Innovative techniques for structural assessment: The case of the Holy Shroud Chapel in Turin

A. De Stefano, D. Enrione & G. Ruocci
Politecnico di Torino, Turin, Italy

ABSTRACT: Environmental degradation, inevitable aging, negligence and extreme events are some of the most frequent factors that can threaten the structural integrity of historical constructions. Hence, architectural heritage owners and administrators urgently require cheap and effective tools for structural health assessment. Restoration works on the Holy Shroud Chapel in Turin, Guarino Guarini’ s masterpiece which was extensively damaged by a fire in 1997, offered the authors the opportunity to test some innovative techniques that are able to provide an exhaustive picture of the Chapel’s structural health. Dynamic tests were carried out by applying several exciting actions and the signals were acquired to perform a modal identification of the dome in the time-frequency domain. A stochastic multiple model approach, used to update a FE model of the Chapel, is also presented. The PGSL algorithm, implemented in the model updating procedure, is able to define different groups of models, each one referring to a particular damage scenario that the building is probably undergoing. The improved knowledge about the structure is the starting point for the development of symptom-based structural health assessments.

1 INTRODUCTION

Italy, like many other countries throughout the world, has inherited an extraordinary historical treasure from the past. This architectural heritage represents a fundamental resource and a sign of the national cultural background, but the high costs for its maintenance and repairs cause concern. In the last few years, the demand for cheap and effective tools designed for these purposes has increased.

Researchers soon became aware of the need to introduce the concept of “structural health” and to identify some instruments and techniques to assess it in a reliable way. This growing interest is demonstrated by the huge number of publications and conferences expressly devoted to these topics.

The term “structural health” stands for the condition in which the structure assures a suitable level of safety. The definition of this safety level in turn implies the knowledge of a set of all those parameters which could affect it. Hence, the necessity of identifying sensitive elements arises and, more in general, it is important to acquire as much information as possible about the construction conditions. Monitoring systems become in this sense essential elements in strategic and monumental structures.

The structural health assessment problem can be seen under a different light. The structure to be monitored can be considered as a “patient” whose diseases have to be diagnosed through a meticulous analysis of the surveyed symptoms. This symptom-based approach has been extensively adopted and improved in the mechanical and aerospace fields. Ancient buildings have to bear damage that arise during their life-cycle from different concurring causes, such as material quality degradation, environmental injuries, inaccurate human interventions and modifications of the structural body. All these situations represent examples of so-called “damage scenarios”, i.e., the provoking causes which lead to damage symptoms on the construction.

Identifying damage scenarios and their probability of occurrence requires that the existing knowledge bases, whenever available, should be explored and realistic simulations, capable of relating each possible scenario to the severity of its consequences and the meaningfulness of its symptoms should be conducted. Dynamical tests and modal identification are powerful tools that can provide this required knowledge. In addition, simulations performed with stochastically updated models supply reliable estimations of the residual performance a building is still able to provide after structural changes inferred by each particular damage scenario. This kind of information allows the health condition of the construction to be predicted for each damage hypothesis.

In the following chapters, a more detailed discussion is given with some innovative techniques which
have been applied as the starting point for the development of symptom-based structural health assessments: the Holy Shroud Chapel is presented as an example.

2 STRUCTURAL HEALTH ASSESSMENT TECHNIQUES

The monitoring of common structures represents a well established and widespread practice, whereas the situation of monumental buildings is rather different. Only a few cases can be found referring to research due to the strict constrains necessary to preserve the cultural and artistic value of the buildings. Tools which combine a suitable level of reliability with less invasive interventions are preferred. Dynamic system identification in this sense constitutes an optimal compromise which is finding widespread approval among experts. Dynamic tests are very powerful identification techniques which are able to reveal global quantities such as natural frequencies, modal shapes and damping features of the structure under examination. These parameters are closely related to the variations in stiffness of the system and are therefore extremely sensitive to damage and deterioration phenomena. Many modal identification techniques are now available but the complexity and uncertainty that affect ancient masonry constructions drastically reduce their applicability possibilities. Time-frequency domain methods have proved to be accurate in treating non-stationary signals and they are robust against noise. Furthermore, some instantaneous estimators, obtained as auto and cross-correlation of bi-linear time-frequency signal transforms, allow the modal features of systems to be reliably detected.

In the structural health assessment field FE modelling also plays a very important role, even thought in many cases the lack of numerical modelling accuracy and a deficient correspondence to reality represent decisive limitations. There is the risk of choosing model parameters which do not fit real structure properties well. Model Updating (MU) provides a valuable solution to the problem. It can be considered as the missing link between structural identification and FE modelling since it gives a model calibration criterion on the basis of the experimental results. Model updating techniques have undergone an exponential growth during the last few years due to their latent potentialities. Recently, stochastic approaches have become more and more popular and can be distinguished from traditional deterministic methods due to their capacity to deal with behaviour uncertainties and problem complexity in a robust way. Deterministic methods, whether direct or parametric, focus on model calibration through the minimization of a target function obtained as the difference between experimental results and analytical data. Since Model Updating represents an inverse problem, the solution that is obtained cannot be considered as the only possible one. Furthermore, there are many error and uncertainty sources that condition the final result. These should be considered in order to obtain a consistent estimation of the model parameters and consequently a reliable structural health assessment.

On the basis of the remarks made so far, the authors focused attention on the development of a model updating method which could meet monumental building requirements:

- the treatment of errors obtained from the acquisition of experimental measures;
- the treatment of uncertainties due to construction complexity (mechanical properties, constructive methodologies, unknown design details, etc.);
- the management of information redundancy obtained from many distributed sensors;
- extrapolation ability in the definition of numerical models.

Solution accuracy is the main problem which the authors tried to solve in a convincing way. As a unique optimal solution for this problem cannot be found, the authors concentrated on the possibility of generating a set of different but sufficiently reliable models. The adopted approach is generally referred to as the “multiple-model” due to the fact that it generates a huge number of models to solve the problem of the solution uniqueness. Application of the adopted method to the case study has allowed some models to be defined and has made them able to accurately predict its structural behaviour. An interesting development the authors intend putting into practice regards the identification of possible damage scenarios for each model obtained using the updating procedure. The natural consequence is the estimation of the residual performance a building is still able to supply, i.e., its structural health.

The case of the Holy Shroud Chapel in Turin is presented in order to clarify the concepts introduced so far.

3 CASE STUDY: THE HOLY SHROUD CHAPEL IN TURIN

3.1 The experimental campaign

The Holy Shroud Chapel in Turin (Fig. 1) is universally recognized as a outstanding example of Italian Baroque architecture. Emanuele Filiberto di Savoia entrusted its design to the famous Italian architect Guarino Guarini, who built the Chapel from 1667 to 1694. Since the very beginning, the monarch’s intent was that of housing the precious relic of Christianity in a more prestigious seat. The architectural results obtained by Guarini are extraordinary. The whole building conveys the Guarini’s obsession for architec-tonic originality and a sense of mystery which are well
expressed by the structural complexity and the richness of perfect shapes and theological, astronomic and mathematical symbols. The chapel is composed of a tambour bored by six large windows and surmounted by three big arches which sustain the dome. On the inside, a series of small arches overlapped and disposed on six levels, creates an hexagonal geometry which diminishes towards the top where it becomes the circular base of a lantern. On the outside, another series of small arches creates a complex plaiting effect and the alternation of black marble and grey stone grants a particular sense of dynamicity.

The recent history of the Holy Shroud Chapel has been marked by a tragic event. A fire broke out in 1997 during some restoration works and it seriously damaged the structure, producing incalculable economic and artistic loss.

In the following months, the Sovraintendenza dei Beni Architettonici envisaged the Politecnico di Torino with the project to carry out a general experimental campaign on the materials and structure (Prof. P. Napoli) and a dynamic test program (Prof. A. De Stefano).

Mainly in situ investigations were performed in order to obtain detailed knowledge of the structural morphology in terms of geometry, marble and masonry organization, position of metal ties, etc. The investigations, conducted through topographic and camera surveys and deep extraction of samples, allowed the experts to detect some structural elements that had previously been covered over. As a result of these investigations, a 3D computer geometrical model of the entire building was set up and more detailed knowledge in the structural morphology was acquired.

The mechanical properties of the materials were measured both in laboratory and in situ tests, in the latter case using cross-hole ultrasonic measurements. The tests revealed the chemical degradation induced by the heat on the surface of the elements and a reduction in the material load carrying capacity in the zones affected by stresses caused by the effect of constrained thermal deformations.

Local inspections provided useful information concerning the mechanical properties of the materials and structural configuration and allowed a first preliminary estimation of extent of the damage to be obtained. However, due to their spatial limitation, these tests were not able to completely identify the global behaviour of the construction. They therefore had to be integrated with other techniques that were capable of predicting the residual structural capacity of the building considered as a whole.

In order to achieve a complete overall image of the Chapel’s structural health, the Research Unit to which the authors belong, in association with the University of Kassel (Prof. M. Link), designed a dynamic testing programme, prepared a FE model and adjusted it according to the acquired experimental knowledge.

In order to perform the dynamic experiments, 25 accelerometers were positioned on six different levels to measure the response of the structure along three different orthogonal directions: radial, vertical and horizontal normal to the radius. The dynamic tests were realized adopting four different exciting actions:

- environmental excitation (traffic, wind, microquakes);
- impulsive excitation produced by hammering;
- impulsive excitation caused by a sphere dropped to the ground near the foot of the building;
- wind turbulence produced by a Fire-Brigade helicopter flying around the top of the dome.

The obtained signals were used to identify the structure of the dome using the TFIE (Time Frequency Instantaneous Estimators) method.

3.2 Modal identification

The results obtained from the dynamic tests performed on the chapel provided the starting point for the subsequent structural identification phase. A well-designed structural health monitoring programme cannot disregard this fundamental step which supplies information concerning the overall behaviour of the system and it is the basis for the FE model calibration.

Many effective techniques are now available for structural identification, but in the case of complex
monumental buildings not all are suitable to robustly face the several uncertainties that can affect this kind of structure. Generally, output-only methods are preferred to input-output ones since they are less invasive. Identification techniques can also be distinguished on the basis of the parameters that need to be identified. It is therefore possible to choose between direct methods, which try to determine the \([M], [C] \) and \([K]\) matrices of motion equation (1):

\[
[M][\ddot{x}] + [C][\dot{x}] + [K][x] = [f]
\]

and indirect methods working on modal parameters such as the frequencies, damping and modal shapes. Another classification criterion concerns the domain in which the data are numerically treated and thus provides three possibilities:

– frequency domain;
– time domain;
– time-frequency domain.

Frequency domain methods (for example FDD, PSD, etc.) have gradually been replaced by time domain ones (for example ARMAV, ERA, Random Decrement, etc.) in order to solve problems concerning frequency resolution and modal density. Methods developed in time-frequency domain offer several advantages which are here summarized:

– precise accuracy in parameter estimation;
– the possibility of effectively managing non-stationary signals;
– the ability to handle moderate non-linearities;
– high robustness against noise.

The main drawback that affects both time-domain and frequency-domain methods concerns the assumption that the modal parameters do not evolve versus time and vibration amplitude and that the input is at least weakly stationary. Since in the civil engineering area the excitation is generally non stationary and the presence of noise during the data acquisition phase is unavoidable, the structural response cannot be regarded as an unvarying-versus-time signal. These considerations forced the authors to adopt an adaptive and robust identification technique, that is able to handle these types of non-stationary excitations. The implemented method is based on special amplitude and phase estimators defined in the time-frequency domain known in literature as Time-Frequency Instantaneous Estimators (TFIE).

The Amplitude Ratio and PHase difference estimators are expressed by equations (2) and (3), respectively:

\[
AR(t,f) = \frac{D_{s_1}(t,f)}{\sqrt{D_{s_2}(t,f)}}
\]

\[
PH(t,f) = \text{phase}\left[D_{s_1,s_2}(t,f)\right] = \arctg\left(\frac{\text{Im}[D_{s_1,s_2}(t,f)]}{\text{Re}[D_{s_1,s_2}(t,f)]}\right)
\]

where \(D_{s_1}(t,f)\) and \(D_{s_2}(t,f)\) are the auto and cross bi-linear time – frequency transforms of two components of the same vibration mode belonging to signals acquired in two different nodes of the structure. The thus defined estimators maintain time dependency and, in this way, they make it possible to ascertain whether a certain frequency could be a possible vibration mode. At the modal frequency the phase difference in (3) becomes almost constant in time and its standard deviation along the time axis approaches 0, if the noise level is low (Fig. 2). However a downward peak in the standard deviation of the phase difference process, plotted versus frequency, marks an expected modal frequency. If this occurs, the AR in equation (2) computed at that frequency also remains almost constant versus time and marks the amplitude ratio of a modal shape.

The TFIE method has been applied to several sets of signals, generated by the different types of excitation adopted in the dynamic tests performed on the Holy Shroud Chapel. Modal frequencies were identified using all the consistent signal pairs in all the combinations of the following sampling parameters:

– sampling frequency: 25 or 50 pts/s
– signal length: 256, 512 and 1024 pts.

The TFIE diagrams computed from signals with identical sampling frequencies and lengths were averaged in order to make the downward peaks that mark the modal frequencies clearly visible. The records obtained from the excitation of the dropped sphere, with a sampling rate of 25 pts/s and length of 1024 pts,
Table 1. Subdivision of the elements in the FE model.

<table>
<thead>
<tr>
<th>Type of element</th>
<th>Total number of elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shell with 3 or 4 nodes</td>
<td>11871</td>
</tr>
<tr>
<td>Beam 3D</td>
<td>1646</td>
</tr>
<tr>
<td>Truss</td>
<td>48</td>
</tr>
<tr>
<td>3D solid</td>
<td>28177</td>
</tr>
<tr>
<td>Spring</td>
<td>277</td>
</tr>
</tbody>
</table>

provided the best results. The TFIE potential is evident as it is able to detect the two first flexional modes of the chapel, whose modal frequencies are very close to each other ($f_1 = 2.246$ Hz and $f_2 = 2.344$ Hz).

The modal shapes were identified using the same data pairs and sampling conditions which allowed the best results in the frequency search. The first flexional shape is oriented in the NE-SW direction, the second in the NW-SE direction. In general, it is convenient to use signals in cylindrical coordinates to identify modes where torsion prevails whilst Cartesian coordinates work better to extract modal shapes with prevailing translation.

3.3 The finite element model

A FE model of the Chapel was prepared adopting geometrical data of the model created using the Rhinoceros3D programme by Arch. Abrardi and Arch. Gallo (May 2001). Their very accurate geometrical model, reproduced for the Soprintendenza dei Beni Architettonici, was simplified to build a numerical model with ADINA.

The bottom part of the model has a lower degree of detail than the upper one. The base of the Chapel was modelled to have a simplified distribution of the mass and stiffness necessary to reproduce the iteration between the upper and the lower parts. The internal provisional steel structure has not been modelled for the sake of simplicity. The model is constituted of 17334 nodes and 42019 elements, divided as reported in Table 1.

The model was divided into 28 sub-structures. The assonometric projection of the model and its subdivision in sub-structures are shown in Fig. 3.

The modal frequencies and mode shapes depend on various factors:

- the geometry and typology of the model;
- the finite element mesh;
- the mass and stiffness distribution.

The calibration of a numerical model cannot be conducted adopting an arbitrary number of variables. The number of parameters is influenced by the amount of experimental information. Choosing a larger number of parameters than the identified frequencies and mode shapes leads to an ill-conditioned problem with resulting unreliable solutions.

For this reason, a preliminary sensitivity analysis was performed to reduce the number of parameters. The elimination of some insensitive parameters also permits, on the one hand, to reduce the computational weight and, on the other, to reduce the noise level.

The sensitivity analysis was performed modifying the parameters one by one, in a uniform way over a defined range and the obtained values were recorded. The results are reported in Figure 4; the shown quantities are calculated as the mean of the ratio between the variation of the modal properties (the first 5 frequencies) with respect to that of the parameters. The most sensitive parameters are the numbers 19 (3DLivello02-2), 11 (Tamburo Esterno), 6 (Timpani) and, to less extent, 18 (3DLivello03) and 12 (Tamburo Interno).
All these parameters are found in the central and lower part of the structure. These parts in fact have a greater influence on the global behaviour of the structure, mainly for the first modal shapes.

All the selected parameters are the Young's Modula of different sub-structures into which the model was previously divided. Each substructure is an axial-symmetric structure; this fact influences the behaviour of the structure, making it more regular in every direction. To avoid this, a further subdivision of each sub-structure into four different ones was made. This subdivision leads to an increase in the number of selected parameters from 5 to 20 and is necessary because the data obtained in the identification stage highlight a non axial-symmetric behaviour of the structure.

3.4 The stochastic model updating

In order to solve the intrinsic problem of the solution uniqueness and to treat error and uncertainty sources a stochastic “multiple-model” approach has been adopted to update model parameters. This method can be divided into the three following phases:

1. generation of a huge number of models varied on the basis of some structural parameters through the minimization of objective functions that are able to explore a consistent part of the solutions space;
2. selection, among all the generated models, of those which best fit the system behaviour with a prescribed level of accuracy;
3. analysis of the detected model properties and their classification through clustering techniques.

The adopted method implements the PGSL algorithm introduced by Smith (1998) which creates the models and assigns them parameter values derived from probability distributions. The principal assumption is that better points are likely to be found in the neighbourhood of families of good points. Hence, the search is intensified in regions containing good solutions. The search space is sampled by means of a PDF defined over the entire search space. Each axis is divided into a fixed number of intervals and a uniform probability distribution is initially assumed. As the search progresses, the intervals and probabilities are dynamically updated so that sets of points are generated with a higher probability in regions containing good solutions. The search space is gradually narrowed down so that convergence is achieved.

The algorithm includes four nested cycles:

1. the Sampling Cycle, where a certain number of models is generated and analysed through the target function, using the actual probability distribution. The Best Sample is selected, memorized in the database and then used to recalculate the probability distribution;
2. the Probability Updating Cycle, in which all the probability distributions are updated as follows: the probability values of the sub-interval containing the Best Sample selected in the preceding cycle and its neighbours are increased, while, the probabilities in the other regions are decreased.
3. the Focusing Cycle, which modifies the structure of the variation interval of each parameter in order to focus the search near the actual best solution.
4. the SubDomain Cycle, which works on the solution space and increase the resolution in order to ease the confluence.

Each operation performed by the algorithm is managed by specific parameters which have to be chosen carefully because some of them present a high dependence on the considered problem.

In the case study, the Root Mean Square Error between the identified and calculated frequencies is utilized as the objective function which has to be minimized. At each step, a new parameter distribution is created by the algorithm and new model outputs are obtained. In order to match the numerical and experimental modal shapes, the MAC function, that gives a measure of similarity between two different modal shapes, is calculated.

The model generation procedure has been divided into two different phases, each one referred to a particular objective functions. Firstly, the PGSL algorithm generates a huge number of models through the minimization of a function set on the first modal frequency, which is the best-identified in the dynamic tests. The second objective function instead utilizes the first three model frequencies and mode shapes matched by means of the MAC function. This second step allows to select only some of all generated models, while models that have a higher value than a certain threshold are neglected.

All these selected models can be considered as reasonable candidates to represent the real building, but their large number makes necessary the application of some data mining techniques that can be applied to discover different types of patterns in the model data.

The PCA (Principal Component Analysis) is performed to generate a new set of variables called principal components that are linear combinations of the original ones. The goal of the PCA is to find a system of principal components that are sorted so that the first components can explain most of the data variance. In this way the number of dimensions can be reduced by choosing only the first two or three principal components. Thus the original data are represented by a linear combination of the original parameters in a new and lower dimensional space. The application of the PCA and the examination of the first three principal components supplied an important result. The first three principal components are not sufficient to explain most of the data variance. For this reason it
is not possible to represent all data in a 3D reference system.

Finally, some clustering techniques have been applied to identify and collect models into groups. The adoption of the k-means algorithm, which sub-divides the data into k subsets minimizing the distances within each group and maximizing the distances between the k different groups, allowed the definition of 9 models. These models are the centroids of the 9 groups identified by the k-means algorithm and can be considered as the best candidates to represent the real structure. The obtained results are reported in Figure 5, where the percentage of the selected models which belong to each group is shown.

4 CONCLUSIONS

Some innovative techniques, which are able to assess the structural health of monumental buildings, have been presented in this article. The application of these methods to the Holy Shroud Chapel in Turin was carried out in order to identify both their potentialities and limitations.

A brief description of the experimental campaign, carried out to acquired more detailed knowledge of the structural morphology, is first given. The dynamic test programme designed by the research group the authors belong to is also presented and the different exciting sources adopted are listed. The results obtained with the TFIE modal identification method are shown in the subsequent part of the paper. The powerfulness of this adaptive and robust tool is mainly demonstrated by its ability to handle the non-stationary acquired signals and to detect the first two flexional modes of the chapel, whose frequencies are very close to each other. The numerical model of the building, its subdivision into sub-structures and the sensitivity analysis, performed in order to reduce the number of the subsequently updated parameters, are also shown.

The last part of this study is focused on the development of a stochastic model updating technique. The adopted approach is known as “multiple-model” due to the fact that it generates a huge number of models to solve the problem of the impossibility to find an optimal unique solution and to treat error and uncertainty sources. The PGSL algorithm is implemented in order to create these models and to assign parameter values derived from their probability distributions, progressively recalculated around those values which minimize a target function. The application of this kind of model updating procedure raises the problem of information redundancy, which can be faced through the adoption of some data mining techniques such as the PCA and clustering. The final obtained results are some models that can be considered as reasonable candidates to represent the real structure.

The models obtained from the updating procedure can be considered as the starting point for the following phase of damage detection and structural health assessment. It is now important to underline that these results are obtained from a linear analysis while damage and degradation effects are strictly non-linear phenomena. Therefore, the subsequent numerical simulations, applied to identify symptoms which can reveal possible damage scenarios on the construction, cannot disregard these non-linear implications. The updated models supplied by the multi-model approach represent a useful resource in order to estimate the health condition of the building. Non-linear analyses performed on the obtained models can reveal the effective residual performance the construction is still able to provide for each damage scenario.

REFERENCES


