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In situ investigations, structural analysis and strengthening of a stone masonry bell tower

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IN-SITU INVESTIGATIONS, STRUCTURAL ANALYSIS AND STRENGTHENING OF A STONE MASONRY BELL TOWER

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SUMMARY

A typical example is presented of the work which is being carried out by the authors in the field of structural evaluation and strengthening of ancient masonry towers.
The design of the restoration interventions and the assessment of their actual efficiency, are based on a combined experimental-numerical procedure, which is assumed to allow reliable structural analyses, consisting of the following major steps:

- in-situ evaluation of the actual state of stress, of the strength and of the deformability of the masonry by means of the flat jack technique;
- analysis of the masonry composition and bonding by means of bore-hole video inspections;
- in-situ measurement of ambient vibrations, before and after the execution of the strengthening work, from which an estimate of the overall structural behaviour can be derived calculating the fundamental period of vibration;
- construction of a numerical model, assuming the mechanical properties of the material derived from experimental investigations;
- calibration of the model through static and eigenvalues analyses, comparing experimental and theoretical values of local stresses and of the fundamental period of vibration measured before the restoration;
- evaluation of the numerical calculation for the fundamental period of vibration after the restoration.

KEYWORKS: MASONRY, TOWER, NON-DESTRUCTIVE TESTS, DIAGNOSIS, NUMERICAL MODEL, RESTORATION, STRENGTHENING

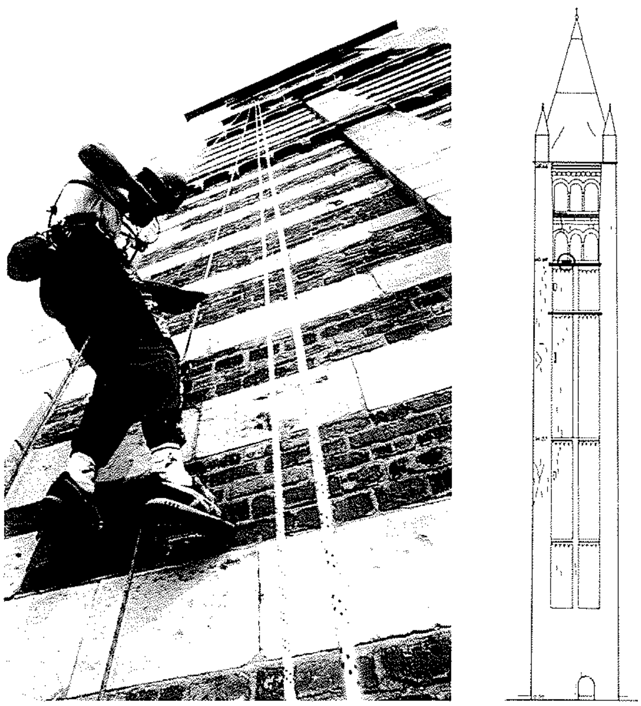
1. INTRODUCTION

The methodological approach proposed by the authors for the diagnostic analysis of the static conditions of ancient masonry towers is based on a combined experimental - numerical procedure. This method, which recently has been applied with success to several important monuments, is a reliable tool to analyse the structural behaviour of the tower and to design the strengthening works.
In the following, the major steps of the methodology are summarized and an example of application to an ancient stone masonry bell tower is presented.

2. INVESTIGATION METHODOLOGY

2.1 Crack pattern investigation

After the geometrical or photogrammetric survey is completed, a detailed investigation on the surface of the building must be carried out for the survey of the crack pattern and of the damaged zones.This kind of inspection must be carried out visually by trained technicians, usually with the aid of alpinist guides to avoid the very high costy of scaffoldings. It is the only reliable way for assessing the patters of the cracks which are relevant form the structural point of view.
An example of application to the bell tower of the Church of S.Zeno (XII Century) in Verona is shown in Fig. 1. The large cracks at the top of the tower are visible from the ground level, but only this investigation allowed a precise check of their propagation and the measure of the relative displacements



a) b)

Figure 1: Crack pattern investigation on the external wall of the bell-tower of the Church of S. Zeno (Verona)
a) Investigation carried out by a climbing technician
b) Crack pattern on the North wall of the bell-tower

2.2 Coring and borehole video survey

To understand the structural properties of the different types of masonry of which a building is composed, it is important to core small diameter boreholes taking samples in the most representative points of the structure. This operation becomes indispensable in the very frequent case when the masonry consists of two surface layers in regular bond with internal irregular packing.Coring must be done with a rotary saw using a diamond cutting edge. This coring operation allows samples to be extracted from the material on which laboratory tests can be made; this is particularly important when identifying the chemical-physical and mechanical characteristics of mortars. Inside the boreholes, additional investigations can be made which help to define the structural and mechanical properties of the masonry.
A small colour video camera (d = 11 mm) may be inserted into the borehole allowing a detailed study of the surface of the borehole. The results of this study may be recorded and archived for further analysis after the boreholes have been sealed. The information obtained by this survey include:
- the bonding characteristics of the masonry;
- the measurements of the size of the internal cavities;
- the analysis of the propagation of internal cracks and measurements of their openings.

2.3 Measurement of the state of stress

An interesting testing technique, based on the use of flat jacks, was developed in the ISMES laboratory a few years ago for the measurement of the state of stress of existing masonry structures. This very simple and reliable technique, which is carried out by introducing a thin flat jack into the mortar layer, is only slightly destructive. After the test is completed, the flat jack can easily be removed and the mortar layer restored to its original condition. The determination of the state of stress is based on the stress release caused by a plane cutting normal to the surface of the wall. Fig. 2 shows the different phases of the test.

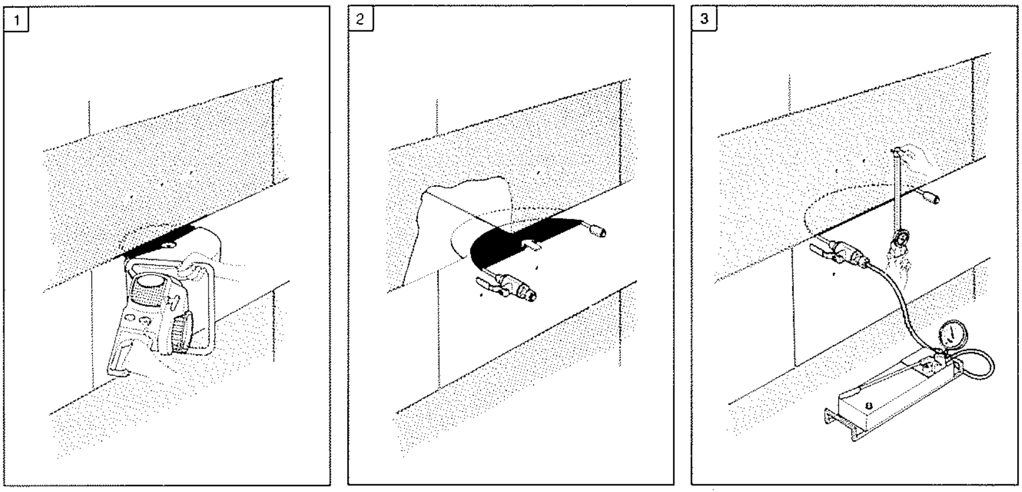


Figure 2: Scheme of the flat-jack testing phases on a stone masonry wall

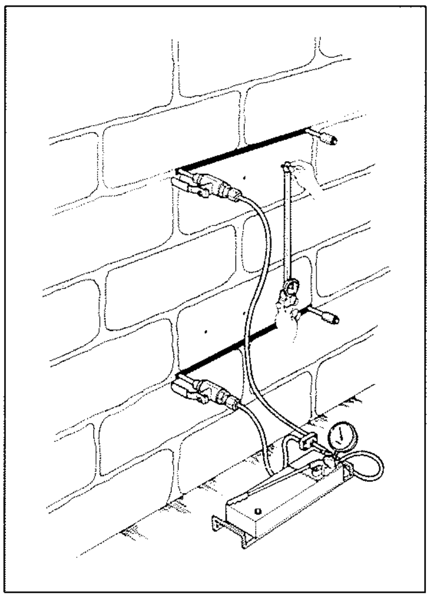
Two reference points are installed on the wall surface and the initial distance between the two points is measured. A slot perpendicular to the wall surface is then made and stress release is determined by a partial closing of the slot edges. A thin flat jack is placed inside the slot, and the pressure is gradually increased to cancel the previously measured convergency. In this condition, the pressure inside the jack is related to the pre-existing state of stress in a direction normal to the plane of the slot. The value obtained, which depends on the ratio between the flat jack and the cut surfaces and on the stifness of the welded boundary, must be corrected by a adeguate coefficient which is determined at laboratory on the base of accurate calibration tests. The use of flat-jack technique allows the analysis of the state of stress in different sections of the tower in order to recognize the zones where a stress concentration occurs.
Recently ISMES has developed the procedure of application of this technique directly on the external wall of towers with the aid of climbing operators without using scaffoldings. Fig. 3 shows an example of application of this technique to a brick masonry tower in Pavia.

Figure 3: Special application of flat-jack test on the external wall of a tower in Pavia without the aid of scaffoldings

2.4 Determination of deformability and strength characteristics

For this purpose a testing technique based on the use of two parallel flat jacks is used. The two jacks, inserted at a distance of about 50 cm one from the other, delimit a masonry sample of appreciable size to which they apply compression stresses. In this way a compression test is carried out on an undisturbed sample of large area. Fig. 4 shows the scheme of the test and an example of a test carried out on a stone masonry.

Several loading cycles are performed at gradually increasing stress levels in order to determine the deformability modulus of the masonry in its loading and unloading phases. This test can also be used to evaluate the compressive strength of the masonry. The load is increased until the first cracks in the bricks appear, then the strength limit of the masonry can be evaluated by extrapolating the stress-strain curve. The effect of the lateral confinement of the sample may be taken into account by calibration tests done in the laboratory.



a)

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Figure 4: Test with two parallel flat-jacks to determine deformability characteristics.
a) scheme of the test
b) example of a deformability test performed on the external wall of the San Francesco Church in Arezzo

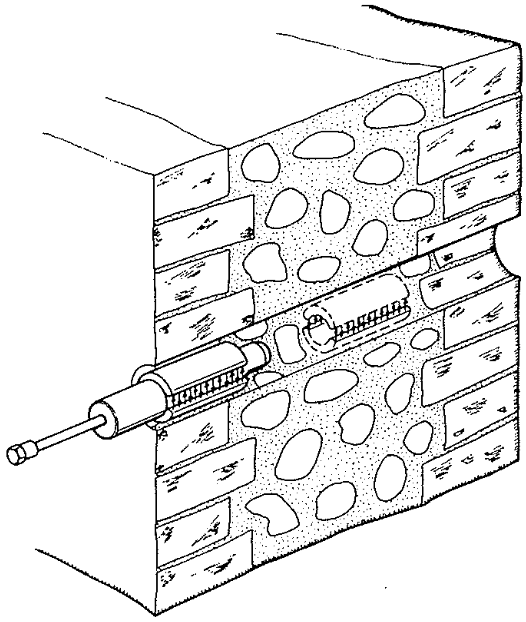


Figure 5: Scheme of borehole dilatometric test that determines the deformability characteristics of the surface and inner layers

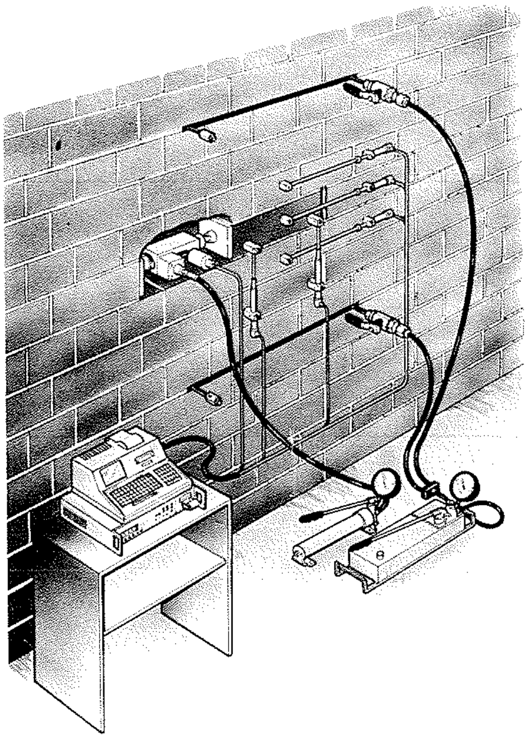


Figure 6: Scheme of a shear test along the mortar layers: the normal stress is applied by two flat-jacks and the shear stress is applied with a hydraulic jack

It has been observed that, when nearing failure conditions some cracks appear in the bricks, but the damage suffered by the masonry is quite negligible and can be repaired easily.
Using the tests with parallel flat jacks one can only determine the deformability characteristics of the superficial layer of masonry. In order to acquire information on the internal masonry it becomes necessary to carry out borehole dilatometric tests using a special probe about 25 cm long. As the portion of masonry used for this test is very limited, the values obtained by the dilatometric test are less representative than those obtained by the flat jack tests. This testing technique, however, is undoubtely useful as it determines the ratio of deformability of the internal masonry to the outer layer. Fig. 5 shows the scheme of borehole dilatometric test.

2.5 Determination of the shear strength along a mortar layer

The flat jack testing technique, combined with a hydraulic jack, can also be used to determine the shear strength characteristics of the mortar between the brick layers. A brick is extracted from the center of the masonry samples delimited by two flat jacks and a hydraulic jack of the same size is inserted in its place for the application of a shear force (Fig. 6). The testing technique determines the peak and residual shear strength of the mortar layers. By doing several tests with different values of the stress in a direction perpendicular to the joint, the friction angle and the cohesion of the mortar can be determined.

2.6 Dynamic analysis

The in-situ testing using dynamic methods can be considered a reliable non-destructive tool to verify the structural behaviour and integrity of a building. Dynamic investigations can be carried out according to the following procedures:

a) Through the analysis of data gathered as a response to dynamic loads continuously imposed to the structure (urban and railroad traffic, bells ringing, etc.) or from irregular actions. A seismometric network is installed in different parts of the structure and the signals are analysed in terms of amplitude and frequency content. Through spectral analysis techniques it is then possible to evaluate the dynamic modal parameters.

b) By subjecting the construction to low intensity forced vibration tests (so as to produce vibrational levels that do not affect the structural integrity) and recording the system response in terms of displacements, velocities and accelerations.The forced vibrations are induced by vibrodynes and the response measured by seismometric sensors. This second kind of analysis allows the identification of dynamic behaviour of the structure through the evaluation of its modal parameters (natural frequencies, modal shapes, damping ratios). The knowledge of these parameters allows the computation of the structural response to any type of dynamic load with known characteristics, and in particular for evaluating the seismic vulnerability of the masonry construction. Forced vibration tests repeated over a length of time, allow the evaluation of possible modal parameter variations. These variations may be associated with modifications in the structural integrity, enabling the actual structural degradation of the masonry elements to be quantified. It must be stressed that the information collected not only quantifies the structural degradation of the buildings or parts of them, but they are also important in the planning stage of any structural adaptations, when choosing the type and size of appropriate strengthening works.

2.7 Numerical models

Numerical models are constructed assuming the mechanical properties of the material experimentally derived and inspected as previously described. The model are calibrated through static and eigenvalues analyses, composing experimental and theoretical values of local stresses and of the fundamental period of vibration. The general state of stress can be then evaluated by means of the calibrated models, and the efficiency of the restoration works can be estimated by repeating the measurement and the numerical calculations after restoration.

2.8 Monitoring

Installing measuring instruments to monitor the structural behaviour of a building can be considered a reliable method for a non-destructive evaluation of the static conditions of the structure. This investigative technique is gaining popularity because, besides supplying information on the static conditions of the building, it is considered the only way to guarantee the safety of the structure before, during and after the consolidation works. The main features which are monitored are the following:

- openings and sliding of the main cracks in masonry structures;
- absolute and relative horizontal movements of vertical structures;
- rotation of vertical and horizontal structures;
- internal and external temperature;
- behaviour of soil and rock foundations;
- dynamic response.

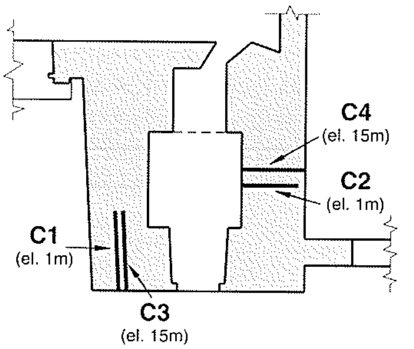
3. PRINCIPAL CHARACTERISTICS OF THE BELL TOWER OF NANTO (VICENZA)

The bell tower and the ancient church of Nanto (province of Vicenza) were built (probably in the 11th century, with some changes during the 16th century) using the popular soft limestone employed in the venetian architectural and decorative production of the last centuries and still quarried in the region today.
The monument is situated on a rock slope covered by a thin layer of soft limes varying in thickness very quickly: the foundations of the tower were found to be based on the rigid and irregular surface of the bedrock. Probably due to the local ground conditions, the poor quality of the materials (expecially of mortars), and to the lack of maintenance, the tower suffered major problems from deterioration.
The primary concern from the structural point of view was from the small and diffused cracks in the stones and from a large crack which vertically splits the south wall of the tower. The first type of cracks show dangerous distributions of stresses, especially when taking into account the typical "through-the-thickness" inhomogeneity of the masonry, which apparently has better quality stone on the outer covering; the second type can jeopardize the overall stability of the structure.
The design of the restoration interventions was based on the combined experimental-numerical procedure which was described in paragraph 2.

4. ANALYSIS AND STRENGTHENING DESIGN

4.1 In-situ non destructive tests

The masonry composition and bonging was first investigated by means of a bore-hole video survey; four 56 mm diameter cores were drilled in the positions indicated in Figure 7a, two at the base of the tower (1000 mm from ground level) and two at 15.000 mm from ground level. From the analysis of the cored material (Figure 7b) and from visual inspections conducted with a small video camera inserted in the holes, the precise "through-the-thickness" composition of the masonry was obtained.
A typical example of masonry composition is shown in Figure 7c, where a rather bad quality masonry clearly appears behind the external (approximately 200÷300 mm thick) leaf made with dressed stone units. The mortar, which does not completely fill the large spaces between the irregular stones, is very poor and without any apparent consistency. During che drilling operations it was, in fact, completely lost.



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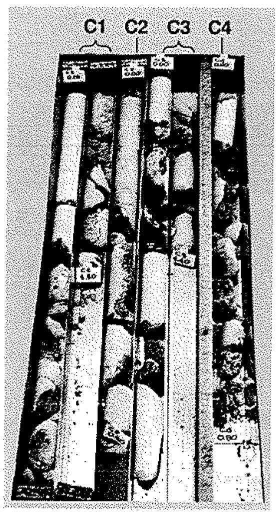

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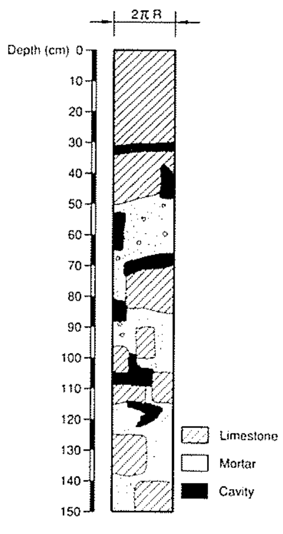

c)

Figure 7:
a) position of the drilled cores;
b) cored material;
c) typical "through-the-thickness" masonry composition.

Figure 8: The flat-jack test

The flat-jack technique (2) (Figure 8) has been used to determine the state of stress in six points (position 1 to 6 in Figure 9a) and the strenght and deformability on both sides of the masonry at the base of the tower (positions 4b and 5b in the same Figure). The results are summarized in Figure 9a, where the elevation from the ground level of the testing points and the measured stress is indicated in each position.

Figures 9b+c show typical stress-strain curves that were measured on the external (position 4b) and internal (position 5b) sides of the masonry.

The stress distribution indicates quite different states of stress in the two sections of the tower separated by the openings and by the major vertical crack. The mean value of the normal stress in the east part is approximately double that of the west part of the tower; and the external, more stiff, masonry leaf induces very significant stress concentration.

The diagrams in Figure 9b+c clearly show that:

1) the deformability of the internal leaf (5c) is approximately three times higher then the deformability of the external one;
2) at the maximum imposed stress level (2.4 MPa) the slope of the stress-strain curve significantly changes in the first case, demonstrating that the maximum compressive resistance has almost been attained, while in the second case the behavior is still linear-elastic.

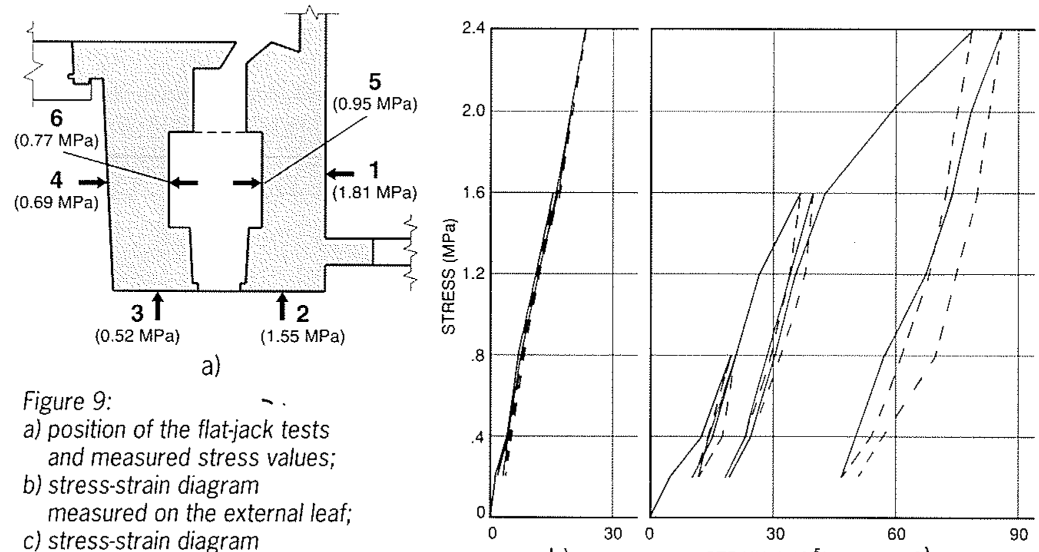

Figure 9:
a) position of the flat-jack tests and measured stress values;
b) stress-strain diagram measured on the external leaf;
c) stress-strain diagram measured on the internal leaf.

The ambient vibrations were finally measured at the top of the tower (pavement of the bell cell) before the structural restoration. A typical record of an acceleration time-history and the corresponding power spectrum are displayed in Figure 10a+b. The value of the fundamental period of vibration is clearly shown in Figure 10b and will be compared with the numerical results. Similar measurements will be performed after the restoration works will be completed.

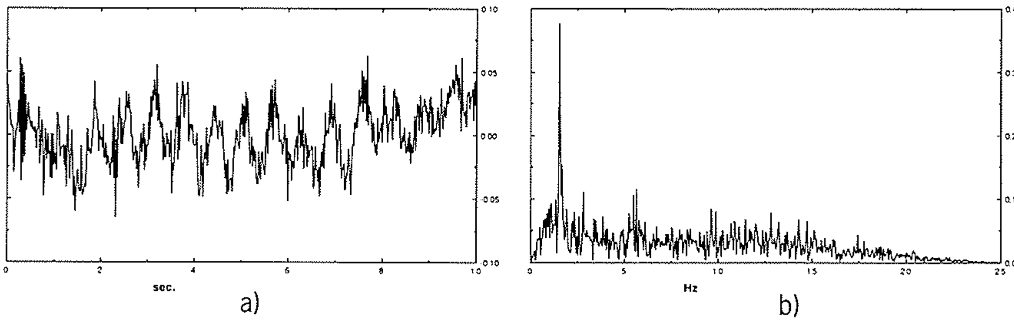

Figure 10: a) Typical ambient vibration record - b) Corresponding power spectrum

4.2 Numerical modelling and analyses

Figure 11 and 12 show the basic F.E. mesh (made with solid eight nodes elements) which was adopted to build three numerical models and the principal results of the static and eigenproblem analyses. The first model (disregarding the vertical crack on the south wall) was used to evaluate the "theoretical" effect of the crack on the distribution of stresses and on the overall structural behaviour (i.e. on the eigenvalues) by comparing the results obtained with those from the second model.

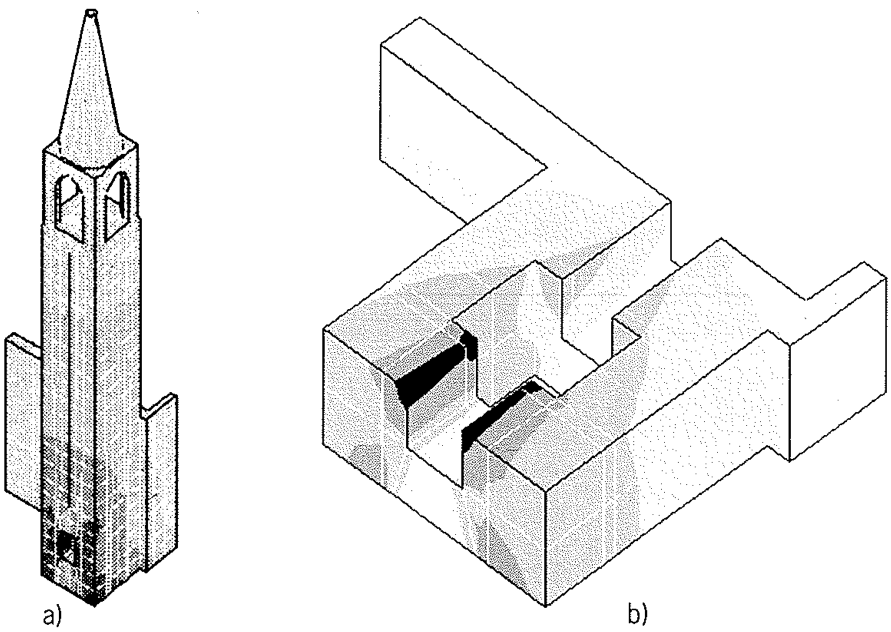

Figure 11: a) General view of the model - b) Detail of the "theoretical" distribution of normal stresses due to the gravitational load.

The crack, which schematically appears in Figura 11a, is taken into account in the second case as a lack of continuity along a plane of the elastic model; the third model includes the steel frames and ties used for the structural restoration.
These models took the scope of the analyses into account by including the evaluation of the present state of stress under the gravitational load and of the dynamical properties under ambient excitation sources of very small intensity, and assuming linear elastic material properties derived from the flat jack stress-strain curves.
Typical results of the static and eigenproblem analyses are summarised in the Figure 11 and 12 respectively. Of course no significant differences can be expected between the states of stress under the gravitational loads: a comprehensive overall view of the normal stress distribution can be drawn from Figure 11a, and a significant comparison between theoretical and experimental results can be made on the basis of Figure 11b, representing the normal stress distribution at the base of the tower (black, 0.8 MPa; white, 0 MPa). The local inhomogenity of the materials shown by the flatjack measurements can cause over-stresses in the order of three to four times the theoretical values.

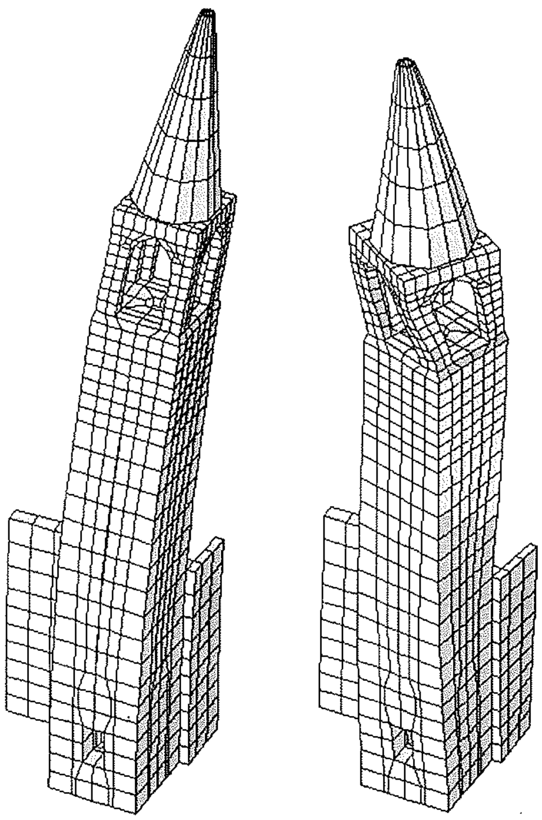

Figure 12: a) Modal shapes corresponding to prevailing flexural and torsional deformations of the tower.
b) Model shapes corresponding to prevailing torsional deformations

Even more interesting are the results of the eigenproblems solutions. In Figures 12a+b the modal shape corresponding to the fundamental period of vibration and to prevailing torsional deformations of the three models are represented. The calculated eigenfrequencies of the uncracked, cracked and strengthened models respectively were 1.91, 1.79 and 1.92 Hz in the first case, 8.39, 7.6 and 8.5 Hz in the second case. The models seem then capable to represent the actual overall structural behaviour of the tower, the effects of both the crack and of the restoration works included.
Further calibrations, and in particular the comparison with the measurements which will be performed after the structural restoration will be concluded, are expected to confirm the possibility of using the numerical models for reliable analyses, in particular in order to control the efficiency of different possible restoration techniques.

5. STRENGTHENING TECHNIQUE

The most important observations drawn from the experimental and numerical investigations were the following:

- the values of the normal stresses measured on the internal face of the masonry walls seemed not too far (scarcely by a factor of 2) from the dangerous stress levels corresponding to significant softening of the stress-strain curve of the material (Figure 9c);
- the major cracks actually behaves like a "structural" joint.

It seemed then reasonable to intervene by both increasing the compressive strength of the masonry, especially at the base of the tower, and improving the ability to transmit internal forces along the crack. Local injections and steel ties can resolve the first requirement; horizontal steel frames and ties, as shown in Figure 13, tend to make the walls co-operate structurally with a beneficial local confinement effect, that is capable of improving the compressive strenght of the masonry.

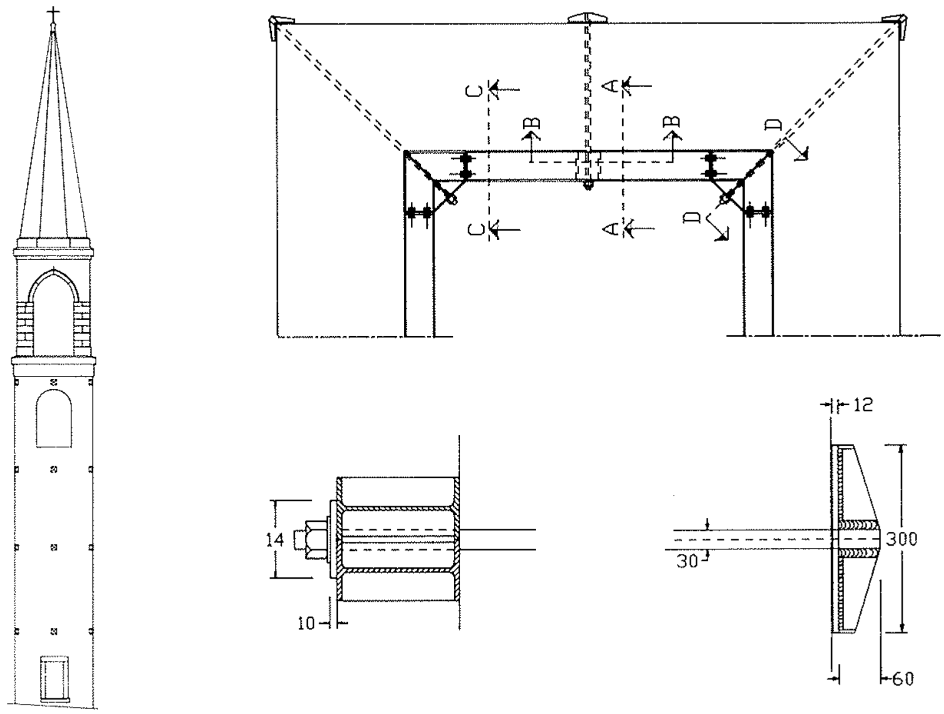

Figure 13: General view and details of the steel works made for strengthening the bell tower.

The second type of intervention is being executed using stainless steel bars and plates for the ties passing through the masonry and for their external anchoring devices. Bolted connections are used and the ties are inserted in small holes drilled through the masonry which will not be filled with any material, so that the strengthening steel structure is entirely domountable: this comply with construction reasons, and mostly with general conservation requirements. In figure 13 details of the frame and ties are given, while their position is indicated in the general view of Figure 13, which shows the effects of the restoration work on the external appearance of the tower. The intervention is very critical for the overall stability of the tower, and the most attention is in fact being payed to both its execution and, as previously explained, to the efficiency control.

6. CONCLUSIONS

The general methodology which has been proposed and pratically applied by the authors for the analysis and the strengthening design of masonry towers has been described.
The design of the structural restoration of a stone masonry bell tower based on such comprehensive combined experimental and numerical procedure has been presented.
The results of the flat-jack and video bore-hole surveys have been used for both evaluationg the strength, the deformability and the composition of the masonry, which are required for the constructions of the numerical models, and for the estimation of the actual local state of stress which can be used for safety checks and for calibrating the refined numerical models, and for safety checks of the actual local state of stress which can be used for safety checks and for calibrating the refined numerical models. Further calibrations of the models are based on the comparison between measured and calculated eigenvalues. Using the same technique for calculating and comparing experimental and theoretical eigenvalues, the efficiency of the structural restoration is also controlled. The relevant details of the structural restoration works are then presented.

7. REFERENCES

(1) *Modena, C. "Tecniche per la diagnosi e il consolidamento e per il monitoraggio di strutture murarie", Atti del Convegno Tecnologia e Tecnica delle Murature Antiche, Padova, 24 Nov. 1990.*

(2) *Rossi, P.P., "Non destructive evaluation of the mechanical characteristics of masonry structures", Proc. of the Conference Non Destructive Evaluation of Civil Structures and Materials, University of Colorado, Boulder, Oct. 1990.*

(3) *Modena, C. "Italian practice in evaluating, strenghthening and retrofitting masonry buildings", Proc. Int. Seminar Evaluating, Strengthening and Retrofitting Masonry Buildings, Gaithensburg-Boston-Chicago-Los Angeles, The University of Texas at Arlington Pub., Arlington, Texas, 1989.*

(4) *Riccioni, R., Rossi, P.P., "Restauro edilizio e Monumentale: diagnosi e condolidamento", il Cigno Galileo Galilei Edizioni di Arte e Scienza, Roma, 1990.*

(5) *Modena, C., Gori, R., "Indagini dinamiche per la caratterizzazione strutturale dell'Arca di Mastino II della Scala in Verona", R.I. 1/90, Istituto di Scienza e Tecnica delle Costruzioni, Padova, 1990.*

(6) *Castoldi, A., Chiarugi, A., Giuseppetti, G., Fanelli, M., "In-situ dynamic tests on ancient monuments", IABSE Colloquium, Bergamo, 1987.*

(7) *Modena, C., Rossi, P.P., Bettio, C., "Diagnosis and strengthening of an ancient bell tower" Proc. 9 IBMaC, Berling, Oct. 1991.*