Structural Analysis of Historic Construction – D'Ayala & Fodde (eds)
© 2008 Taylor & Francis Group, London, ISBN 978-0-415-46872-5

Experimental assessment of historic building safety: The case of the Isso Tower in Castelleone, Italy

L. Binda, P. Condoleo, A. Saisi, C. Tiraboschi & L. Zanzi
DIS-Department of Structural Engineering, Politecnico of Milan, Milan, Italy

ABSTRACT: In order to assess the structural condition of the Isso Tower in Castelleone, an extensive investigation was carried out on-site by using non-destructive and minor destructive techniques together with laboratory tests and analytical calculations. The most relevant feature of this tower, as of other medieval towers is the presence pf an external leaf used as a cladding of the bearing wall. The possible detachment of this leaf had to be carefully surveyed for safety reasons. In fact, a lightning during a storm in 19th century produced serious damages along a corner; other parts of the cladding were lost for unknown reasons. Therefore, if other detachments are present instability phenomena could cause in long-term, the failure of the detached cladding leaf.

1 INTRODUCTION

The failure of monumental buildings is luckily an exceptional event; nevertheless, when their safety assessment is required, any risk factor that may affect the integrity of the buildings has to be taken into account. Ancient buildings often show diffused crack patterns, which may be due to different causes in relation to their original function, to their construction technique and to their load history. In many cases the dead load, usually rather high in massive monumental buildings, plays a major role into the formation and propagation of the crack pattern.

Prevention and rehabilitation can be successfully accomplished only if a diagnosis of the state of damage of the building has been formulated. The investigation also may require long-term monitoring of the structure. The diagnosis should result from an experimental investigation on-site and in laboratory (Binda et al. 2000a), (Binda et al. 2003) aimed to define the characteristics of the materials and of the structure itself and from the structural analysis based on appropriate mathematical models (Binda et al. 2000a).

An extensive diagnostic investigation is being carried out on the Isso Tower in Castelleone. Beside other damages the Tower is showing a wide lack of the external masonry leaf (Fig. 1). A similar problem was already studied by the Authors on other case histories. In fact, the Authors applied non destructive and minor destructive techniques (radar, sonic tests, boroscopy and flat-jack) in order to investigate the situation of the Tower of the Cremona Cathedral, called the Torrazzo (Binda et al. 2000c). Interesting results concerned the

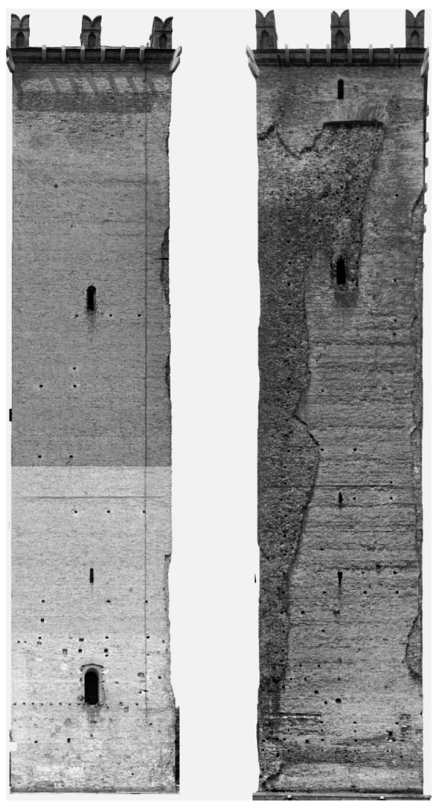
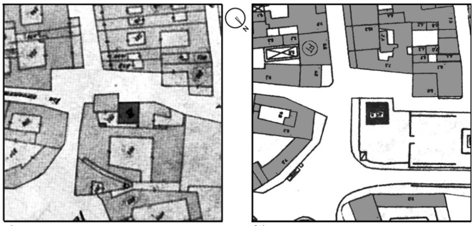


Figure 1. Isso Tower: view of the South-East and North-East prospects.



a) b)

Figure 2. Layout of the Isso Tower area in a map of Castelleone of the 1901 and recent.

Figure 3. Isso Tower: details of the detached cladding in the external and internal sides of the bearing walls.

detection of the presence in some parts of the Tower, of an external thin leaf one brick thick which was partially detached from the rest of the wall section (Binda et al. 2000b), (Binda et al. 2001b), (Binda et al. 2005).

In the case of the Isso Tower the detachment represents a rather dangerous situation since a collapse of large parts of this leaf can be very dangerous. Then a safety problem is here evident.

After preliminary tests, GPR investigation was carried out to find and define the extent of the detachment of the thin external leaf of the load bearing wall. The results were calibrated with local inspections and were correlated with the crack pattern to understand the causes of the damage.

The survey, carried out on the Isso Tower is here described.

2 DESCRIPTION OF THE PROBLEMS

The Isso Tower, dating back to 11th-12th century, was used during 20th century as the container of the water tank for the city aqueduct. The tank was built in r.c. at about 20.5 m only supported by 3 walls of the Tower. Furthermore, until 1919 several buildings were adjacent to the base of the Tower (Fig. 2).

The walls made with solid bricks appear to have been covered on both sides with a sort of cladding (Fig. 3), one brick thick or more, which was built with regular bricks and thin mortar joints. The cladding hid the underneath rough surface. This was a technique frequently applied in the medieval times and also later to tall towers.

Since the first inspection, the detachment of the external leaf seemed the most relevant problem taking into account the possible effects of a sudden loss of part of it during some event (tornado, earthquake, etc.). The presence of this cladding and its eventual detachment had to be surveyed for safety reasons.

In fact, a lightning during a storm on 1845 produced serious damages along a corner; other parts of the cladding were lost for unknown reasons (Fig. 1). Therefore, instability phenomena could cause in long-term, the failure of the detached leaf. Together with the visual investigation, the use of NDT was necessary to investigate the extension of the eventual defect over these large surfaces.

An extensive investigation programme (including sonic, radar, flat-jack, coring, boroscopy, etc.) has been planned to support the preservation and restoration actions of the Tower.

The Authors applied systematically georadar in order to detect the detached area. The methodology, already successfully applied on another historic Tower, was able to localize on-site the presence of the detachment, after a calibration procedure. In the following the type and the extent of the damage will be described.

3 DETACHMENT OF THE EXTERNAL LEAF OF THE TOWER WALLS: A DIFFUSE PROBLEM

The Authors have already studied in previous research similar damages. A meaningful example was the situation of the Cremona Torrazzo (112 m high), found during the on-site investigation campaign (Binda et al. 2000c). At the same height of the tower, a large difference between the stress values measured by single flat-jack tests in the internal part of the wall and in the external cladding was found. The inner stress value of 1.76 N/mm^2 was definitely higher than the outer one (0.40 N/mm^2), suggesting the presence of detachments of the external leaf of the wall (Binda et al. 2001b). The fact appeared strange as in this area the wall of the tower was supposed to be solid; other flat-jack tests revealed similar situations.

The presence of the detachment of a sort of external leaf was noticed in several parts of the Tower. Coring and boroscopy were also showing this phenomenon (Fig. 4) (Binda et al. 2001b).

By visual investigation it was impossible to understand whether this detached part was built after the walls as a sort of cladding or was born as a solid part of

Figure 4. Local inspection of the external leaf detachment in the Cremona Torrazzo.

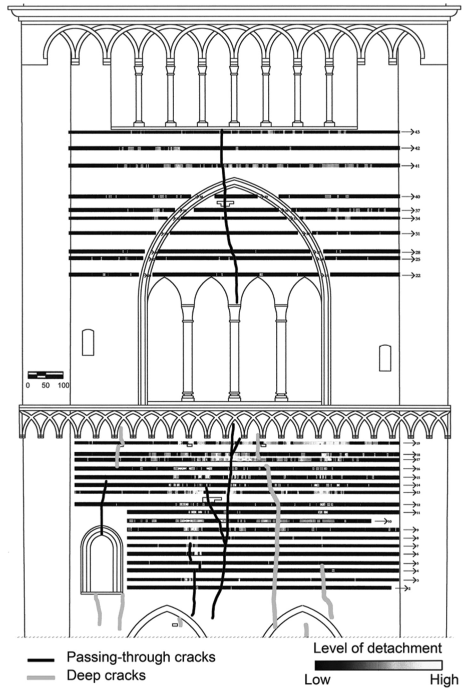


Figure 5. Detection of the areas affected by the detachment problem. The grey-scale map is associated with the intensity of the detachment phenomenon.

the wall only partially connected to it and subsequently detached as a consequence of the damage occurred to the Tower due to long-term behaviour of the masonry. In both cases, a safety problem was affecting the Tower, since a collapse of large parts of this leaf can be very dangerous.

Due to the dimensions of the tower prospects, it was necessary to investigate the extension of the defects over large surfaces by GPR. The wall was surveyed with a high frequency antenna (1.5 GHz) along many parallel profiles so that a 3D reconstruction of the external part of the wall was possible (Binda et al. 2005).

The results were calibrated with local inspections and were correlated with the crack pattern to understand the causes of damage.

An example of the radar result is shown in Figure 5 (Binda et al. 2005). The detachment is revealed on the radar data by a strong reflection that appears at a constant depth of approximately 12 cm. The radar profiles were pre-processed in 2D mode and then assembled in two 3D volumes, which were then submitted, to a 3D processing procedure. The resulting data volume was explored according to planes parallel to the external surface.

At a depth from the external surface of the wall corresponding to the thickness of one brick (about 12 cm) appears an image, as the one reported in Figure 5. The map is associated with the intensity of the radar energy back scattered by the void space behind the external leaf. Thus, white indicates areas with serious detachment problems while black areas are expected to be safe. The images were overlapped to the crack pattern survey to facilitate the correlation of the detachment with the stress state apparently affecting this side of the Tower. The lower part in Figure 5, in fact, was more affected than the upper one by cracks and deformations of the external surface induced by the stress state. This deformation trend is very likely the main reason of the detachment problem affecting this area. A coincidence can be observed between the most critical detached areas and the crack pattern: most of the white areas are located in the centre of the tower, below the mullioned window (with four lights), where the most important cracks were observed (Fig. 5).

After the experience on the Cremona Bell-Tower the observation of the Isso Tower damage appeared to be a very similar case, but with a much more advanced state of damage.

Even the historic documentation does not give any description, it seems clearer that when the bearing walls of the medieval towers (more than 2.00 m thick in the case of Cremona Torrazzo, 1.40 m thick in the case of the Isso Tower) were made by solid brick masonry but with rough construction technique, their external and internal surfaces were covered by a 12 cm thick brick masonry leaf made with regular bricks and mortar joint.

It is evident that this leaf grew up with the wall having averaging every 12 to 13 courses a course of header bricks to connect it to the rest of the wall (Fig. 6). The other courses are only partially connected with header and hence in many parts only the mortar is a contact between the leaf and the internal walls.

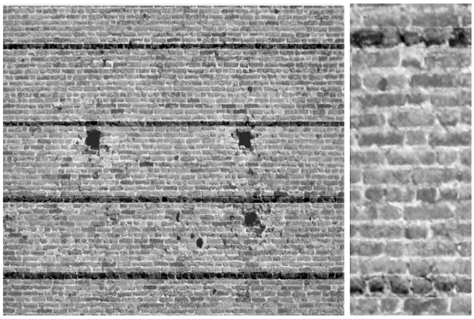


Figure 6. Isso Tower: regular presence of header bricks.

Figure 7. Mobile platform for the on-site survey of the prospects.

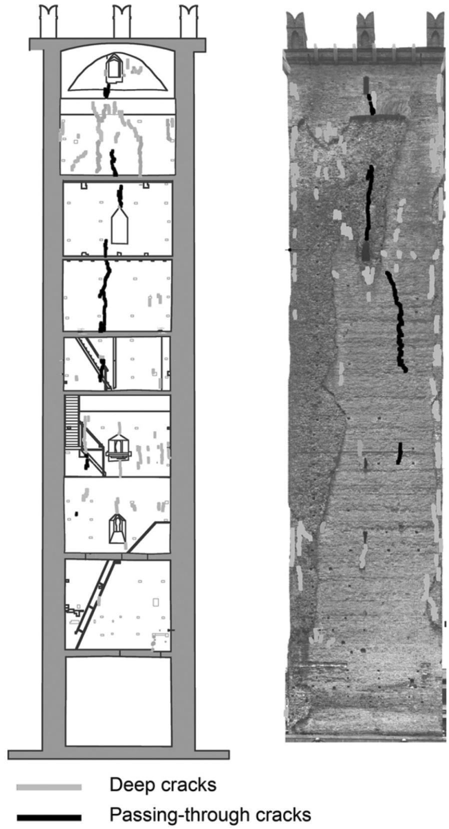


Figure 8. Crack pattern survey of the internal and external prospect of the North-East side.

4 CHOICE OF THE INVESTIGATION PROGRAM

The investigation carried out on the Isso Tower concerned several aspects: (i) the geometrical survey, (ii) the survey of the crack patterns and of the deterioration distribution on the internal and external surfaces of the walls, (iii) on-site measurements of the state of stress caused by the dead loads and of the stress–strain behaviour of the load bearing walls (Binda et al. 1999), (ASTM 1991a), (ASTM 1991b), (RILEM 1990a), (RILEM 1990b), (iv) use of sonic pulse velocity to detect the inhomogeneous density of the walls (Binda et al. 2001a), (RILEM 1997), (v) georadar investigations to detect the existence of the external masonry leaf and its detaching from the rest of the wall, and therefore subjected to possible dangerous local failure; on the external prospects, the accurate survey of the damages and the GPR investigation were possible by using a mobile platform (Fig. 7); (vi) numerical structural analysis.

5 RESULTS AND DISCUSSION

5.1 *The crack pattern survey and its importance in the diagnosis of the tower*

A preliminary on-site survey was useful in order to provide details on the geometry of the structure and in order to identify the points where more accurate observations had to be concentrated. Following this survey a more refined investigation can be carried out, identifying irregularities (vertical deviations, rotations, etc.). In the meantime the historical evolution of the structure has to be known in order to explain the signs of damage detected on the building.

Especially important is the survey and drawing of the crack patterns and the surface damage (Fig. 8). The interpretation of the crack pattern can be of great help in understanding the state of damage of the structure, its possible causes and the type of survey to be performed.

Evident damages are correlated to the lightning which struck the Tower during a storm in 1845 causing

Figure 9. Detachment of the cladding in the North corner.

Figure 10. Examples of cracks concentration around the corner and cladding detachment.

a large part of the external cladding to collapse (Figs 1, 3, 9).

The prospects show several repairs and replacements but also several cracks, with a dangerous concentration around the corners are correlated to the cladding detachments (Figs 10, 11).

The crack pattern survey identified some passing-through cracks on top of the Tower in the North corner.

5.2 *Investigation of the detached leaf*

The mobile platform allowed an accurate survey of the damage, often not visible from the ground level, but also to evaluate directly the detachment of the cladding.

It was possible to introduce underneath the detached leaf a rigid metal ruler up to more than 80 cm (Fig. 12).

Figure 11. General view and detail of a repaired crack.

Figure 12. Introducing underneath the detached cladding a rigid metal ruler to calibrate radar tests.

This demonstrates the danger of the potential instability of the masonry.

Furthermore, around the margins of the missed areas several cracks increase the possibility to loose parts.

Since the potential of high frequency radar investigations for the control of leaf detachments had already been tested in the Cremona Torrazzo (Binda et al. 2005), it was decided to systematically apply this method to the areas suspected to be seriously affected by the problem.

The wall was surveyed with a 2 GHz bipolar antenna (Aladdin system provided by IDS SpA) by executing more than one hundred horizontal profiles on each side of the Tower.

The data analysis was calibrated with specific tests to estimate the velocity of the radar signal and with local tests on selected points where it was possible

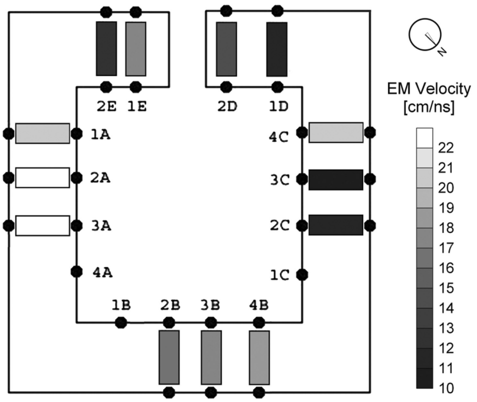


Figure 13. Distribution of the EM velocity measured by transmission at the Tower base.

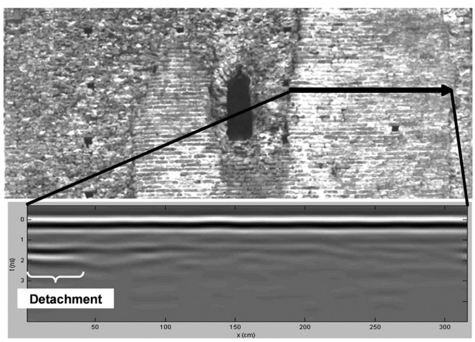


Figure 14. Radargram which indicates the detached area.

to insert and extract a metal shield to enhance the reflection from the detachment (Figs 12, 13).

An example of the radar result is shown in Figure 14. The detachment is revealed on the radar data by a strong reflection that appears at a constant time of approximately 1.5–2.0 ns. The elaboration of the data is still going on.

5.3 *Structural analysis and flat-jack tests*

A 3D finite element model of the Tower was created based on the geometrical and damage survey. The Tower was modelled by using 8-node brick elements.

A refined finite element mesh has been used, so that all the main openings and unregularities in the load-bearing walls could be reasonably represented.

The main aims of the on-going structural analysis are the evaluation of the state of stress due to the dead loads, the effects of the eccentric layout of the water tank and the stress increase due to the water infilling.

A further control concerns the stress concentration caused by the several intervention at the Tower base, revealed by the on-site survey.

Table 1. Stresses measured by single flat-jack test.

Test	Stress [N/mm^2]	Height [m]	Side
TCL-J8S	0.37	28.00	S-W
TCL-J7S	0.36	23.00	S-E
TCL-J5S	0.75	4.60	S-E inside
TCL-J3S	0.37	1.00	S-E inside
TCL-J9S	1.22	2.00	S-E outside
TCL-J4S	1.25	1.75	S-W
TCL-J2S	0.71	1.80	N-E
TCL-J1S	1.56	1.50	N-W inside
TCL-J6S	0.74	1.55	N-W outside

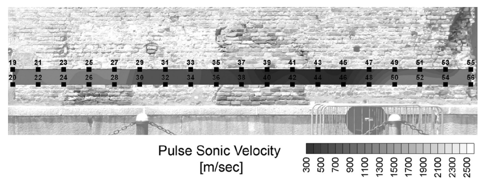


Figure 15. Distribution of the pulse sonic velocity measured at the base by transmission on the South-East wall.

The on-site investigation is of course used to calibrate the model parameters, which are modified according to the sequence of the on site results.

The model tuning and the structural analysis are still in progress.

5.4 *Flat-jack and sonic tests and masonry quality*

The localisation of the flat-jack tests were chosen in order to calibrate the FE model and to control the stress distribution caused by the eccentric position of the heavy tank. In detail, flat-jack tests were carried out at the base and at the tank levels (Table 1).

At the base level, the masonry shows several discontinuities caused by the numerous past interventions. Sonic tests were carried out before the flat-jack tests, to control the masonry characteristics along the whole perimeter of the basement. The tests were very precious to evaluate the compactness of the masonry section and the effects of the past repair. E.g. in the South-East and North-West side a low velocity area would revel several filled openings (Figs 15, 16).

The distribution of EM and pulse sonic velocity at the base of the (Figs 13 and 16) gives similar results. Usually, materials present complementary behaviours with respect to sonic and EM velocity (i.e., slow sonic materials are generally fast materials for EM waves and vice-versa). In both cases, lower compact area was found in the South-East wall.

Furthermore, the high unhomegeneity of the masonry could explain also the unregular distribution

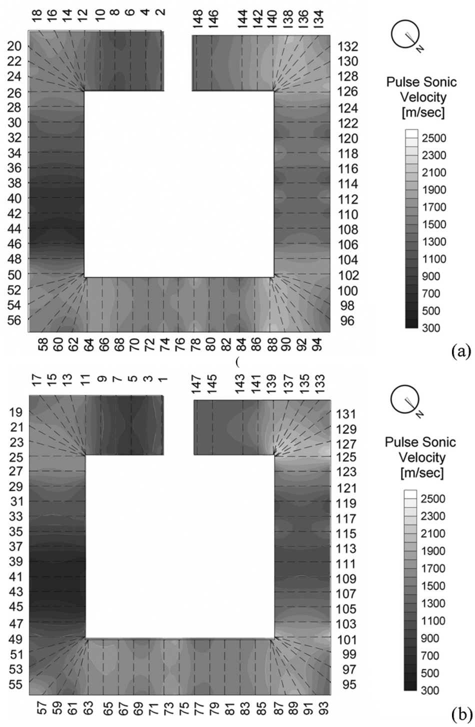


Figure 16. Distribution of the pulse sonic velocity at the Tower base respectively at 1.5 (a) and 1.8 m (b).

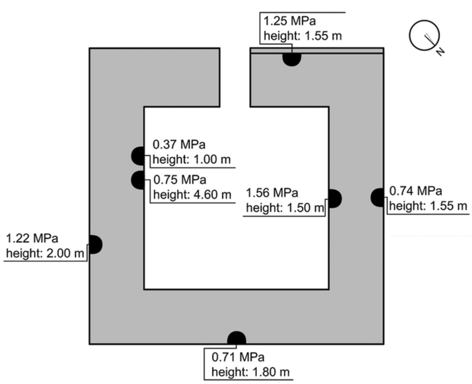


Figure 17. Local state of stress found by single flat-jack tests at the Tower base.

of the stresses measured by single flat-jack test at the base level of the Tower (Fig. 17).

As an example in the N-W side, a consistent difference between the measurements in the internal an external side was found (Fig. 17).

The direct on-site survey of the masonry bond and texture gives important information on the building techniques. The presence in average every 12 brick courses (about 1.0 m), of a header bond could guarantee the connection of the external cladding. However, in many situations the bricks crack during the time, failing their function of preventing the detachment and overturning of the cladding (Fig. 18).

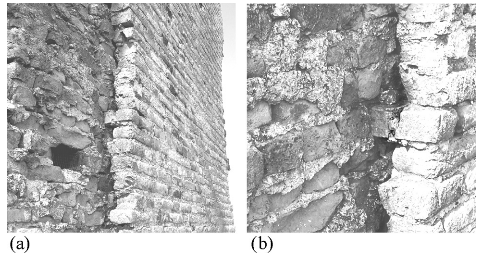


Figure 18. View of the cladding connection (a) and detail of a cracked brick in the header bond (b).

6 CONCLUSIONS

The research has shown the importance of a global approach in the assessment of the safety of historic buildings. The available information on historic evolution, masonry characterisation and on-site survey could help in the damage interpretation but also to give information for the structural analysis.

In the case of the Tower of Castelleone, the detailed knowledge of the building allowed to recognise dangerous elements. The past insertion of a water tank and the detachments of the cladding were found as relevant problems.

In particular, the cladding detachment is a serious problem for the Tower safety. It involves local damage that can be evaluated only by direct inspection.

The calibration of the theoretical model and further investigation are still on-going, collecting other information on the general behaviour of the structure.

The future intervention will be finalized both to repair directly the occurred damage and to eliminate the vulnerability sources.

ACKNOWLEDGEMENT

The Authors are grateful to IDS SpA and Boviar Srl for providing the Aladdin system that was used for the GPR investigations. Authors wish to thank M. Antico, M. Cucchi, M. Iscandri, the students A. Cazzador, L. Conti, N. Labbadini, V. La Rotonda, E. Spandre, the Architects L. Cantini, R. De Ponti and the Engineers M. Carsana, S. Munda for their contribution in the experimental on-site work. Special thanks for their collaboration go to the responsibles of the structural modelling Prof. A. Taliercio, G. Sacchi-Landriani and

Eng. P. Taranto. The research was supported by the Municipality of Castelleone.

REFERENCES

ASTM 1991a. ASTM C 1196-91: Standard test method for in-situ compressive stress within solid unit masonry estimated using the flat-jack method, Philadelphia.

ASTM 1991b. ASTM C1197-91: Standard test method for in situ measurement of masonry deformability properties using flatjack method, Philadelphia.

Binda, L. & Tiraboschi, C. 1999. Flat-Jack Test as a Slightly Destructive Technique for the Diagnosis of Brick and Stone Masonry Structures, *International Journal for Restoration of Buildings and Monuments*, Zurich, 1999, 449–472.

Binda, L., Saisi, A. & Tiraboschi, C. 2000a. Investigation procedures for the diagnosis of historic masonries, *Construction and Building Materials*, 14(4), 199–233.

Binda, L., Forde, M., Saisi, A., Valle, S. & Zanzi, L. 2000b, Application of radar test in the survey of the load bearing walls of the Torrazzo of Cremona, *Proc. 5th International Congress on Restoration of Architectural Heritage*, Firenze, 2000.

Binda, L., Falco, M., Poggi, C., Zasso, A., Mirabella Roberti, G., Corradi, R. &Tongini Folli, R. 2000c. Static and dynamic studies on the Torrazzo in Cremona (Italy): the highest Masonry Bell Tower in Europe, *Proc. International Symposium Bridging Large Spans: from Antiquity to the Present*, Istanbul, Turkey, 2000, 100–110.

Binda, L., Saisi, A. & Tiraboschi, C. 2001a. Application of sonic tests to the diagnosis of damage and repaired structures, *NDT&E International,* 34(2) 123–138.

Binda, L, Saisi A, Tongini Folli, R, Zanzi, L. 2001b. Boroscopy, flat-jacks and NDT as complementary tools, *Proc. International RILEM Workshop: On-site control and non-destructive evaluation of masonry structures*, Mantova, Italy, 13-14 November 2001, RILEM, 279–87.

Binda, L., Lualdi, M., Saisi, A. & Zanzi, L. 2003. The complementary use of on site non destructive tests for the investigation of historic masonry structures, *Proc. 9th North American Masonry Conference 9NAMC, Clemens, South Carolina*, 978–989.

Binda, L., Zanzi, L., Lualdi, M. & Condoleo, P. 2005. The use of georadar to assess damage to a masonry Bell Tower in Cremona, Italy, *NDT&E International*, 38(3), 171–179.

RILEM 1990a. Lum 90/2 Lum D.2 In-situ stress based on the flat jack.

RILEM 1990b. Lum 90/2 Lum D3, In-situ strength and elasticity tests based on the flat jack.

RILEM 1997. Recommendation TC 127-MS, MS.D.1 Measurement of mechanical pulse velocity for masonry, *Materials and Structures*, 30, 463–466.