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Integrated Methods for the Assessment of the Structural Vulnerability of Historic Towers

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ABSTRACT: The methods so far used for vulnerability or risk assessment are based on qualitative parameters or experts opinions, hence highly affected by a level of subjectivity and unreliability. These methods, particularly for some structural types, require further validation by experimental data or in situ investigation, as to enhance the effectiveness of the method itself, by weighting the importance of the parameters processed, and finally calibrating the same results. This is particularly required for very slender structures, as towers and likewise structures, the behaviour of which is strongly influenced by the dynamic performance. The paper presents a work, still in progress, according to which two parallel methods (respectively speedy assessment of vulnerability and dynamic identification) are both used as complementary tools. After a short introduction to the state of the art of the two approaches, the paper presents the development of a new survey form associated with an on line data storage, capable to run speedy vulnerability analysis, with a first application on a sample of more than 100 towers. One representative structure of the sample is chosen for the dynamic identification, the results of which are used for improving the possible failure mechanisms, and for drawing future enhancement of the method.

1 INTRODUCTION

The state of the art on speedy methods for vulnerability or risk evaluation, provides a wide range of literature, with methods for different types of structures or monuments: from those based on typological, heuristic, and experts approaches to those based on qualitative or mechanical parameters, as the evaluation of the ultimate load factor.

In the field of the cultural heritage, it deserves to be mentioned the work carried out in Italy by the ICR (Central Institute for Restoration), which produced territorial distribution maps of different types of cultural heritage, as monuments or archaeological sites, as well as of their associated risk (Accardo et al., 1996, 1997). The method focuses on the state of conservation of architectonic and decorative features of monuments, but with just some weak attempt in the definition of the structural behaviour. In a more engineering field, speedy approaches are pursued in Italy for forecasting the seismic vulnerability either by using score assignment process or probabilistic damage distributions (Benedetti et al.,1984; Braga et al., 1982). Over the last years, beyond the vulnerability of buildings and infrastructures, the research has focused on historic heritage and monuments, and among these, churches have been investigated in more detail by Lagomarsino et al. (1997, 2004).

The weak point of the above methods is that most of them are based on a "subjective" evaluation of vulnerability, based on direct observations and qualitative parameters, which yields to a final "quantitative" assessment of the feasible damage. In addition to this, some structural types, as towers, being characterised by a notable slenderness, are presumably featured by a dynamic nature, which notably influence the feasibility of failure mechanisms, and hence requires specific research work by experimental data.

By these considerations arises the need to calibrate speedy methods through the wide experience gathered over the last years in the field of the dynamic identification. These techniques, and in particular those related to identification under unknown (or unmeasured) ambient excitations (wind, traffic, micro-tremors of the ground; see De Angelis et al., 2003 and Capecchi et al., 2004, and references there quoted), can be considered particularly useful when applied to the historical monuments, whose mechanical and structural characteristics are often uncertain. In this field such techniques are receiving increasing attention (see Carusi et al., 2004 and references there quoted), mainly because of the relatively low cost and easy employment of both in situ measurements and elaboration of the results. Moreover the measurement of experimental data can be considered rather “objective”, though a certain amount of “subjectivity” can be introduced in the results interpretation, depending on the expertise of the operators. The information obtained can be immediately useful from a “relative” point of view, e.g. allowing to recognise significant variations of the structural characteristics between the situations before and after a strong external excitation (e.g. seismic) or before and after a retrofitting intervention. This provides just a “qualitative” evaluation of the safety level of a structure, though the same information processed through the dynamic identification can also give useful suggestions to enhance numerical models, and hence to predict structural damage or even associate the most likely damage mechanism, which can be further introduced in the speedy methods.

The paper presents a work, still in progress, according to which the above two different methods, respectively speedy assessment of vulnerability and dynamic identification (and structural monitoring), are both used as complementary tools, for outlining the behaviour of these type of monuments, and finally produce an optimal operative tool. This combination is particularly needed for towers and bell towers, rather representative of the Italian historic environment.

2 INSPECTION AND VULNERABILITY ASSESSMENT OF TOWERS

2.1 Survey form and vulnerability assessment

Tower and bell towers are scattered over the Italian Country with different densities and features from North to South. Although characterised by different stylistic decorations, age of construction and origin function, their comparable geometric and structural ratios yield to the definition of an autonomous structural type. In a very concise definition, towers and bell towers can be described as monuments where the total height is the prevalent dimension. Consequently, these monuments are featured by notable slenderness, and this also represents one of the main differences from most of historic monuments (churches, palaces) or even ordinary buildings.

So far, towers and likewise structures, have been considered in previous researches as one of the constitutive elements (or macro-elements) of more complex systems (as churches, palaces fortresses and so on). However their geometric, constructive and structural features are such peculiar that specific vulnerability/ risk functions require to be specifically formulated.

Previous works aimed at large scale surveys of monumental emergences over the whole Country, have indirectly investigated towers, through survey forms specifically developed for other architectonic types as churches (Lagomarsino et al., 1997), monastery and fortresses (GNDT-CNR, 2001). Early speedy attempts are formulated in the same works even for assessing the vulnerability through few parameters of towers and similar structures.

The starting point for the new research carried out by the Dept. PRICOS of University “D’Annunzio”, was a critical review of these early methods, and then their combination and implementation into a new survey form, named VulneT (Vulnerability of Towers), specific of the type considered (Figure 1). The main goal of the form is to collect data and built up a database on the state of conservation and structural appraisal of historic towers and similar structures. The data can be collected according to a multi level stage of knowledge of the monument, according to the level of information available. The attempt is to formulate a model not merely suitable for predicting the seismic vulnerability, but also for formulating a global judgement on the state of the monument, also analysing its decay and its economic value. According to this criterion, the information collected enable a complete description of the monument, which might be used by local Administration for monitoring and managing the structures over the competent territory. Sections 1 and 2 of the form (Figure 1) are aimed to a global description of the monument, under an architectonic, structural, cultural and urbanistic point of view.

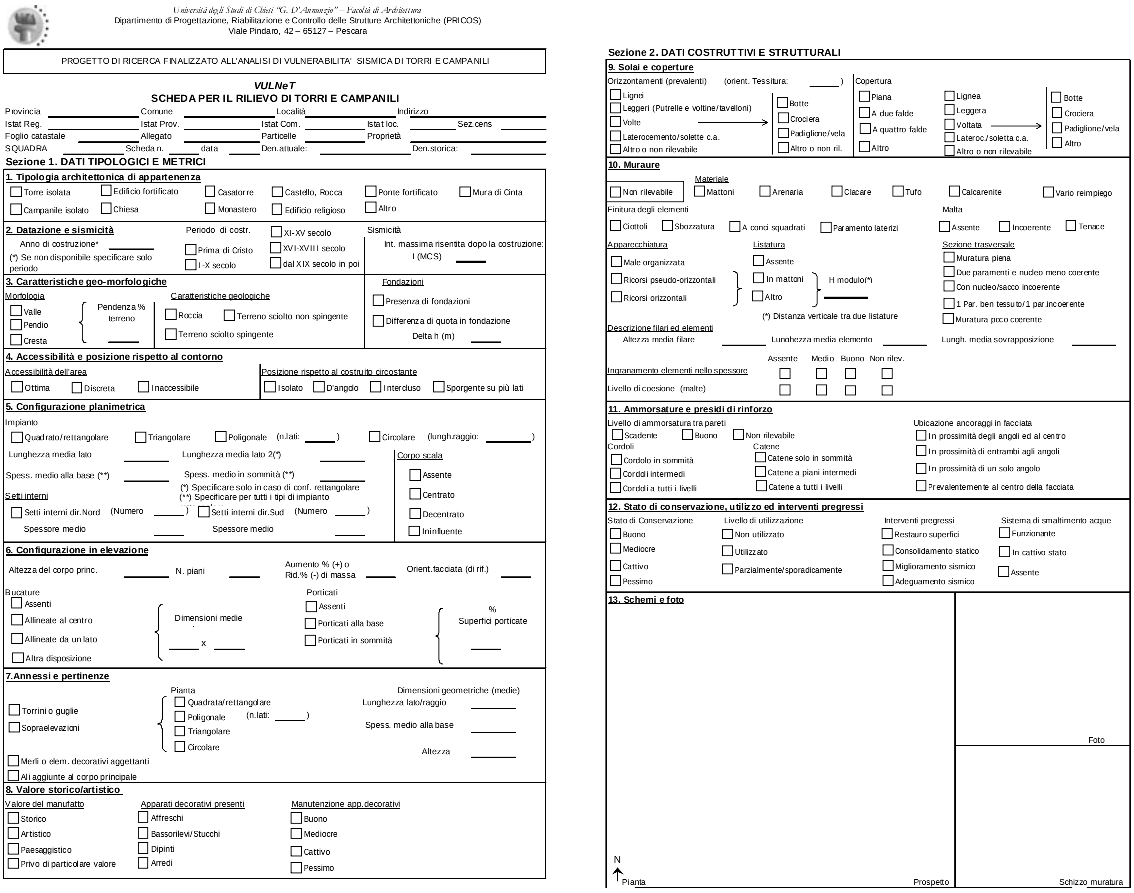


Figure 1 : Sections 1 and 2 of the form VulneT

A first test of the form has been carried out over a sample of 107 towers and similar structures, the data of which have been partially taken by previous investigations carried out by CNR-GNDT (2001), over different monument types in the Natural Parks of the Country, and partially by in situ surveys. The database obtained, outlines some major features of this monumental type, and even specify further sub-types. Figure 2 (left and right) highlights the distribution of the slenderness over the sample. One can note that towers and bell towers are featured by different slenderness as the latter are commonly slender than the former. Beyond this, a third class of likewise towers can be identified, which is the so called house-towers (original name is Case Torri), typical defensive house, shaped as a bulk tower. As a matter of fact, house towers are lightly squatter than the rest of the sample. The diagram on the right of Figure 2, outlines the data fitted by a normal distribution, and these are compared with ordinary buildings which are clearly squatter with an average slender ratio of 1.4, compared with 2.17, 2.65 and 3.68 associated with house towers, towers and bell towers respectively.

The vulnerability is processed using different models, depending on the type of vulnerability considered (static, seismic, superficial decay and so on) and on the level of accuracy of information available. When just qualitative data are present, only rough estimations can be provided, but these can be however helpful for an early screening of the sample.

One example is carried out on the tower stock above illustrated, where the poorness of data just allowed the application of the method for the seismic vulnerability, formulated by Cherubini et al. for all the monuments of the Regional Parks of the Country (CNR-GNDT, 2001). The few data required to run the method (Local MCS intensity experimented after construction date, level of usability and conservation), yielded to the vulnerability distribution of Figure 3.

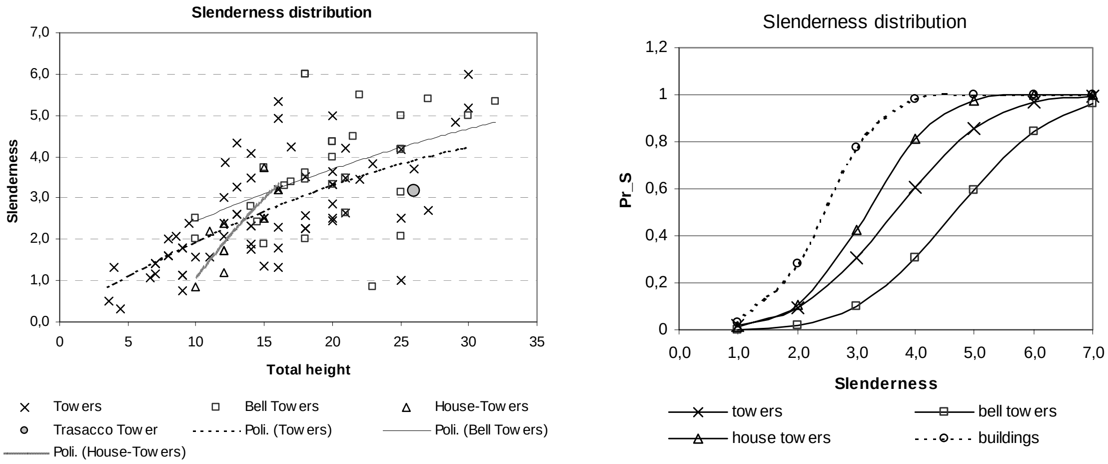


Figure 2 : Distribution of slenderness over the sample considered

The diagram on the left highlights the correlation between the level of conservation and highest intensity (MCS) felt by the monuments. The vulnerability indicators (normalised to 100) range between 20 and 80. Among them the vulnerability associated with the Tower of Trasacco has been highlighted, as this was chosen as sample for the dynamic identification (Sect.3). The diagram on the right compares the vulnerability curves associated with different structures. One can note that despite the higher slenderness, the bell towers show lower vulnerability compared with the other two types, and this is likely due to the higher level of conservation and usability.

Fragility curves aimed at correlating the earthquake severities with expected damage (normalised to 1) can be obtained by the above distributions, by transforming the average level of vulnerability into expected average damage.

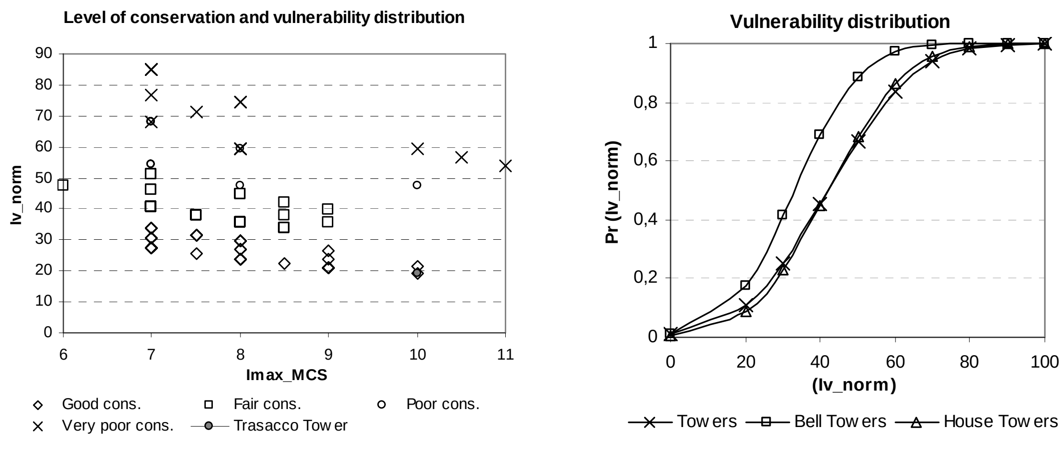


Figure 3 : Distribution of vulnerability of the sample using the speedy method of CNR-GNDT 2001

The curve obtained for towers is correlated in Figure 4 left with the expected damage related to ordinary buildings (class A and C of EMS'98 respectively), resulting by Damage Probability Matrices (DPM) of Irpinia earthquake (Braga et al., 1982). The diagram shows the different trend of towers compared to buildings, as these show an increase in damage (compared to class A) for MCS intensity higher than VIII. The damage average obtained for the sample under exam, is also correlated in Figure 4 (right) with the expected average damage formulated by Lagomarsino et al. (2004), as function of parameters (V and Q, vulnerability and ductility indices, respectively), specific of towers. One can note that the distribution of the sample fairly fits with the analytical ones. However the two parameters governing these curves can be further refined on the basis of results of the dynamic identification.

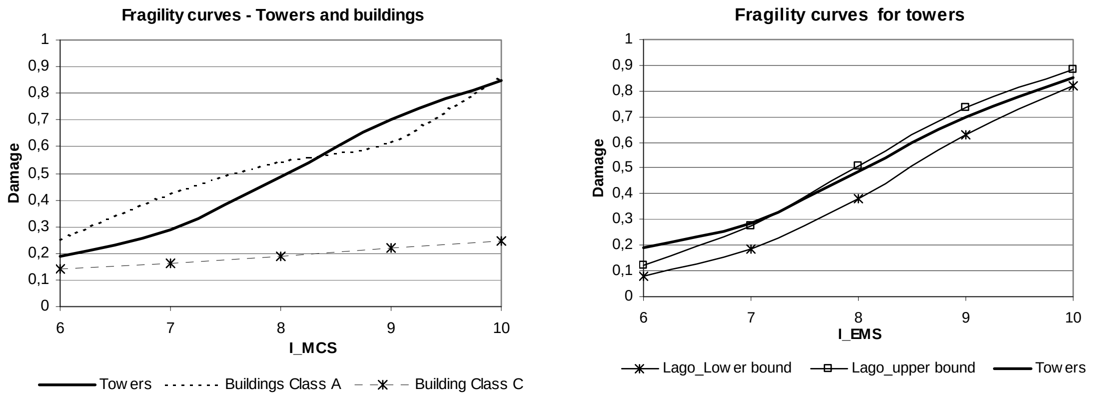
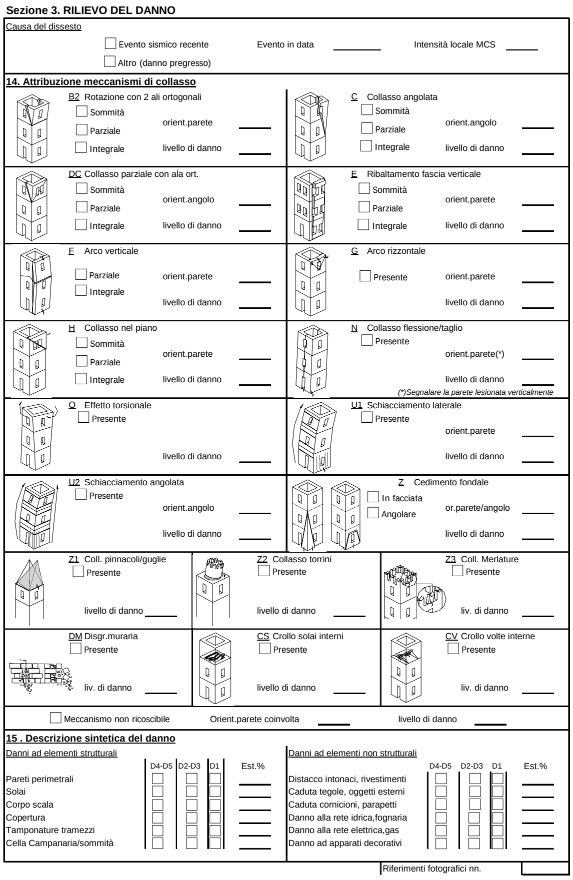


Figure 4 : Fragility curves for towers and ordinary buildings (left); correlation between expected average damage of the sample with the one formulated by Lagomarsino et al (2004) (right).



Sezione 3. RILIEVO DEL DANNO

Causa del dissesto

☐ Evento sismico recente Evento in data ____ Intensità locale MCS ____

☐ Altro (danno pregresso)

14. Attribuzione meccanismi di collasso

B2 Rotazione con 2 ali ortogonali — ☐ Sommità ☐ Parziale ☐ Integrale — orient.parete ____ livello di danno ____

C Collasso angolata — ☐ Sommità ☐ Parziale ☐ Integrale — orient.angolo ____ livello di danno ____

DC Collasso parziale con ala ort. — ☐ Sommità ☐ Parziale ☐ Integrale — orient.angolo ____ livello di danno ____

E Ribaltamento fascia verticale — ☐ Sommità ☐ Parziale ☐ Integrale — orient.parete ____ livello di danno ____

F Arco verticale — ☐ Parziale ☐ Integrale — orient.parete ____ livello di danno ____

G Arco rizzontale — ☐ Presente — orient.parete ____ livello di danno ____

H Collasso nel piano — ☐ Sommità ☐ Parziale ☐ Integrale — orient.parete ____ livello di danno ____

N Collasso flessione/taglio — ☐ Presente — orient.parete(*) ____ livello di danno ____

(*)Segnalare la parete lesionata verticalmente

O Effetto torsionale — ☐ Presente — livello di danno ____

U1 Schiacciamento laterale — ☐ Presente — orient.parete ____ livello di danno ____

U2 Schiacciamento angolata — ☐ Presente — orient.angolo ____ livello di danno ____

Z Cedimento fondale — ☐ In facciata ☐ Angolare — or.parete/angolo ____ livello di danno ____

Z1 Coll. pinnacoli/guglie — ☐ Presente — livello di danno ____

Z2 Collasso torrini — ☐ Presente — livello di danno ____

Z3 Coll. Merlature — ☐ Presente — liv. di danno ____

DM Disgr.muraria — ☐ Presente — liv. di danno ____

CS Crollo solai interni — ☐ Presente — livello di danno ____

CV Crollo volte interne — ☐ Presente — liv. di danno ____

☐ Meccanismo non ricoscibile Orient.parete coinvolta ____ livello di danno ____

15 . Descrizione sintetica del danno

Danni ad elementi strutturali	D4-D5	D2-D3	D1	Est.%	Danni ad elementi non strutturali	D4-D5	D2-D3	D1	Est.%
Pareti perimetrali	☐	☐	☐	____	Distacco intonaci, rivestimenti	☐	☐	☐	____
Solai	☐	☐	☐	____	Caduta tegole, oggetti esterni	☐	☐	☐	____
Corpo scala	☐	☐	☐	____	Caduta cornicioni, parapetti	☐	☐	☐	____
Copertura	☐	☐	☐	____	Danno alla rete idrica,fognaria	☐	☐	☐	____
Tamponature tramezzi	☐	☐	☐	____	Danno alla rete elettrica,gas	☐	☐	☐	____
Cella Campanaria/sommità	☐	☐	☐	____	Danno ad apparati decorativi	☐	☐	☐	____

Riferimenti fotografici nn.

Figure 5 : Section 3 of the VulneT form: damage inspection

2.2 Damage investigation of Towers

One special section of the VulneT form is related to the damage inspection (Figure 5). Similarly to a method previously developed by one of the authors, and focused on ordinary buildings (D'Ayala and Speranza, 2003), this section pursues a double purpose: identification of failure mechanisms which have occurred and description of the crack pattern.

The mechanism is required to be identified only when the severity of damage is sufficient to allow a collapse pattern, whether incipient or fully developed, to be recognised. The forms collects a range of feasible mechanisms which have been identified either by pictures of past earthquakes (Doglioni et al., 1994), previous researches (Lagomarsino et al., 1997), and by the dynamic identification process. To make an example, the failure mechanism O is typical of towers, as the torsional mode corresponds to one of the early vibration modes. Some mechanisms found out for buildings, can similarly involve towers, as those from B to H, directly associated with those of FaMIVE, related to buildings (D'Ayala and Speranza, 2003). Conversely some others, like the detachment of the façade, are in this case rather uncommon due to usual good connection at quoins, as result of their synchronic construction process. Mechanisms of type U, include failures caused by overcoming of the compressive strength at the base, and this can occur particularly in presence of out ot plumbs, and might be independent of the seismic effect. Similarly, damage modes of type V, are associated with geotechnical problems. The group Z refers to the collapse of additions or decorations, as previously highlighted by Lagomarsino et al. (1997).

When the failure mechanism is not immediately recognisable, or the damage level seems too slight for a reliable opinion to be expressed, the surveyor is required just to describe the overall damage at the bottom of the form (field 15). The description is required in terms of damage level and extent, either for structural and non structural elements, like decorations, plasters and so on.

The description of the damage through failure mechanisms plays a central role for the calibration of the method, and for the final assessment of the vulnerability. One of the possible future development of the research is represented by the creation of damage probability matrices, developed through photographic material and direct observations, as to outline the likelihood of each failure mode for different earthquake severities. Precious indications can be achieved by the dynamic identification analysis, introduced in the following.

3 DYNAMIC IDENTIFICATION METHODS

The medieval "Febonio" Tower is situated in the small centre of Trasacco (near l'Aquila, Italy) at about 685 m above sea level on the southern borders of the ancient Fucino Lake.

The building, which has a square base section, becomes circular at two-thirds of its height, giving to the tower itself a particular look, unique in the Abruzzo region (Figure 6); between the square and the circular parts of the tower there is a concrete floor which was built in 1970, together with other interventions required as a consequence of structural damages due to the devastating earthquake of 1915. The dimensions of the bottom square section are 8.20 metres for the external sides and 5.40 metres for the internal ones, with a base thickness of about 1.40 m, and the overall height of the tower is about 29 metres.

Due to the importance and peculiarity of the monument, it was considered useful to perform in-situ test to get further information on some mechanical characteristics of the tower, in the occasion of restoration works on the tower. Dynamic in-situ measurements were performed by the Department of Structures (Dip. PRICOS) of the University of Chieti-Pescara in several times, before, during and after the retrofitting of the tower. In these tests, precision accelerometers were used to record the very low intensity vibrations due to external "noise" and ambient loads, namely due to the vibration induced by an aerial platform (Fig.6) and by other building-yard equipments operating near the tower.

The dynamical identification performed on the basis of in situ measurements (cf. Carusi et al., 2004 and Carusi, 2006, for further details on the tower and on the tests), gave useful information on some mechanical parameters of the tower, namely masonry density and elastic modulus, allowing to update the Finite Elements (FE) Model implemented for the structure.

The results of dynamical identification generally confirmed the first modal shapes obtained through the FE Model (Fig.7); in particular, they showed the possibility of a torsional mode under ground displacements, due to mass eccentricities and to some lack of symmetry of the tower not evident at a first sight; the experimental evidence of a torsional mode was one of the motivations for the torsional collapse mechanism (Q) included in the VulneT forms (Fig.5), also confirmed by cracks still visible on the tower after the earthquake of 1915. More generally the modal analysis, if confirmed by in situ tests, can show (at least from a qualitative point of view) global or local displacements shapes useful to individuate, for a given structure, collapse or damage mechanism prone to be activated by seismic excitations, interesting the whole structure or its parts.

Moreover, although a certain amount of “subjectivity” can be introduced in the results interpretation, depending on the expertise of the operators, the measurement of experimental data can be considered rather “objective”. The information obtained, therefore, can be useful also from a “relative” point of view, e.g. allowing, in case of modal identification of linear or linearised models, to recognise significant variations of the structural characteristics (first of all natural frequencies and damping coefficients) between the situations before and after a strong external excitation (e.g. seismic) or before and after a retrofitting intervention. As already said, the same information processed through the dynamic identification can also allow to enhance the numerical model, and hence to improve the mechanical characterisation of the structure.

Figure 6 : The “Febonio” Tower in Trasacco (near L’Aquila, Italy)

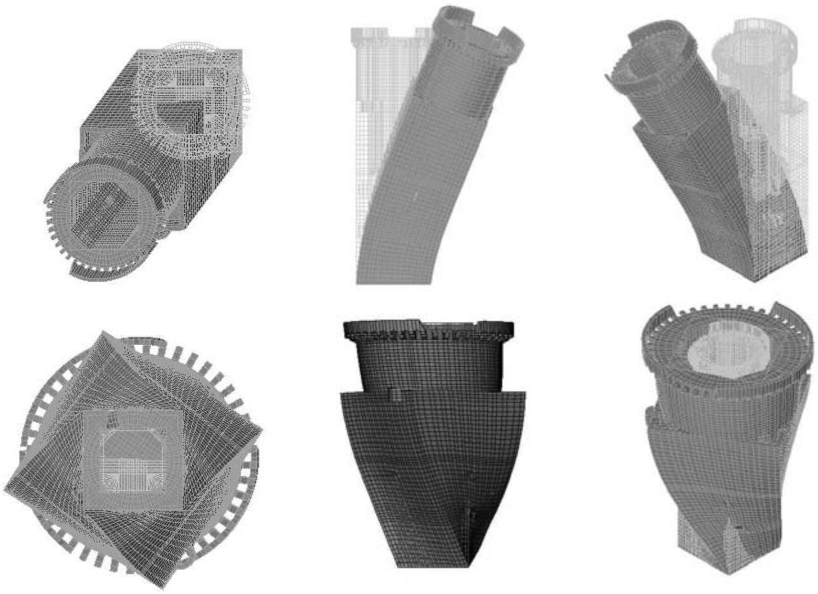


Figure 7 : First modal shape (1st flexural, top) and second modal shape (1st torsional, bottom) of the FEM model: plan, lateral view and axonometric view

The results reported in the quoted papers also confirm that a satisfactory investigation of this kind of structures can be performed under ambient (low-intensity and no-cost) excitations, without the need of using artificial excitations (e.g. due to vibrodyne), that are often incompatible with the safeguard of the historical heritage. The research, still in progress, will also try to include the vulnerability forms and procedures in a more general database structured in a GIS (Geographic Information System) framework (cf. Palka et al., 2005).

4 CONCLUSIONS

The integration of these two structural vulnerability assessment methods seems to be potentially very effective. It needs however some further developments and refinements. Mainly it is necessary to better "quantify" the information given by the dynamic identification regard to the possible collapse mechanisms. This may be possible carrying out dynamic tests on some other different samples in such a way to reach a "parametric" relationship among the results of these tests and the other parameters involved (geometrical proportions, materials characteristics, etc.).

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REFERENCES

Accardo G., Salvemini M. 1996, User needs in city planning and risk evalution of cultural heritage, in *2° EC – GIS Workshop*, 26-28 June, 1996, Genova, Joint Research Centre – ISPRA.

Accardo G., 1997, La carta del rischio del patrimonio culturale, in *Esritalia News* Anno II – n° 3, Roma.

Benedetti, D., Petrini V, 1984. Sulla Vulnerabilita' sismica di Edifici in muratura: un metodo di valutazione. In: *L'industria italiana delle costruzioni*, n.149. pp.66-74.

Braga F., Dolce M., Liberatore D. (1982), Southern Italy November 23, 1980 Earthquake: A Statistical Study on Damaged Buildings and an Ensuing Review of the M.S.K.-76 Scale. *CNR-PFG Edition*. n.503, Roma.

Carusi P., Sepe V., Viskovic A. 2004. Techniques of structural identification for the monitoring of historical buildings, *IV International Seminar "Structural Analysis of Historical Construction" SAHC05, November 2004*, Padova, Italy.

Palka P., Speranza E., Viskovic A. 2005. GIS maps, historic structures conservation and seismic vulnerability assessment, *simposium IABSE "Structures and Extreme Events", 14-17 September, 2005*, Lisbon, Portugal.

Capecchi D., De Angelis M., Sepe V. 2004. Modal model identification with unknown nonstationary base motion. *Meccanica 2004*; 39: p. 31-45.

Carusi P. 2006. Identificazione e monitoraggio di strutture monumentali soggette ad azioni di tipo ambientale, PhD Thesis (in Italian), University of Chieti-Pescara, Faculty of Architecture, Dept. PRICOS

D.D'Ayala, E.Speranza, Definition of Collapse mechanisms and seismic vulnerability of Historic Masonry Buildings In: *Earthquake Spectra*, 2003 (August). Pp. 479-509.

De Angelis M., Sepe V., Capecchi D. 2003. Identification of Modal Parameters with Unknown Input, Problems in Structural Identification and Diagnostics: general aspects and applications (Ed. Davini and Viola), CISM *Courses and Lectures n.471, 2003*, ISBN 3-211-20492-X.

Doglioni F., V. Petrini, A. Moretti, 1994, Le chiese e il terremoto, *ed. LINT*, Trieste.

GNDT-CNR (2001) Censimento relativo alle emergenze a carattere monumentale ed ambientale nei Comuni ricadenti in tutto e in parte all'interno di Parchi naturali nazionali e regionali. Lavori socialmente utili (LSU). Civil Protection of Rome.

Lagomarsino S., Brencich A., Bussolino F., Moretti A., Pagnini L.C., Podesta' S. (1997). Una nuova metodologia per il rilievo del danno alle chiese. In: *Ingegneria Sismica, XIV*, n.3, Sept-Dec. pp-70-82.

Lagomarsino S., Podestà S., (2004). Seismic Vulnerability of Ancient Churches:I. Damage Assessment and Emergency Planning. In: *Earthquake Spectra* -- May 2004 -- Volume 20, Issue 2, pp. 377-394

Lagomarsino S., Podestà S., (2004). Seismic Vulnerability of Ancient Churches:II Statistical analysis of surveued Data and Methods for risk analysis. In: *Earthquake Spectra* -- May 2004 -- Volume 20, Issue 2, pp. 395-412