysis: Enhanced Frequency Domain Decomposition (EFDD), which operates in the frequency domain, and the Stochastic Subspace Identification (SSI) using Unweighted Principal Components (UPC), which operates in the time domain.

In Fig. 8 the Artemis model with the considered 14 accelerometers, noting that channel 9 and 10, corresponding to the accelerometers indicated with 35211 and 35208 not properly working, have been removed from the analysis. In Fig. 8 is also reported the reference system xyz previously introduced. In Fig. 9 the SSI identification for the Test 3, where more frequencies appear but that have not been considered for the specific type of the mode (local) also considering the results of the model introduced in the following paragraph.

The identified frequencies by using the SSI method for all the four environmental tests are summarized in Table 2. It is evident the good repeatability of the identified frequencies for all the environmental tests; moreover, similar results were obtained also adopting the EFDD technique. The corresponding modes for the first 3 frequencies are depicted in Fig.10; the description of the modes' characteristics is also reported in the last column of Table 2.

As indicated in Table 2, the first mode related to the first identified frequency corresponds to a flexional mode along y axis, while the second mode, also a flexional one, is mainly oriented toward the x axis; the third mode is a torsional one. In Fig.10, the modes are represented and it is evident that the main oscillation is referred to the structure part included between the height of 12.5 and 21 meters, the two levels monitored with the accelerometers; the different oscillations of the two levels had been also noted and underlined in analysis of the time histories (Figs 6 and 7).

In order to carry out a statistical analysis of the results obtained through the operational modal analysis for the four experimental tests, in Table 3 the minimum value, the maximum value and the mean value of the first 5 identified frequencies for the 4 tests. The mean value will be considered the target value for comparing the characteristics of the structure model.

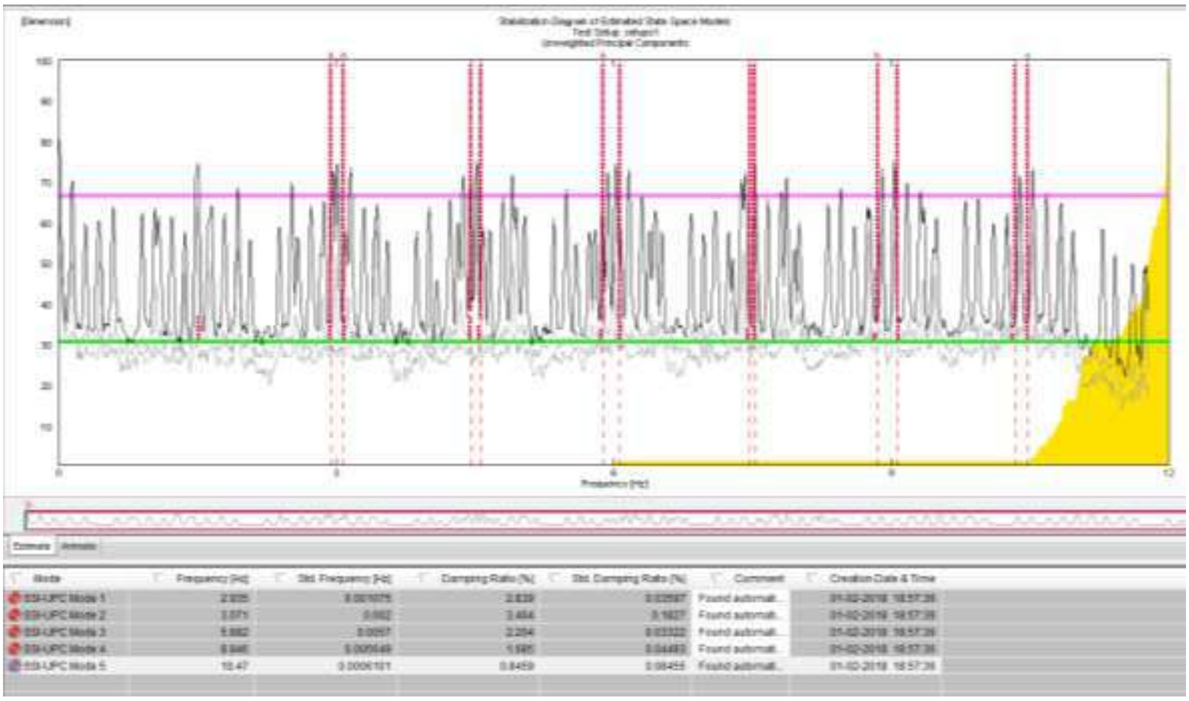


Figure 9. *SSI identification results for Test 3*

Table 2. Estimated frequencies from experimental environmental tests

Frequency number	Test 1 [Hz]	Test 2 [Hz]	Test 3 [Hz]	Test 4 [Hz]	Mode type and direction
1	2.97	3.02	2.93	3.04	Flexional along y
2	3.06	3.15	3.07	3.25	Flexional along x
3	5.97	6.02	5.88	6.06	Torsional
4	8.02	8.98	8.84	8.87	Flexional along y
5	10.5	-	10.47	-	Flexional along x

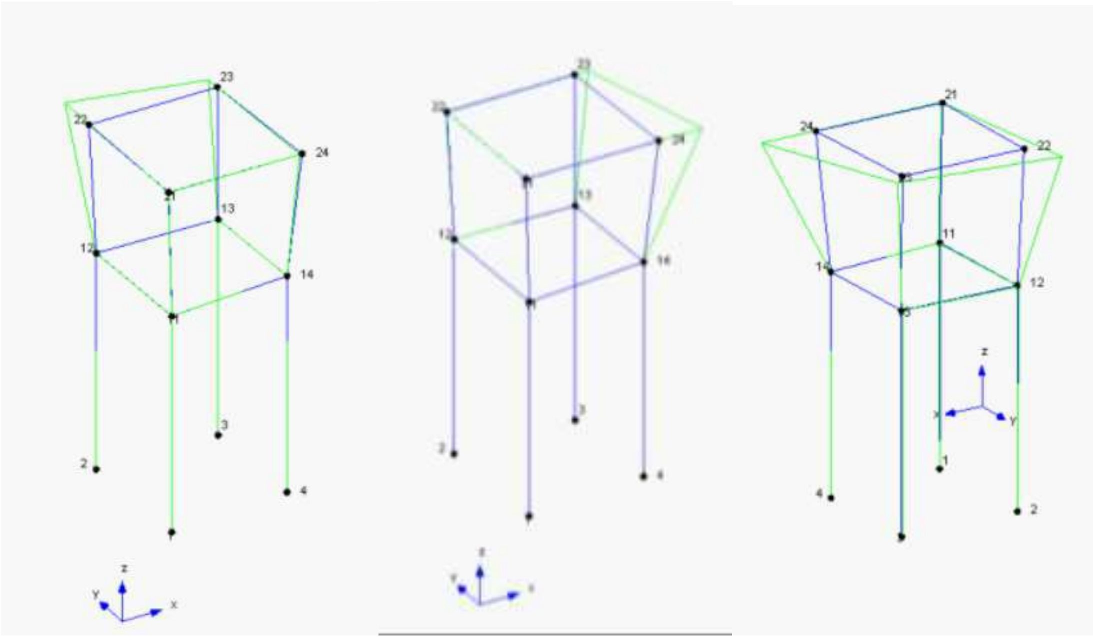


Figure 10. *Modes related to the first 3 identified frequencies.*

Table 3. Statistical analysis of the first 5 identified frequencis for the 4 tests

Frequency number	Minimum [Hz]	Maximum [Hz]	Mean [Hz]
1	2.93	3.04	2.99
2	3.06	3.25	3.13
3	5.88	6.06	5.98
4	8.02	8.98	8.68
5	10.47	10.5	10.48

4. THE FE MODEL OF THE NORMAND TOWER OF CRACO AND COMPARISON WITH THE IDENTIFIED MODES

It has been realized a tridimensional model with finite element (FE model) by using Straus software [7]; some simplifications have been adopted, such as considering a plane slab with a thickness of 75 cm instead neglecting the multiform slots having ornamental function, and so on.

For modeling the structure 10818 quadrangular elements (type Quad4) have been used with a uniform distribution along all the tower height, maintaining the length of each quadrangular plane element of about 30 cm; moreover 12134 nodes and 48 vertexes have been used for modeling the tower geometry. Finally, in the model 2060 beams elements have been inserted, having the function of springs for the connection of the building with the extern.

The structure is placed on a rock land quite resistant and not directly notched by the landslide; so it has been chosen to model the tower fixed at the basis, imposing the translations to be null in the main directions. The different boundary conditions that characterize the North-West and South-East side with the contact with other small structures have been modelled with local elastic springs represented by beams elements placed perpendicularly to the tower till the height of 4.7 meters, covering the contact area between the tower and the adjacent structures. The beams elements have been designed through the concept of 'axial equivalent stiffness' and have the following geometrical characteristics: length L 30 cm, circular section area A 5 cm^2, elastic modulus E 240000 MPa and a stiffness k defined by (1) equal to 400000 N/mm^2 (Fig. 11).

$$k = \frac{EA}{L} \tag{1}$$

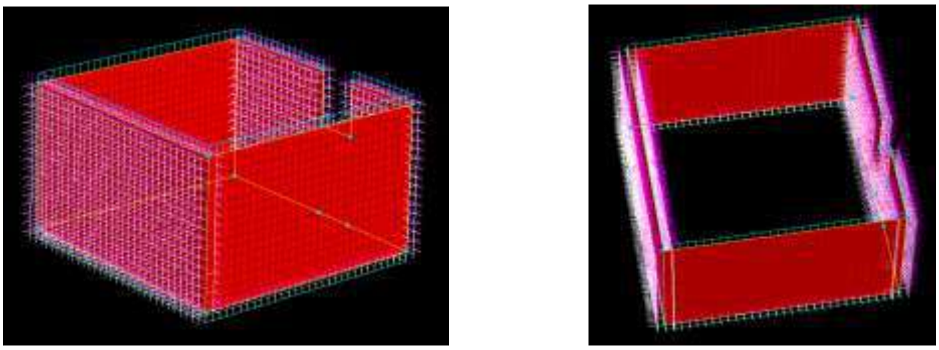


Figure 11. *Details of FE model: beams elements having springs function on both the facades*

The full model is depicted in Fig.12 from 3 different point of view. In the model, as it is evident from Fig. 12, also the internal concrete tank has been modelled, with opportune simplifications, with a cylinder with plane triangular elements Tri3 type. Also the tank was considered fixed at the basis The tower masonry walls have been modelled taking the real geometrical and mechanical properties into account: in Fig. 12 the different colors are representative of different value of the thickness at different heights. Until the height of 12.5 meter, the thickness is almost constant 215 cm, then it assumes a value of 170 cm until the superior covering slab where the thickness is equal to 85 cm. The mechanical properties used for the masonry of the FE model are the following: Elastic Modulus E= 1050 MPa (estimated from the index of construction quality), Poisson Modulus ν = 0,2, specific masonry weight w = 19 kN/m^3.

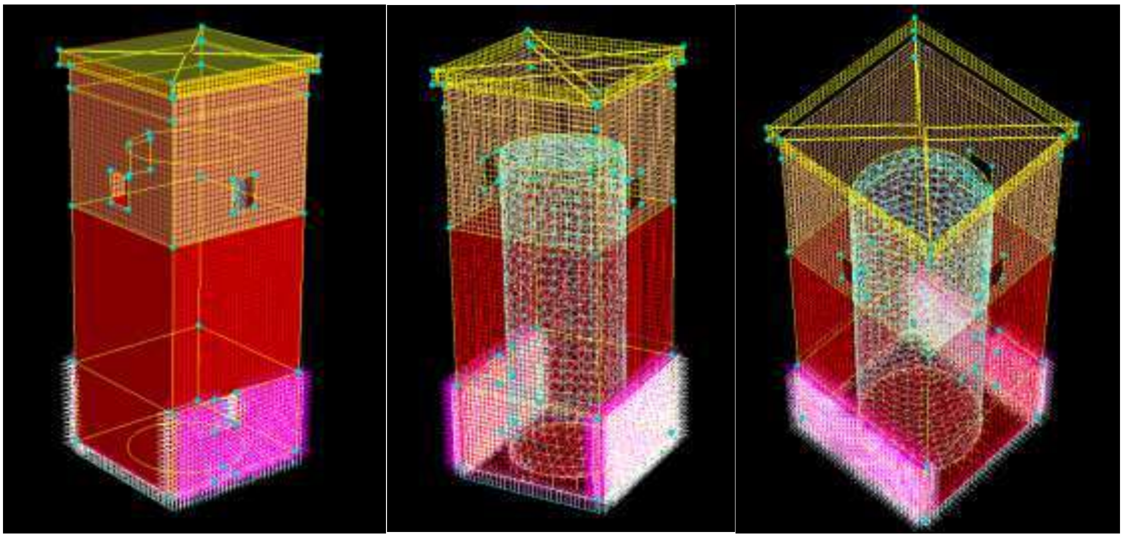
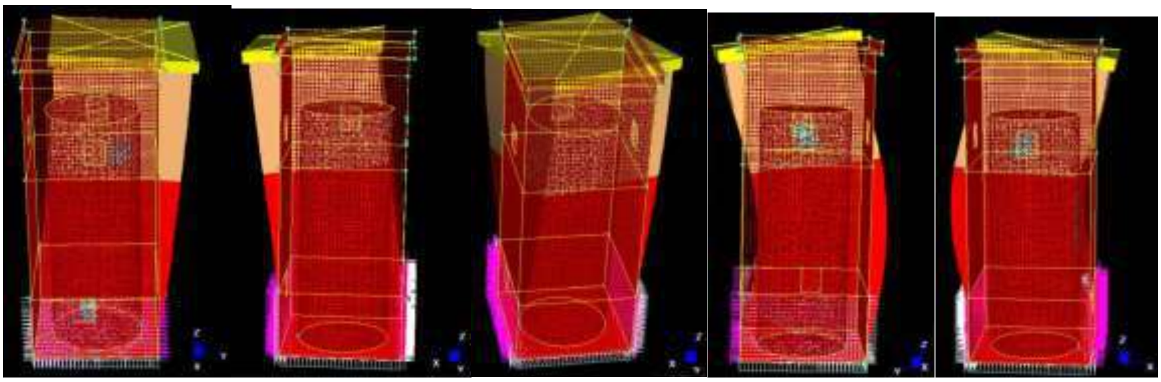


Figure 12. *FE model a) Sud-Est view; b) North-West view c) Sud-West view*

After completing the model, a modal analysis has been carried out in order to calculate the model frequencies. In Table IV the obtained results for the first 5 numerical frequencies, with the indication of their Modal Mass and of their partecipation factor (PF) with respect to the directions x,y,z are reported, while in Fig. 13 the graphical representation of the first five modes are shown.

Table 4. Modal analysis results of the FE model

	Frequency [Hz]	Modal Mass	PF-X (%)	PF-Y (%)	PF-Z (%)
1	2.96	776.5	0.005	60.37	0
2	3.14	635	47.8	0.006	0.367
3	5.49	870	0.005	0.044	0
4	8.43	643.9	0.001	11.97	0
5	10.61	388.5	11.29	0.005	0.046



a) **b)** **c)** **d)** **e)**

Figure 13. *FE model modes: a) first mode b) second mode c) third mode d) fourth mode; e) fifth mode.*

From Table 4 and Fig. 13 it is evident that the first two modes are bending modes, the first one directed toward y direction (North-South), the second x direction (East-West), the third is a torsional one, and fourth and fifth are bending modes respectively along y and x. The quadrangular geometry of the tower justifies the close values of the first two frequencies; anyway the sides placed along x axis have a bigger stiffness due to the small structures connected to the tower, mainly along x direction. This justify the fact that the first frequency is related to a mode along y-axis.

4.1. Comparison between model and experimental modal parameters and tensional analysis of the validated model

The comparison between the FE model frequencies and the identified experimental frequencies is shown in Table 5; it is evident that the model fits very well the identified frequencies and the differences between the mean value and the theoretical value, expressed by the variable d_i, is very low for all the first identified frequencies. Moreover, also the identified mode shapes are very similar to the experimental ones permitting to be confident about the accuracy of the numerical model.

Table 5. Modal analysis results of the FE model

	FE Model frequency [Hz]	Experimental frequencies [Hz]			Comparison
		Mean	**Minimum**	**Maximum**	**d_i**
1	2.96	2.99	2.93	3.04	0.03
2	3.14	3.13	3.06	3.25	-0.01
3	5.49	5.98	5.88	6.06	0.49
4	8.43	8.68	8.02	8.98	0.25
5	10.61	10.48	10.47	10.5	-0.13

So, a final analysis has been carried out to verify the safety level with reference to a hypothetical subsidence to the basis and evaluating the structure reaction such as the foundations ground was touched by a landslide.

It has been considered a subsidence equal to 2.5 cm at the tower basis, in correspondence with the south side, which is the one closer to the landslide front, and a subsidence allocated from 0 to 2.5 cm to the east and west side of the structure, in such a way to make the displacements more homogenous.

The tensional analysis has been carried out with the Von Mises criterium.

In Fig.14 are shown the critical curves related to the tensional state referred to the imposed subsidence. It is evident that in the zone closer to the subsidence there is a higher stress; this situation should correspond in the reality to strong structural damages and serious threats to the building stability, nevertheless the considered small amount of subsidence. So, in order to define the level of danger with respect to the advance of the landslide front, it should be necessary a constant monitoring of the territory, foreseeing a structural reinforce of the tower to safeguard an historical building of Italian architectonic heritage.

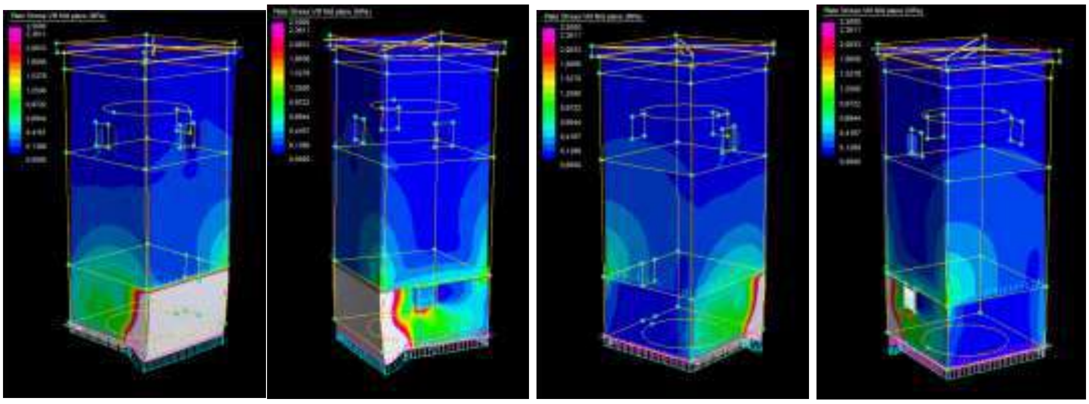


Figure 14. *Critical curves and tensional state: a) South-East b) South-West c) North-West d) North-East*

5. CONCLUSIONS

The Norman tower has been one of few buildings in Craco that was subjected to minor damages from the landslide effects that concern the majority of the city bedrock.

In this work, it has been analyzed the structural behavior of the tower by using non-destructive techniques in order to define an accurate model able to reproduce the real tower behavior and defining eventual retrofitting actions. The dynamic analysis of the structure, by means of the identification of modal properties, frequencies and modal parameters, has permitted to validate a numeric FE model very close to the real behavior of the considered tower.

The model validation has excluded the hypothesis of interaction between the tower and the internal cistern.

It is not easy to predict the evolution of the landslide, that at the moment seems to be inactive; anyway a continuous monitoring could be opportune in such a way to get quickly relative movements of the landslide.

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REFERENCES

[1] D. Foti, M. Diaferio, N. I. Giannoccaro, and S. Ivorra (2016) Structural identification and numerical models for slender historical structures, Civil and Environmental Engineering: Concepts, Methodologies, Tools, and Applications Volume 1, 31 January 2016, 196-222.

[2] C. Modena, M.R. Valluzzi, R. Tongini Folli, L. Binda (2002). Design choices and intervention techniques for repairing and strengthening of the Monza cathedral bell-tower, Construction and Building Materials, 16(7), 385–395.

[3] A. Formisano, F.M. Mazzolani, G. Florio, R. Landolfo (2010). A quick methodology for seismic vulnerability assessment of historical masonry aggregates, in: Proc. of the COST Action C26 Final Conference "Urban Habitat Constructions under Catastrophic Events", Federico M. Mazzolani, Chair, Naples, 16-18 September 2010, CRC Press, Taylor & Francis Group, London, 577- 582.

[4] S. Ivorra, V. Brotóns, D. Foti, M. Diaferio (2016). A preliminary approach of dynamic identification of slender buildings by neuronal networks. International Journal of Non-Linear Mechanics, 80, 183-189.

[5] M. Diaferio, D. Foti, N.I. Giannoccaro (2015). Identification of the modal properties of a building of the Greek heritage. Key Engineering Materials, 628:150-159. doi:10.4028/www.scientific.net/KEM.628.150

[6] E.M. Tronci, D. Pietrosanti, G. Cordisco, M. De Angelis (2017). Vibration analysis of the civic tower in Rieti. Procedia Engineering, 199, 2268-2273.

[7] M. Bentivenga, M. Coltorti, G. Prosser (2004). Il movimento gravitativo profondo di Craco (Basilicata Ionica). Il Quaternario, Italian Journal of Quaternary Sciences, 17(2/2), 613-625.

[8] D. Foti, V. Gattulli, F. Potenza (2014). Output-only modal identification in unfavourable testing conditions and finite element model updating of a seismically damaged building, Computer Aided Civil And Infrastructure Engineering, 29(9):659-675.

[9] D. Foti, M. Diaferio, N.I. Giannoccaro, M. Mongelli (2012). Ambient Vibration Testing, Dynamic Identification and Model Updating of a Historic Tower, NDT&E International. 47:88-95.

[10] D. Foti, S. Ivorra, D. Bru, G. Dimaggio (2012). Dynamic Identification of a Pedestrian Bridge using OMA: Previous and Post-Reinforcing, In: B.H.V. Topping, (Editor). Proceedings of the Eleventh International Conference on Computational Structures Technology. Dubrovnik, 4-7 sept. 2012, STIRLINGSHIRE: Civil-Comp Press, ISBN: 978-1-905088-54-6, doi: 10.4203/ccp.9.9

[11] STRAUS 7, v 2.3.3, Strand7 Pty Ltd (AUS).

[12] M. Diaferio, D. Foti, M. Mongelli, N.I. Giannoccaro, P. Andersen (2011). Operational Modal Analysis of a Historical Tower in Bari. In: Conference Proc. of the Society for Experimental Mechanics Series, “IMAC XXIX”. 7 (2011) 335-342, doi: 10.1007/978-1-4419-9316-8_31, 31Jan.- 3 Feb. 2011, Jacksonville, Florida, USA.

[13] M. Diaferio, D. Foti, C. Gentile, N.I. Giannoccaro, A. Saisi (2015). Dynamic testing of a historical slender building using accelerometers and radar, In: Proc. of the 6th International Operational Modal Analysis Conference, May 12-14, 2015, Gijón, Spain, paper ID 153, pp.129-130, ISBN: 978-84-617-3880-9.

[14] M. Lepidi, V. Gattulli, D. Foti (2009). Swinging-bell resonances and their cancellation identified by dynamical testing in a modern bell tower, Engineering Structures, 31(7): 1486–1500.

[15] DPCM 02.09.2011. Valutazione e riduzione del rischio sismico del patrimonio culturale con riferimento alle Norme tecniche per le costruzioni di cui al DM 14/01/2008. (In Italian).

[16] D. Foti, S. Ivorra, M.F. Sabba’ (2012). Dynamic Investigation of an Ancient Bell Tower with Operational Modal Analysis. The Open Construction and Building Technology Journal, 6:384-391, doi: 10.2174/1874836801206010384.

[17] D. Foti (2015). Non-Destructive Techniques and Monitoring for the Evolutive Damage Detection of an Ancient Masonry Structure. Key Engineering Materials, 628:168-177. Trans Tech Publications, Switzerland.

[18] A. Balduzzi, R. Casnedi, U. Crescenti, M. Tonna (1982). Il Plio-Pleistocene nel sottosuolo del bacino pugliese (Avanfossa Appenninica). Geologica Romana, 1982. (in Italian)

[19] Artemis Modal Pro v4.5 (2016). Structural Vibrations Solutions. Aalborg, Denmark.