7th International Seminar on
Seismic Isolation, Passive Energy Dissipation and Active Control of Vibrations of Structures
Assisi, Italy, October 2-5, 2001

STRUCTURAL DYNAMIC INVESTIGATIONS ON THE BELL TOWER FROM THE S. LUCIA'S CHURCH – SERRA S. QUIRICO (ANCONA)

T. Pelella, G. Mannara
S.T.R.A.G.O. s.r.l., Pozzuoli, Italy, ricercasviluppo@strago.it

E. Cosenza, I. Iervolino
Dipartimento di Analisi e Progettazione Strutturale, Università di Napoli Federico II, Italy, cosenza@unina.it, iuniervo@unina.it

L. Lecce
Dipartimento di Progettazione Aeronautica, Università di Napoli Federico II, Italy, leonardo@unina.it

ABSTRACT

In order to support the innovative design activities for the post-earthquake structural rehabilitation of the S. Lucia's Church bell tower, structural dynamic investigations were executed in February 2001.

Tower dynamic behavior was analyzed by using both ambient and forced vibrations. The comparison between results of experimental dynamic analysis and FEM numerical simulations gives the multidirectional vibration modes and the constraint conditions against adjacent buildings.

1. INTRODUCTION

Problems in analyzing structures with and artistic relevance are related with uncertainty on structural schemes and mechanisms, materials properties and state of conservation, and real reliability factor. Designed retrofitting interventions have to respect arts restoration principle, *e.g.* the "*non invasivity principle*" that expresses the necessity of interventions that don't modify the structure and that don't change the building appearance, so it shall be *transparent* and *reversible*.

Innovative structural materials, as composites and advanced analysis techniques, according with needs listed above, were helpful in the definition of seismic behavior and in the retrofitting design for the *bell tower from the S. Lucia's Church.*

Before the design process get started, both static and dynamic accurate analysis is needed, to define the present seismic structure's capacity and seismic behavior. Good preliminary results allow designer to build up a more fine intervention that integrate structure's strength but doesn't change the static system.

After an experimental evaluation of material properties a multi-level FEM analysis was executed to establish stresses following the static loads and the vibration modes but also constraint condition between tower and near structures.

This first analysis stated acceptable masonry stress level so a experimental tests, to confirm results and establish the real constrain level, was delivered. The investigations were performed by using both wind excitation (ambient vibration) and a vibrating machine (forced test) positioned on the bell tower's basis, in the last case in order to generate sinusoidal forces with well known characteristics.

There were used 16 force balance's accelerometers for the structural response measurements. There were chosen six measurement points in several heights of the bell tower.

2. THE BELL TOWER FROM THE S. LUCIA'S CHURCH

The bell tower of S. Lucia's church (Fig. 1 and Fig. 2) is in Serra San Quirico, a little town near Ancona, it's 325 m on the sea level in a second category seismic and windy zone. The tower is in the center of the town and it's surrounded by many ancients residential buildings.

It is a calcareous masonry building, walls thickness is 1.20 meters at the basement and 0.80 meters on the top. The building has a rectangular plant and is about 32 meter tall and 1100 tons in weight. The structure is connected on two sides to the contiguous buildings up the height of nine meters and on the others side to the vault roof of S. Lucia Church.

It was built in XV century, but recently, in 1997, it was affected by the *Umbria and Marche earthquake*. On this kind of tall structures seismic actions are strong because the overturning moment is proportional to weight and center of gravity position. So a reliability evaluation and a structural safety improvement were necessary.

Missing constraints and materials show necessity of structural analysis described in the present paper.

Fig.1 The bell tower in Serra S.Quirico (Ancona)

3. FEM MODELLING AND NUMERICAL ANALYSIS

In order to reach a preliminary knowledge base on the structure in terms of bidirectional stress levels under: weight, wind and equivalent-static seismic load, many numerical calculation were programmed.

First step of investigation was masonry sampling to define the material properties, it is a *sac masonry*, we evaluated an equivalent density (1900 kg/m^3) and young's modulus (20000 kg/cm^2). After that a multilevel analysis strategy started up; a continuous dynamic model was first, then a twelve degrees o freedom model was next. Continuous model was a cone, it was useful to reach first approximation proper frequency. By this analysis the estimated period was 0,7 sec.

Starting from detailed relief of the tower, a full 3D Finite Elements Model made by 33.000 nodes and 27.000 elements (Fig.3). Because the uncertainty of constraint condition between tower and next buildings (the church and the cluster), two limit-subcase FEM analysis needed: on a hand the tower was free by the adjacent structures anly constrainet at the base; on the other hand also lateral constraints were considered, they allows only rotations and simulate the cluster's roof (at 4.00m, 7.20 m, e 9.40 m from the tower's base) and church's dome (at 6.20m e 10.40m from the tower's base). In this way were ensured that stresses and vibration frequencies were bounded by FEM analysis results. See Following two pages for FEM analysis results and first three modal shapes. Numerical analysis confirmed the hypothesis that the tower was not in bad state; compression stress did not exceed 4-5 kg/cm^2 (maximum at the base of the tower) that is lower than 1/5 of the masonry strength. They also state that very different modal shapes follow by the two different constraint conditions.

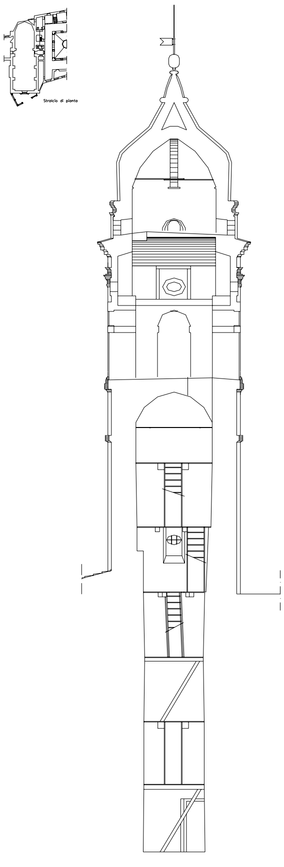

Fig.2 The bell tower relief

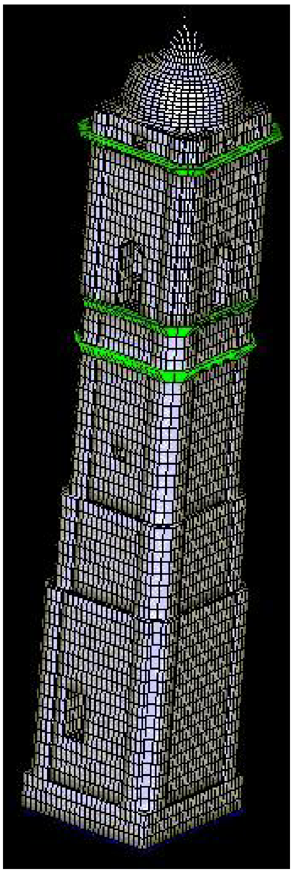

Fig.3 The 3D FEM model

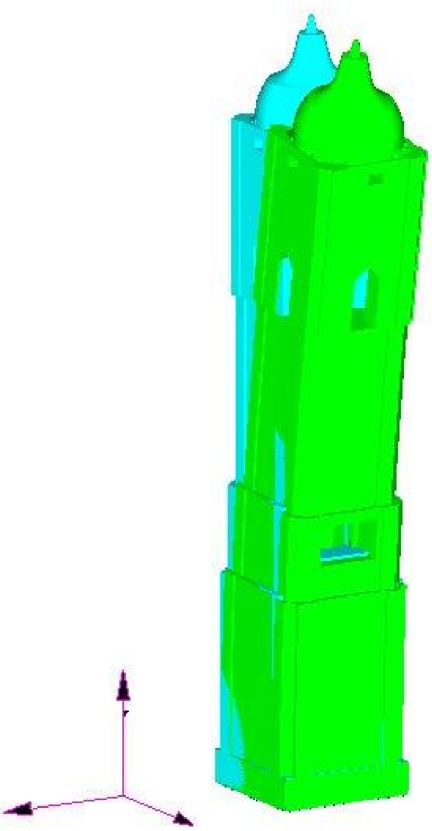

Fig.3 Shape of First Mode (Free Subcase)

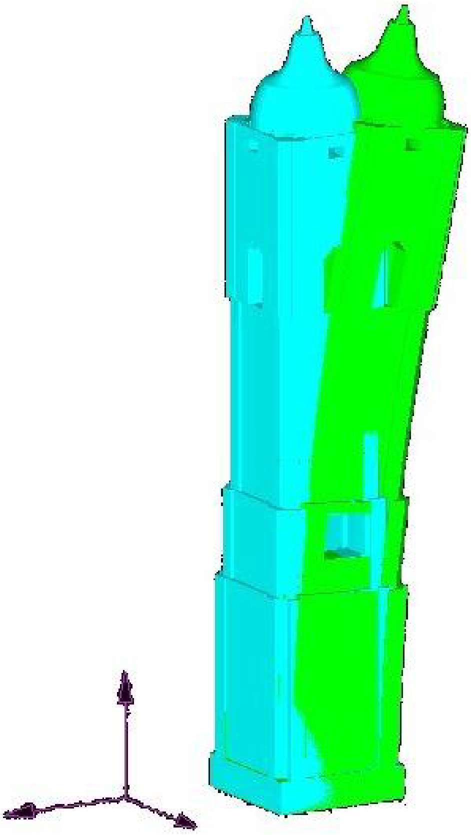

Fig.4 Shape of Second Mode (Free Subcase)

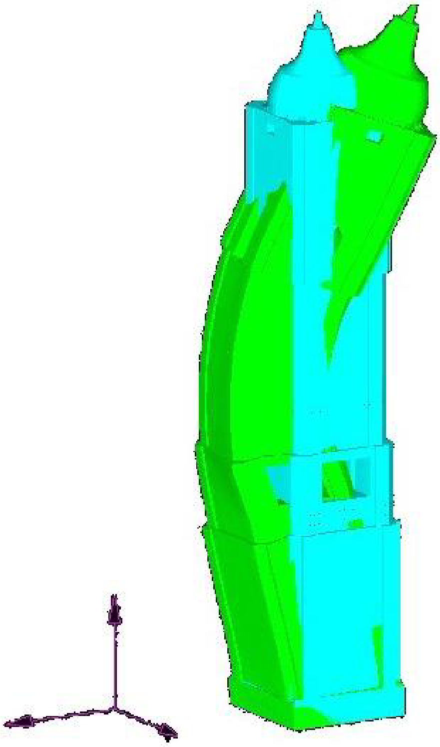

Fig.5 Shape of Third Mode (Free Subcase)

Table 1. FEM Results for Free Subcase

F1 (Hz)	1.28	T1 (S)	0.78
F2 (Hz)	1.32	T2 (S)	0.76
F3 (Hz)	5.66	T3 (S)	0.18

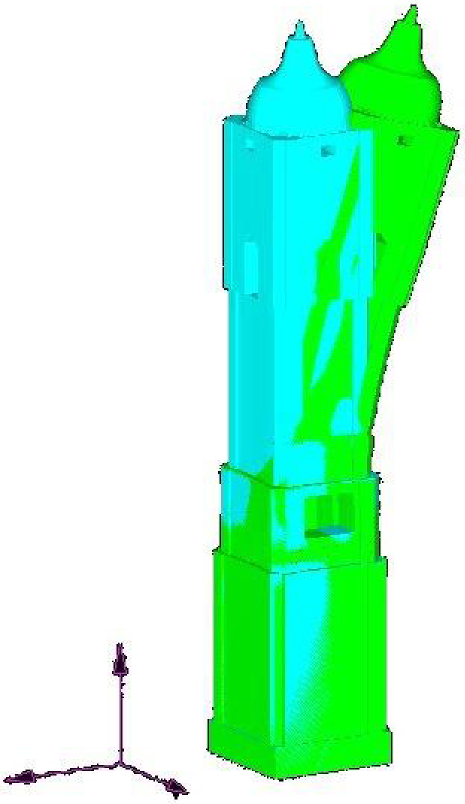

Fig.6 Shape of First Mode (Constrained)

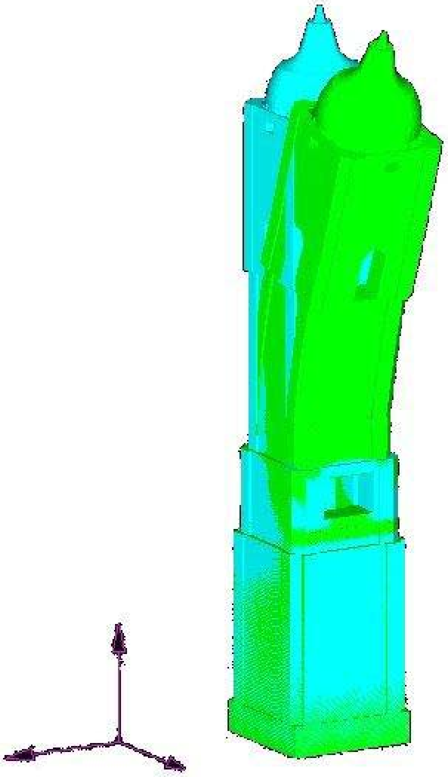

Fig.7 Shape of First Mode (Constrained)

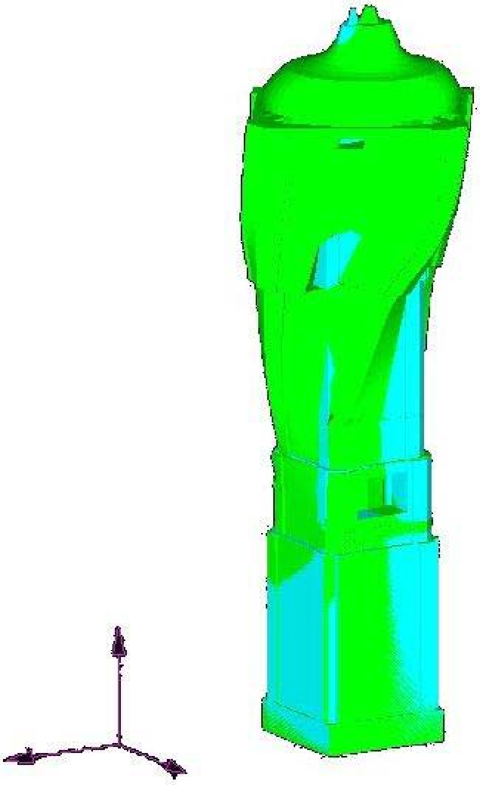

Fig.8 Shape of Third Mode (Constrained)

Table 2. FEM Results for Constrained Subcase

F1 (Hz)	2.64	T1 (S)	0.38
F2 (Hz)	2.80	T2 (S)	0.36
F3 (Hz)	8.4	T3 (S)	0.12

4. DINAMIC EXPERIMENTAL TESTS

To confirm numerical results and establish the real constrain level against adjacent buildings a experimental dynamic analysis was delivered.

The main aims of the dynamic investigation were:

1. Dynamic characterization of the structure (determination of the natural frequencies, vibration damping and modal shapes)
2. Determination of the dynamic reference values of the structure for a following activity of the monitoring of degradation.
3. Validation and up-date of a numerical model (FEM) of the structure.
4. Verify the structure behavior in real working conditions (dynamic response measurement in windy conditions, etc.)
5. Verify the tower constraint conditions against the adjacent buildings

Test were executed by S.T.R.A.G.O. s.r.l. in march 2001 using a vibrating machine (Fig.9). For the structural response measurements were used 16 force-balance accelerometers. The accelerometers were positioned in each measurement point across two perpendicular measurement directions, see fig.10 for accelerometers positions.

The forced excitation was applied at 45° angle to the bell tower's walls, to generate a vibration in both x and y directions.

Fig.9 The vibrating machine

Inducing strong vibration in this kind of structure can be dangerous and can determine the collapse, destroying what wants to preserve, so very sensible accelerometers were used in this case, they can measure acceleration of 10 μg so, was possible to identify tower's proper frequencies (table 3) trough vibration imperceptible at the top of the tower keeping safe conditions.

Table 3. Experimental Analysis Results

MODE N°	Frequency (Hz)	Damping %	Mode shape
1	1.95	2.28	1° bending X
2	2.20	1.76	1° bending Y
3	6.75	2.05	torsional

Accelerometers sensitivity and accuracy, that allows extremely low dynamic forces make this kind of test very interesting in dynamic identification of ancient buildings but also for structures without any existing structural data.

The bending mode natural frequency in the X direction is lower than in the Y direction (Fig. 10). This is because of a lower bending stiffness in this direction and/or because of the different constraint conditions. There is a slope changing of the displacement diagram at the bell tower's junction with the rest of the structure. It demonstrates a good connection between the structure and the other buildings.

As showed by table 3 this behavior is more obvious in the 2.2 Hz shape (direction Y). The vibration amplitude is higher in the Y direction than in the X direction. The conclusion of the data analysis is that there aren't particular abnormalities in the dynamical behavior of the structure in applied load conditions.

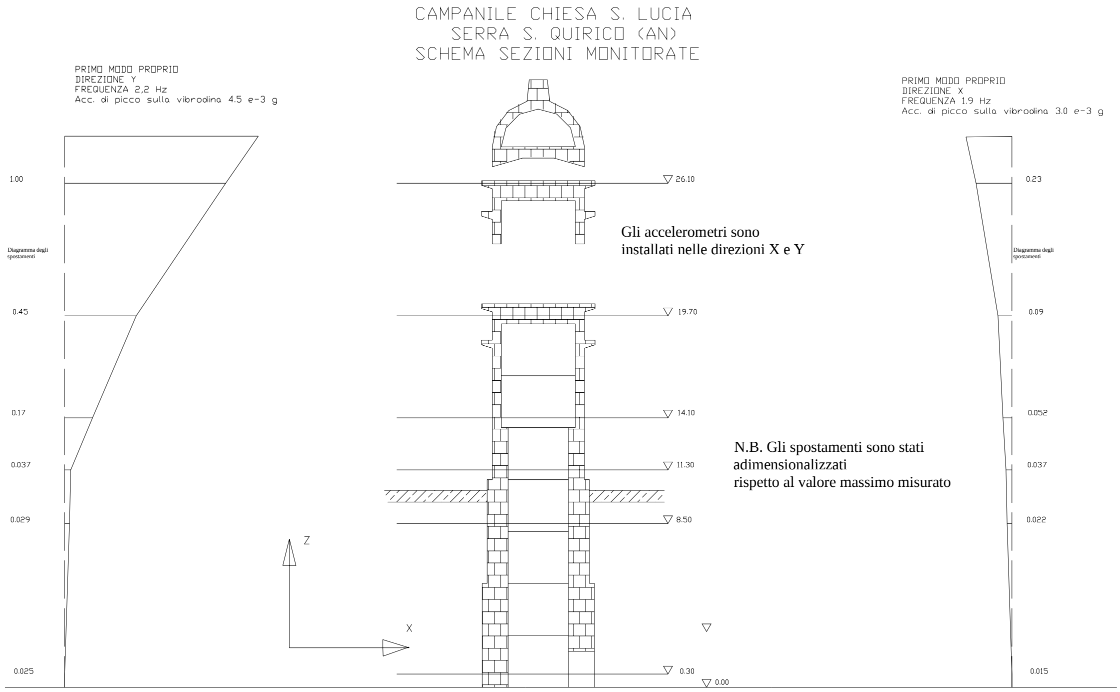

Fig.10 The experimental first mode in x and y directions

5. COMPARISON BETWEEN NUMERICAL AND EXPERIMENTAL DATA

First two observed frequencies were: 1.9 Hz and 2.2 Hz and they are bounded by frequencies obtained in the 3D FEM analysis considering the tower only constrained at his base (1.10 Hz e 1.13 Hz) and firmly linked to church and the cluster (2.27 Hz e 2.40 Hz). So, as expected, the real constraint level is intermediate between two limit conditions simulated in FEM analysis. The modal shapes and frequencies values, that are close to results of FEM constrained subcase, clearly shows that the real behavior it is near the upper bound, that consider the presence adjacent buildings.

The reliability of both results from dynamic and FEM analysis is also established by individuation of a third torsional mode (see. Fig. 8 and table 3).

6. FINAL REMARKS

The main issues in the analysis of structures having an artistic value are related to uncertainties on structural schemes and mechanisms, material properties and state of conservation, and actual reliability factor.

The comparison between experimental outcomes and numerical analysis pointed out that the whole system consisting of church and clucter acts as an effective restraint on the bell tower. In particular, such opinion is confirmed by:

1. values of vibration frequencies,
2. shape of the bending modes;
3. presence of a third torsional mode, consistent with the existence of a restraint; otherwise, it would have been a bending mode.

The selected technique, based on the combination of information from tests by a vibrating machine, vibrations due to wind loads, and records provided by very sensitive accelerometers, allowed for a dynamic characterization obtained by a low energy test. Such method appears to be particularly appropriate for the analysis of historic constructions, which are generally characterized by non-structural parts that need particular care.

Once the structural analysis has been done, the designed retrofitting should respect arts restoration principles such as the "non invasivity principle" stating the need for a strengthening that does not modify the structure and does not change the building appearance; this goal can only be achieved by a transparent and reversible upgrade.

Innovative structural materials, like composites, and advanced analysis techniques, according to the above listed needs, were helpful in order to define the seismic behaviour and design the retrofitting of the bell tower from the S. Lucia's Church

7. AKNOWLEDGEMENTS

The authors would like to thank the "Soprintendenza ai Beni Ambientali, Architetonici e Culturali" of Marche (Ancona), which required the analysis, and in particular architect Enrico Guglielmo, former Soprintendente of Marche , architect Ugo Soragni, present Soprintendente of Marche and architect D'Innocenzo, job supervisor. The retrofitting system was designed by professor Edoardo Cosenza and architect Augusta Cyrillo Gomes.

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