Application of Modal Testing Techniques to a Monitored Building Structure

D. Losanno, M. Spizzuoco & G. Serino
University of Napoli Federico II, Italy

SUMMARY:
The "Our Lady of Tears Shrine" in Syracuse has been recently included in the network of public constructions of the Italian Observatory of Structures (OSS), created by the Italian Dept. of Civil Protection to locally monitor their seismic behaviour: the local monitoring system allows to permanently monitor the structural response, under the control of a network central computer, installed in the National Seismic Service headquarters. The usefulness of structural monitoring systems for the application of dynamic identification techniques represents a more and more important issue in the case of structures of critical interest for the management of seismic emergency and for the complexity of their structural scheme. On the other hand, dynamic identification techniques are able to single out the dynamic properties of a structure (natural frequencies, mode shapes and damping characteristics), in order to improve the calibration and validation of its numerical model.

Keywords: Worship building, health monitoring, seismic isolation, modal testing, FEM model

1. THE WORSHIP STRUCTURE IN SYRACUSE

The "Our Lady of Tears Shrine" (Technical Economical Italian Association of Cement, 2001) represents a combined application of structural health monitoring and experimental dynamic identification (Fig. 1.1(a)). Located in Syracuse, the "Upper Temple" was built at the end of the '80s on the underground structure (consisting of the foundations and the crypt) completed in 1968.

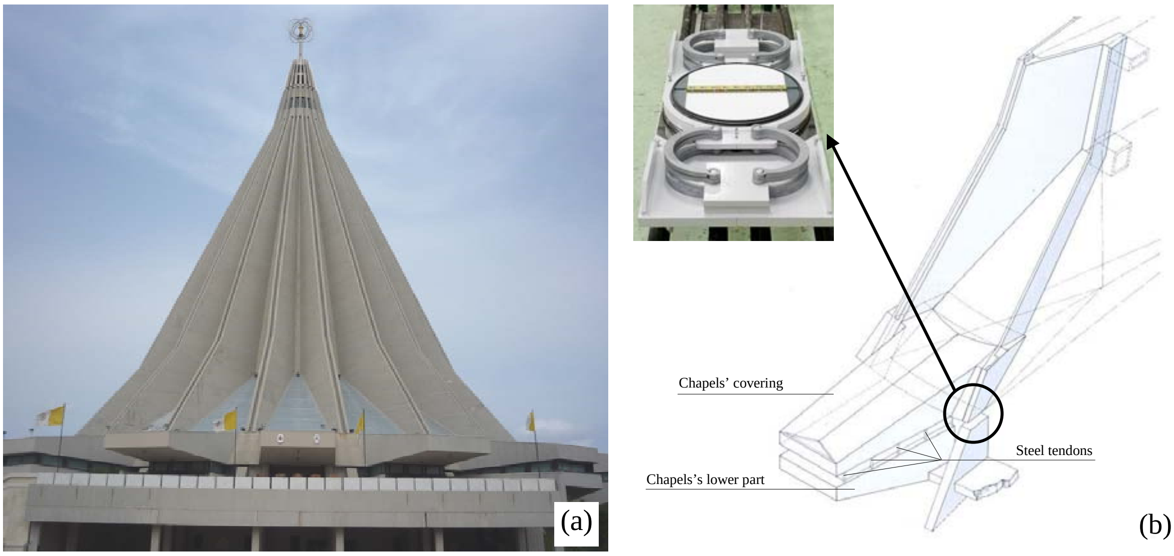

Figure 1.1. (a) View of the Sanctuary, (b) axonometric view of one chapel and the base ring

The church is made of fair-face concrete and consists of an imposing truncated-conical dome, which rises from a prestressed concrete base ring supported by 22 columns. From the same base ring, 19 subhorizontal external cantilevers depart (Fig. 1.1(b)), which represent the covering of an equal number of chapels. The vertical development of the structure is 74,30 m from the extrados of the Crypt's covering plane. The whole dome is supported through the base ring on 22 r.c. piers with trapezoidal shape placed along the perimetrical circle at 10,00 m spacing. Between each column and the base ring above, a pot bearing with a steel-teflon sliding surface and 9810 t capacity was installed. Each bearing allowed the variations of the diameter of the covering's base ring (radial displacements) due to thermal and tensional variations, as well as the rotations of the base ring in the meridian planes of the upper structure, while the displacements in tangential direction were prevented. Before the completion of the construction and the final acceptance testing (1994), a structural monitoring system of the Sanctuary was installed but never started.

In the period February-March 2006 the huge dome was seismically isolated (Serino et al., 2009) from the lower structure, by substituting the pre-existent bearings with new sliding seismic isolators with properly designed dissipative steel elements (see Fig. 1.1(b)). The new antiseismic devices, manufactured by FIP Industriale (Padova, Italy), freely allow the displacements in radial direction due to thermal variations (up to ± 200 mm), and are able to transmit forces in the tangential direction (up to ± 1050 kN at the maximum tangential displacement of ± 150 mm), being characterized by an elastic behaviour with a defined stiffness up to a resistance threshold, above which plastic slip occurs at a practically constant force. In case of a seismic event involving the inelastic behaviour of the structure, the plasticization is concentrated in elasto-plastic dissipators with "moon's sickle" shape. This prevents damaging of the columns because reduces the forces transmitted to them, which represent the most vulnerable elements of the construction. Besides, in case of a moderate earthquake both the church and the new devices should not be damaged, so keeping the total functionality of the construction. After the seismic isolation intervention, it was therefore decided to reactivate the monitoring system through an intervention of overtime maintenance and adaptation to the new constraint scheme of the dome, in order to finally start the operations of monitoring and continuous control of the construction.

1.1. Monitoring system

The rehabilitation and upgrading design of the original monitoring system (Serino et al., 2009) provides a new effective continuous monitoring system of the Sanctuary, based on the use of only one digital dynamic acquisition system with 64 channels, which are planned to be connected to: the 30 pre-existent accelerometers (20 by the Crypt plane and the bearings, and the remaining 10 at elevation +16.40 m and on the top of the dome); 8 new displacement transducers to be placed in couples by 4 of the 22 bearings, and having a stroke compatible with the maximum design displacement of the isolators (±200 mm in radial direction and ±150 mm in tangential direction); 5 thermo-hygrometers to measure the temperature and relative humidity; 1 barometer and 1 tachy-gonio-anemometer measuring the velocity and direction of the wind (Fig. 1.2).

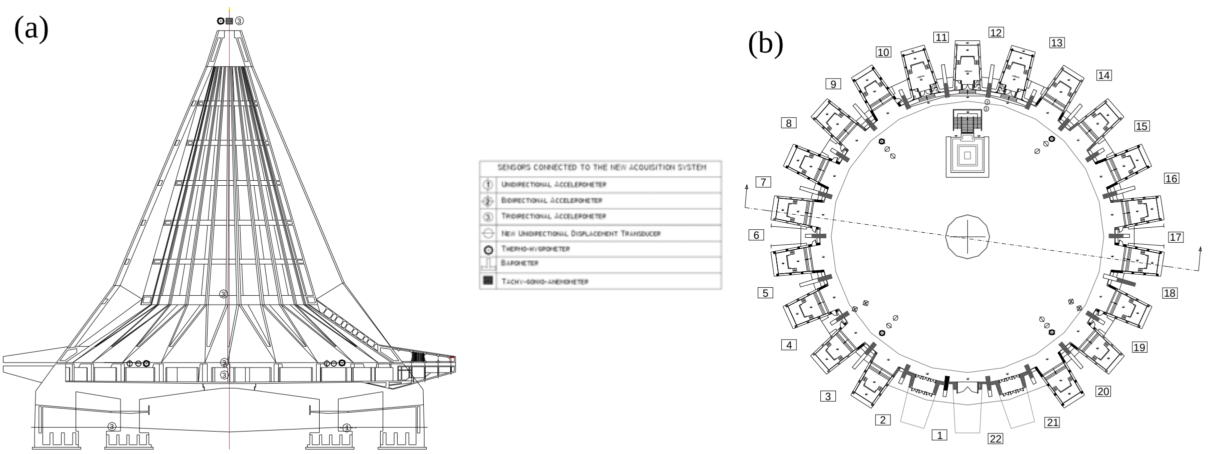

Figure 1.2. Vertical cross-section (a), plane at isolators'level (b) of the new monitoring system

The accelerations are recorded along two horizontal directions (radial and tangential) at 25 points properly distributed among the Crypt plane (in correspondence of the altar and, for the only radial direction, of the columns ④, ⑫ and ⑲ of the Upper Temple), at the top of the same 3 columns and at the intrados of the base ring above, at the level of an intermediate annular beam (elevation +16.40 m) in correspondence of the same columns, and at the top of the structure. The accelerations along the vertical direction are acquired at 5 points located at the altar of the Crypt, at the top of column ⑫ and at the intrados of the base ring, at elevation +16.40 m by column ⑫, and at the top of the structure.

Figure 1.3. Acquisition/processing/storage system and sensors for the monitoring of the Sanctuary

The new continuous monitoring system of the Sanctuary is designed to be connected to the central system of the OSS located in Rome. The digital dynamic acquisition system (Fig. 1.3) with 64 channels consists of two acquisition boards (DAQ), each one with 32 channels, which can be operated in different way in terms of sampling frequency and acquisition strategy. DAQ #1 is connected to the 30 accelerometers and is devoted to a threshold acquisition strategy, which is activated when a seismic event occurs that exceeds a fixed threshold value. DAQ #2 is connected to the 8 displacement transducers, the 5 thermo-hygrometers, the barometer and the tachy-gonio-anemometer, and is devoted mainly to compute and store the mean value recorded by the above sensors using a periodical acquisition strategy, which is going to be activated every 6 hours. Furthermore, using a continuous time acquisition strategy the mean and standard deviation, as well as minimum and maximum values of wind velocity and direction, over a 15 minutes period, is also recorded and stored. Besides, when a seismic event activates a threshold acquisition, the 8 displacement transducers are also acquired at the same sampling frequency of the accelerometers, so as to record dynamically also the relative displacements of the isolators. All the parameters of the three acquisition strategies can be modified by a remote access via ADSL. The updated monitoring system allows the automatic transfer of the data and the transmission of alarms via e-mail and, in case, by SMS to pre-determined addresses, besides having the possibility to be questioned, in case of need, by a remote access via ADSL, upon password

authentication.
The seismic input is considered to be satisfactorily represented by the acceleration records along both x and y directions, at Crypt level (Fig. 1.4(a)) in correspondence of the altar (in the following they are referred to as ′base accelerations′). The structural response (Fig. 1.4(b)) is given by the acceleration transducers located at different points distributed along the height of the Sanctuary: at the top of columns and at the intrados of the base ring immediately above, at the level of an intermediate annular beam at elevation +16.40 m, and at the top of the covering. Fig. 1.4(b) shows the radial and tangential accelerations acquired along the height of the structure; it is worth to note that radial and tangential directions of accelerations at the top of the dome coincide in the radial and tangential directions recorded at column ⑫.

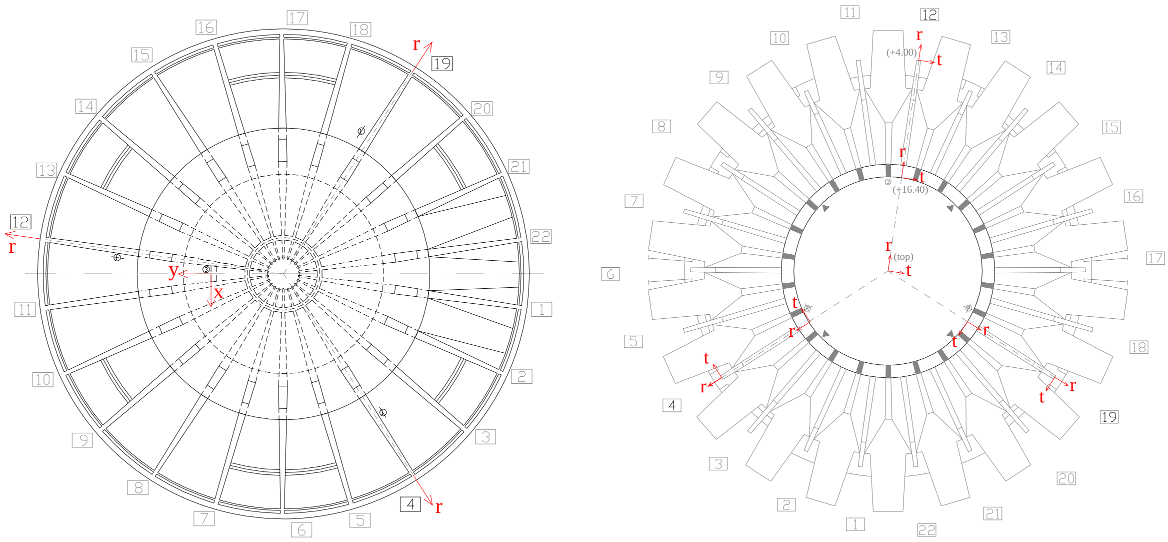

Figure 1.4. Plane view of acceleration directions at Crypt plane (a), along the height (b)

1.2. Numerical model of the structure

A Finite Element Structural Analysis Program (SAP 2000, 2009) has been used to develop both a simplified and a complete numerical model of the structure (Losanno, 2009), based on a different assumption of the dome’s structural behaviour. The simplified model (Fig. 1.5(a)) is obtained by modelling the dome as a rigid body supported on 22 r.c. piers uniformly spaced along the circular perimeter of the Upper Temple’s plan: the columns are defined through 44 nodes and 22 beam elements with variable cross-section and fixed at the base; a body constraint is introduced to connect the 22 nodes placed at the points where the upper plates of the antiseismic bearings are installed on the prestressed concrete base ring; a master node is located at the elevation of the dome’s centroid (positioned 19,20 m above the Upper Temple floor) and is characterized by a translational mass along the three global directions equal to the whole mass of the dome (corresponding to the total raising force F_r = 22.780 t exerted by the hydraulic jacks during the seismic isolation of the dome). The complete model (Fig. 1.5(b)) is able to simulate the effective geometrical and structural complexity of the truncated-conical dome: it has been carried out by using 63 coordinate systems, and consists of 2750 nodes, 2109 beam elements, 814 shell elements, 581 constraint and 22 non-linear elements able to simulate the experimental behaviour of the new seismic isolators.
In both cases the dome is connected to the beam elements representing the columns through 22 non-linear elements simulating the isolation bearings. They are characterized by the following link properties: (i) in the vertical direction, an elastic stiffness equal to the experimentally measured vertical stiffness of the bearings $k_{n,v}$ = 8829 kN·m^{-1}; (ii) in the radial direction, a friction link defined through a friction coefficient of 1% equal to the experimental value determined for the sliding of a steel surface on a lubricated teflon surface; (iii) in the tangential direction, an elasto-plastic Wen-type

law, whose parameters have been deduced by experimental tests (first yielding force F_p = 640 kN, initial elastic stiffness k_e = 69600 kN·m^{-1} and post-yielding stiffness k_{pe} = 1778 kN·m^{-1}, the first yielding displacement thus being 9,2 mm. The modelling of the Sanctuary before the seismic isolation intervention has been simply derived by locking in tangential direction the 22 elements representing the bearings. Tables 1.1 and 1.2 show the most significant modes of the simplified and complete model, respectively, characterized in terms of period, frequency, participating mass ratio and corresponding eigenform.

<u>Italic character has been used to put in evidence just those modes we could find trough experimental methods due to the distribution of accelerometers within the structure. So, there is no possibility to find out local modes regarding the chapels neither displacements along z, not having taken into account vertical accelerations.</u>

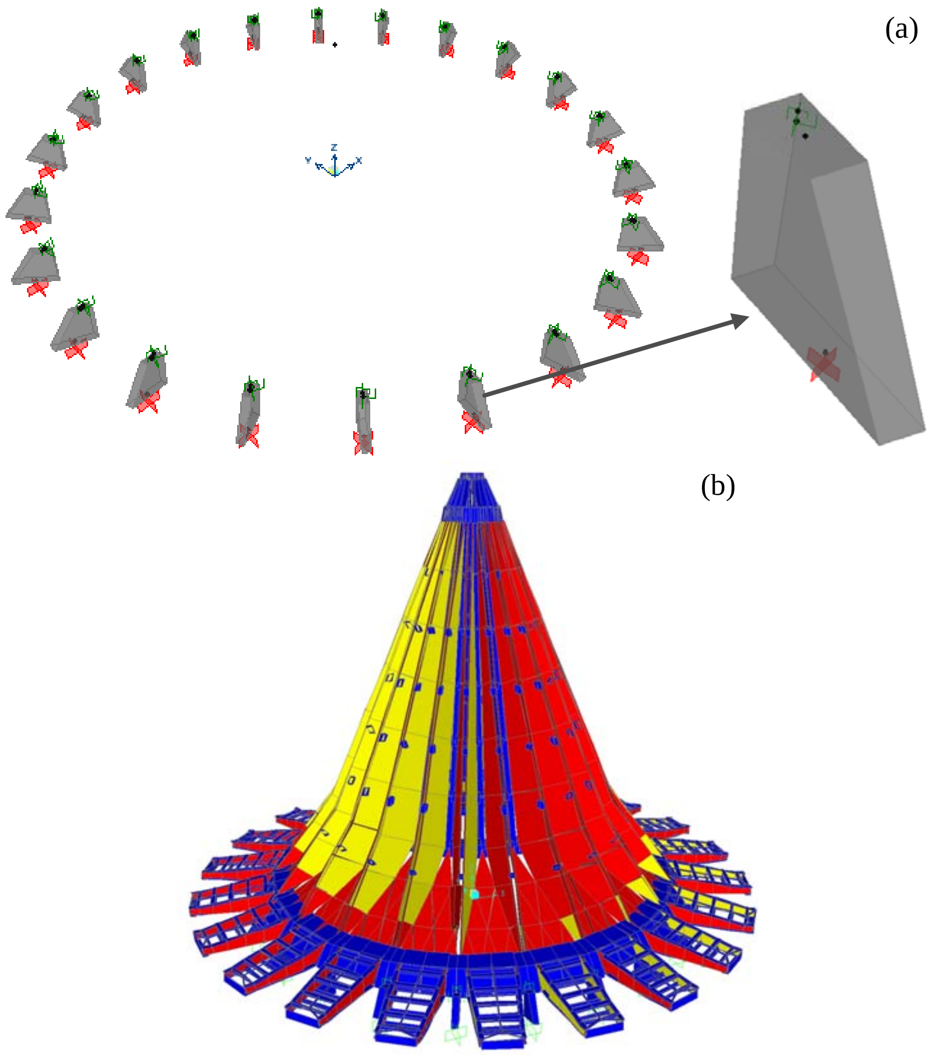

Figure 1.5. Simplified numerical model (a), complete numerical model (b)

Table 1.1. Modal properties of the simplified model

Mode	T	ω	UX	UY	UZ	RX	RY	RZ	Type of mode
[-]	[s]	[Hz]	[%]	[%]	[%]	[%]	[%]	[%]	[-]
1	*0.40*	*2.49*	*0.00*	*0.99*	*0.00*	*0.95*	*0.00*	*0.00*	*Translational along y (global)*
2	*0.40*	*2.49*	*0.99*	*0.00*	*0.00*	*0.00*	*0.95*	*0.00*	*Translational along x (global)*
3	*0.35*	*2.84*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.99*	*Torsional of the dome*
20	0.09	11.40	0.00	0.00	0.99	0.00	0.00	0.00	Translational along z (dome and chapels)

Table 1.2. Modal properties of the complete model

Mode	T	w	UX	UY	UZ	RX	RY	RZ	Type of mode
[-]	[s]	[Hz]	[%]	[%]	[%]	[%]	[%]	[%]	[-]
1	*0.71*	*1.41*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.7*	*Torsional of the dome*
2	0.66	1.51	0.1	0.4	0.0	0.1	0.0	0.0	Translational of the chapels in horizontal plane
3	0.65	1.54	0.2	0.0	0.0	0.0	0.0	0.0	Translational of the chapels in horizontal plane
20	*0.50*	*1.99*	*0.1*	*0.4*	*0.0*	*0.4*	*0.1*	*0.0*	*Translational along y (global)*
21	*0.49*	*2.05*	*0.5*	*0.0*	*0.0*	*0.0*	*0.4*	*0.0*	*Translational along x (global)*
134	0.19	5.31	0.0	0.0	0.3	0.0	0.0	0.0	Translational along z (dome and chapels)

2. DYNAMIC IDENTIFICATION TROUGH MODAL TESTING TECHNIQUES

In the proposed work, two *experimental modal analyses* (EMA) techniques have been applied in order to derive the system's modal properties (Losanno, 2011). They operate in the frequency domain through the use of the Frequency Response Functions (*FRF*s), i.e. the ratio of the response's Fourier Transform to the input's Fourier Transform, where the input is represented by the ′base accelerations′. The "peak-picking method" and "circle-fit method" (Ewins, 2000) are SDOF methods, because they are able to deduce the properties of just one mode at a time: this concept does not imply that the structural system is reduced to a single degree of freedom model, but it means only that just one resonance is considered at a time. Close to resonance, the dynamic behaviour of a system is dominated by one predominant mode: from an algebraic point of view, this means that the magnitude of the *FRF* is determined by one term in the Fourier series, related to the mode shape whose resonance is being observed. The generic term of the *FRF* matrix in case of hysteretic damping (first expression of Eqn. 2.1) can be written as the second expression of Eqn. 1, where the second term is approximately independent of frequency.

$$\alpha_{jk}(\omega)=\sum_{s=1}^{N}\frac{{}_{s}A_{jk}}{\omega^{2}{}_{s}-\omega^{2}+i\eta_{s}\omega^{2}{}_{s}}, \qquad \alpha_{jk}(\omega)_{\omega\cong\omega_{r}}=\frac{{}_{r}A_{jk}}{\omega^{2}{}_{r}-\omega^{2}+i\eta_{r}\omega^{2}{}_{r}}+{}_{r}B_{jk} \qquad (2.1)$$

Different SDOF methods are based on different assumptions about the influence of the residual term ${}_{r}B_{jk}$. The "peak-picking method" or "peak-amplitude method" is the simplest SDOF approach: it assumes that the global response can be attributed to the local mode, while any effect due to all other modes can be ignored. This method can be considered reliable when *FRF*s exhibit well separated modes, but, anyhow, it is always adequate for an initial estimation of the dynamic parameters. The "circle-fit method" is based on the observation that frequency response functions (*FRF*s) of a MDOF system produce Nyquist plots, which include sections of near-circular arcs corresponding to the regions near the natural frequencies.

In May 9 of 2010, a low magnitude earthquake was registered in Syracuse, that exceeded the fixed threshold value of the monitoring system. The recorded accelerations have been properly manipulated trough MATLAB® software (2006), in order to apply the above described experimental modal analyses techniques. In what follows, the generic *FRF* is named as function of the corresponding monitored column (④, ⑫ and ⑲), of the quote of measured response (it is used the term *LOW* at elevation of the top of columns, the term *UP* in correspondence of the intrados of the prestressed base ring, the term *IR* at elevation +16.40 m, and the term *TOP* at the top the dome), and as a function of the direction of the ′base accelerations′ (*x* or *y*) and the output accelerations (*r* for radial and *t* for tangential). Being the structure quite symmetrical with respect to its vertical axis, we expect approximately the same response along *r* and *t* directions.

Fig. 2.1 and Fig. 2.2 show the plots of absolute *FRF*s computed by one of the three columns (column ⑫) with increasing elevation, respectively respect to input along y and x. The maximum considered frequency is 8 Hz, because *FRF*s don't show any relevant information over that frequency.

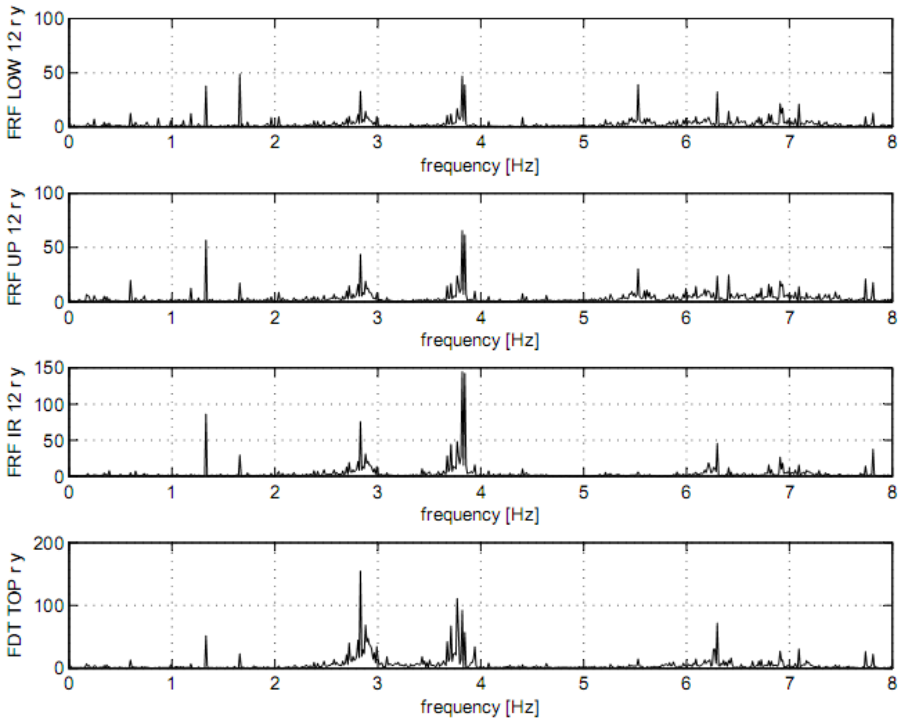

Figure 2.1. FRFs computed at column ⑫ respect to input along y

The more evident resonances have been singled out in the ranges of frequencies 2,8÷3,1 Hz and 3,7÷3,9 Hz, along both tangential and radial directions. Really, more peaks are evident in the spectrum below but these have been considered as related to measurements problems and not to real resonance peaks.

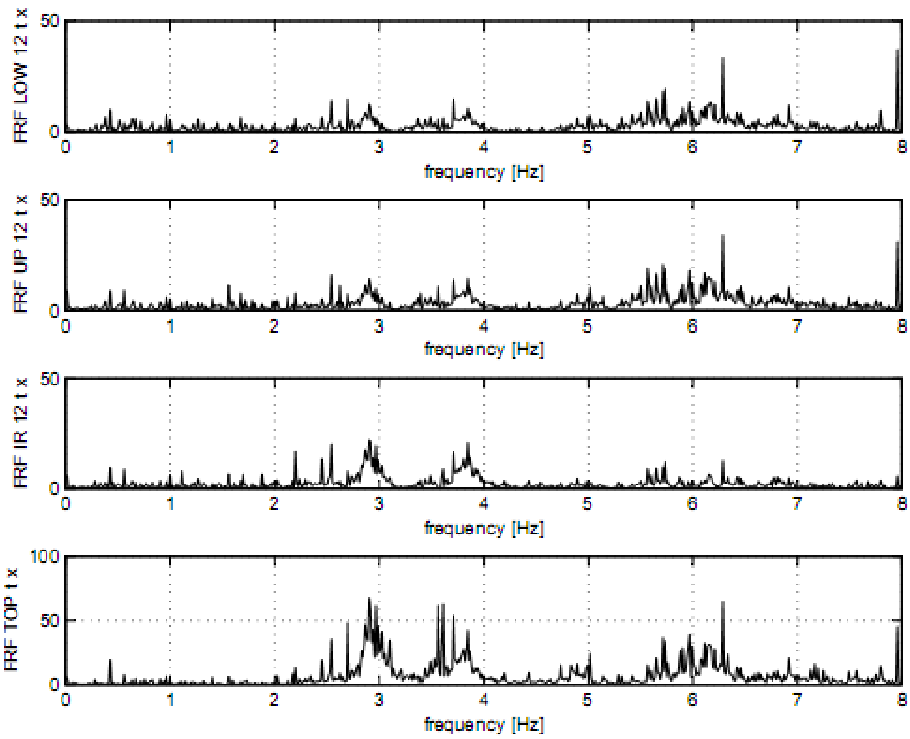

Figure 2.2. FRFs computed at column ⑫ respect to input along x

The first resonance region (2,8÷3,1 Hz), differently from the second one, is more evident in *FRF*s computed with respect to input along x. the radial components of the structural response along the height are always in phase and increasing with the quote, while the tangential components (representing the clockwise or counterclockwise rotation) are characterized by a change of sign between the prestressed base ring (*UP*) and the ring at elevation 16,40 m (*IR* - see Table 2.1): Fig. 2.3 shows the resulting mode shape on a vertical section by column ⑫ and on a plane view.

Table 2.1. FRFs results at 2.8÷3.1 Hz with respect to input along x direction

FRF	w_r	*FRF LOW*		*FRF UP*		*FRF IR*		*FRF UP*	
[-]	[Hz]	absolute	Sign (Im)	absolute	Sign (Im)	absolute	Sign (Im)	absolute	Sign (Im)
04 r x	2.92÷2.98	6	-	8	-	15	-		
04 t x	2.92÷2.98	25	+	30	+	40	-		
12 r x	2.88÷2.92	12	-	18	-	28	-	65	-
12 t x	2.88÷2.92	10	-	13	-	21	+	60	+
19 r x	2.88÷2.92	15	+	20	+	40	+		
19 t x	2.88÷2.92	\	+	12	+	18	-		

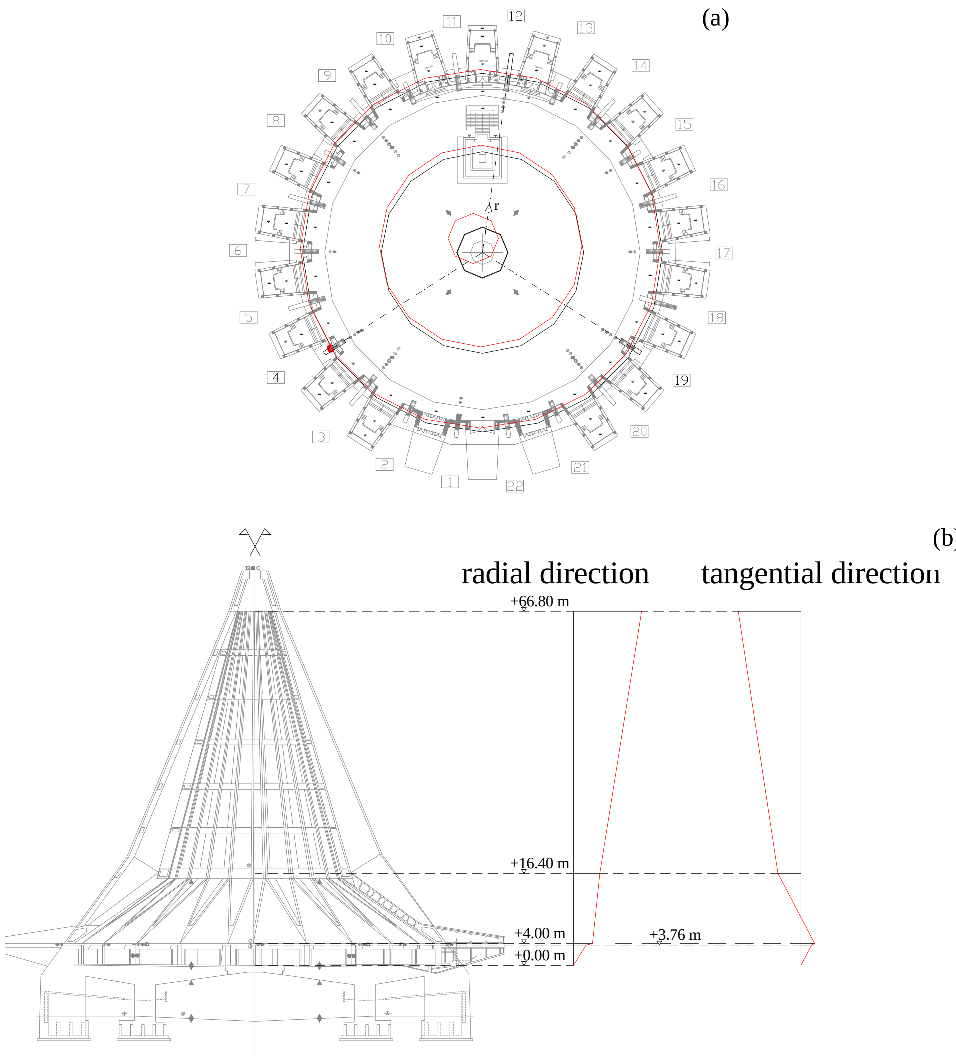

Figure 2.3. Mode shape at 2.88÷2.98 Hz: plane view (a), vertical section by column ⑫ (b)

As regard the range 3,7÷3,9 Hz (see Table 2.2), radial components of the structural response along the height are always in phase but now are not increasing until the top but reduce from elevation +16,40 m to +66,80 m. Tangential components are instead characterized by a double change of sign, the first between the prestressed base ring (*UP*) and the ring at elevation 16,40 m (*IR* - see Table 2.2), and the second between +16,40 m and + 66,80 m. Fig. 2.4 shows the resulting mode shape on a vertical section by column ⑫ and on a plane view.

Table 2.2. FRFs results at 3,7÷3,9 Hz with respect to input along y direction

FRF	w_r	*FRF LOW*		*FRF UP*		*FRF IR*		*FRF UP*	
[-]	[Hz]	absolute	Sign (Im)	absolute	Sign (Im)	absolute	Sign (Im)	absolute	Sign (Im)
04 r y	3.78÷3.83	20	+	30	+	70	+		
04 t y	3.82÷3.85	30	+	35	+	50	-		
12 r y	3.82÷3.85	30	+	40	+	90	+	50	+
12 t y	3.78÷3.85	40	+	50	-	70	+	180	-
19 r y	3.78÷3.85	20	-	25	-	60	-		
19 t y	3.77÷3.82	\	+	20	+	40	-		

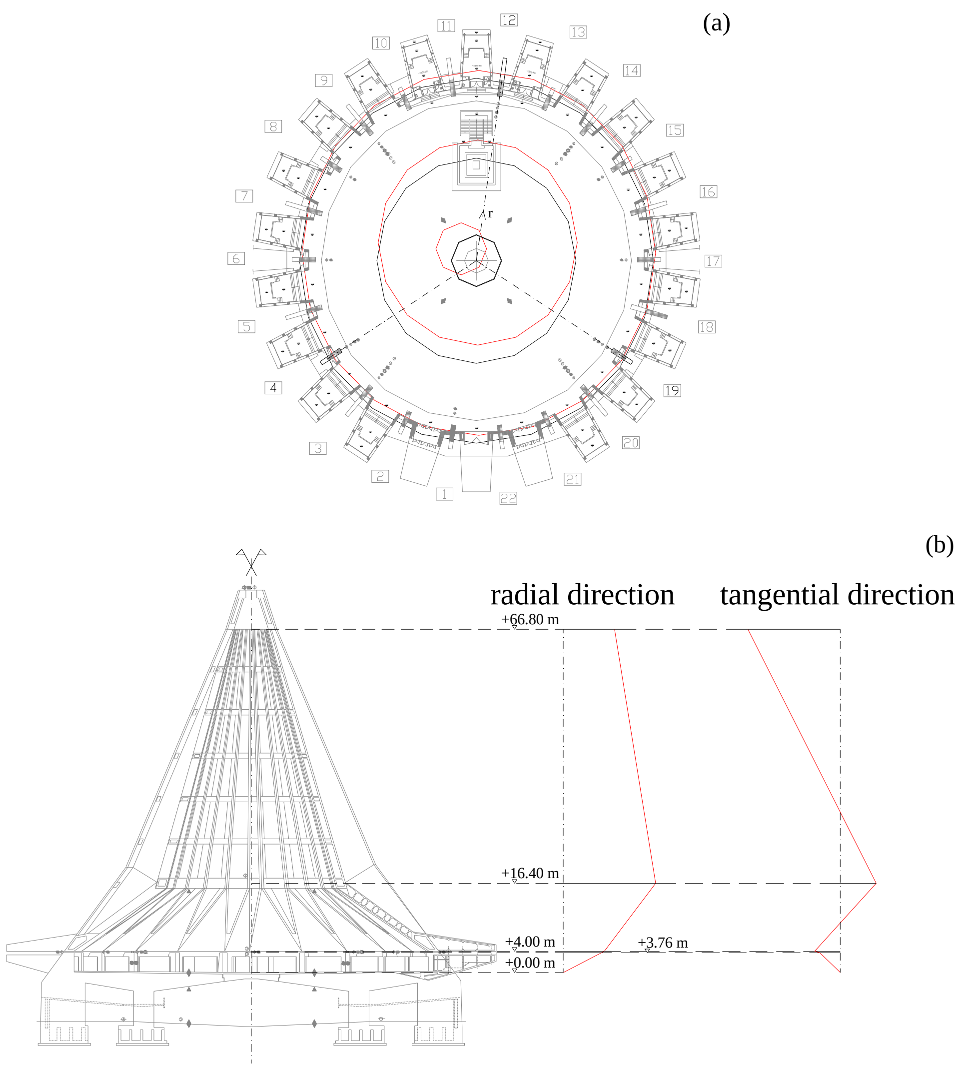

Figure 2.4. Mode shape at 3.78÷3.85 Hz: plane view (a), vertical section by column ⑫ (b)

3. CONCLUSIONS

The two experimental modes investigated above are higher than those global found by FEM analysis, for one or more of the following reasons:

(1) The circular rings and the ribs probably make the dome stiffer than the numerical model, so that the simplified model of the Sanctuary results more reliable to simulate the global behaviour of the structure.

(2) The Young modulus of the concrete is higher than the design value (E_c = 30000 MPa) assumed for the FEM model (the compressive tests performed on concrete specimens during the construction provided a mean value of the concrete compressive strength R_{ck} = 60 MPa much higher than the design value R_{ck} = 35 MPa, with maximum values of approximately 90 MPa).

(3) The stiffness contribution due to non-structural elements is not negligible, as the presence of frames supporting the windows of the dome.

The modal shapes obtained from experimental modal analysis are characterized by the simultaneous presence of translational and torsional components, probably because the structural behaviour is influenced by a stiffness and/or mass distribution less regular with respect to the one assumed in the complete FEM model. For example, the foundation system, that could contribute to this feature is not taken into account in the model.

Therefore, experimental results are of fundamental importance to calibrate and validate the FEM model of the structure. It is also worth to point out that the noise component in the signals produced by the above low intensity earthquake was relevant; for this reason it should be very important to analyze more data acquired by the monitoring system.

ACKNOWLEDGEMENT

The authors would also thank Boviar s.r.l., in particular its Technical Director Dr. Giuseppe Bovio, as well as INDAPRO s.r.l., in particular its General Director Dr. Paolo Pezzoli, which are the companies in charge of the upgrading and reactivation of the monitoring system of the "Our Lady of Tears Shrine" and of providing the new acquisition system and software, respectively. The final management and maintenance of the new continuous monitoring system of the Sanctuary will be performed by the National Seismic Service of the Italian Department of Civil Protection within the network "Seismic Observatory of Structures", directed by the Eng. Mario Nicoletti, which is also gratefully acknowledged.

REFERENCES

Ewins, D.J. (2000). Modal Testing: Theory, Practice and Application (2nd edn). Research Studies Press LTD. Baldock, Hertfordshire (England).

Losanno, D. (2009). Isolamento Sismico, Modellazione e Monitoraggio del "Santuario della Madonna delle Lacrime. Thesis in Civil Engineering, University of Naples Federico II.

Losanno, D. (2011). Modal Testing Techniques: Theory, Measurements, Analysis and Applications. Thesis in Structural and Geotechnical Engineering, University of Naples Federico II.

MATLAB, version 7.3. (2006). The MathWorks Inc.: Natick, MA (USA).

SAP 2000 - Static and Dynamic Finite Element Analysis of Structures, version 11.0.8. (2009). Computers and Structures Inc.: Berkeley, California (USA).

Serino, G., Spizzuoco, M. and Marsico, M.R. (2009). The "Our Lady of Tears Shrine" in Siracusa as recent application of structural isolation and health monitoring. *Structure and Infrastructure Engineering*, ISSN: 1744-8980. **6:5**, 593-610.

Technical Economical Italian Association of Cement (Associazione Italiana Tecnico Economica del Cemento, in Italian). (2001). The "Santuario della Madonna delle Lacrime" in Siracusa. *L'Industria Italiana del Cemento*, Year LXXI. **5** (May 2001), 394-415.