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HEALTH MONITORING OF HISTORICAL MONUMENTS USING EXPERIMENTALLY DETERMINED DYNAMIC PARAMETERS

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Abstract

The paper presents a method for health monitoring of buildings classified as historical monuments. These buildings are invaluable and maintaining their structural integrity is a constant task for humanity, for the benefit of future generations. An efficient approach for the management of the historic environment requires complex demands on the monitoring process quality.
The presented method is an advanced technical investigation and an effective way to identify the behaviour and the state of the structure, being a powerful analytical tool in building assessment. The method, named dynamic identification, is based on achieving dynamic in situ measurements, and provides reliable data and allows assessing the potential degradation caused by extraordinary events such as earthquakes, strong winds, heavy snow or landslides. In building assessment, using finite element method (FEM), the models calibration with real parameter values is necessary for the evaluation of the existing strength structures. The dynamic measurement tests can provide real values of the identified structural parameters for the rehabilitation design of the damaged structure. A database of the periodic measurements included in a structural control plan as part of the technical building record is required for in time and proper interventions during the building life cycle.

Keywords: historical monument, dynamic parameters, frequencies, vibration modals

1. Introduction

Keeping the structural parameters of a historical building as required for strength and stability goes hand in hand with the architectural building characteristics. Each historical building, beside its strength structure, has defined certain architectural features and building-furniture items such as doors, windows, roofs, and ornamental details. These elements, along with the designer name, the style used in the design and implementation of building or some events of special importance in the social and cultural life of a nation, are defining the building classification category of historical monuments. When

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those architectural or furnishing elements are lost or changed, the building is said to have lost its historic architectural integrity. At the same time, maintaining over a long period of time (more than the standardized duration of a building use) the parameters defining the resistance and the stability of a building requires strengthening/rehabilitation interventions due to degradation of materials, components or of the structure as a whole. Sometimes there is also a need to improve the conditions in the existing building, or to adapt them to new functions.

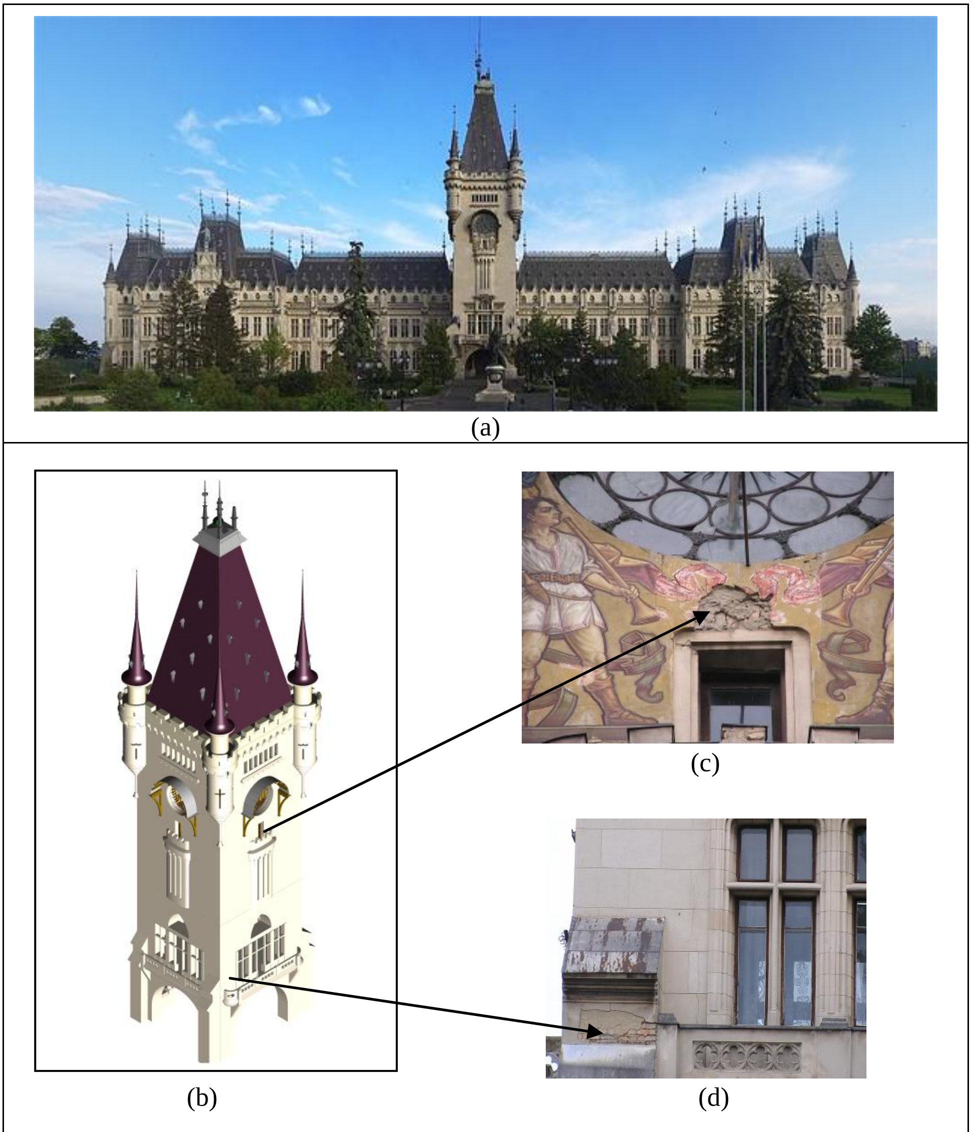


Figure 1. Damages found at the historical monument ‘Palace of Culture’: (a) general view [http://ro.wikipedia.org/wiki/Palatul_Culturii_din_Iasi], (b) clock tower, (c) damage in building structure, (d) damage in building materials.

The existing buildings which include the historical monuments are undergoing a process of degradation in time, leading to a situation when they do not have sufficient bearing capacity to meet the purpose for which they were built. Unfavourable environmental conditions (humidity, salt, development of microorganisms, etc.) and natural disasters (earthquakes, landslides, floods, etc.) are among the most important causes leading to the deterioration of historical buildings. In general, the deterioration causes may be classified in two main groups, though, in practice, the two domains are generally interdependent. The main groups are related to the materials durability and to the building elements or to the structure's resistance. For example, in Figure 1 are presented the damages found at an historical monument from Iasi, Romania [1]. The clock tower is part of the building currently named the 'Palace of Culture', which was completed in 1926. The tower has the plan dimensions of masonry 10.95 x 12.3 (m *x* m) and a height of 35 m.

The materials used for heritage building deteriorate and their duration of use is greatly reduced compared to the expected lifetime of the building. Many construction materials undergo changes as a result of abrasion, freezing and thawing, etc. Earthquakes, landslides or floods greatly affect the structural integrity producing the rupture of elements, large displacements or collapses.

Environmental conditions and their actions on building materials can be easily observed, and the parameters which define them can be monitored. It is clearly essential to define the damages as accurately as possible, before undertaking a rehabilitation program where useful and practical information must be introduced. All too often, rehabilitation is done without accurately defined objectives. Preservation of historic buildings in a continuous beneficial use involves critical evaluation of large volumes of data in order to draw clear conclusions.

Structural damage requires adequate control measures and complex technical investigations, which can accurately determine the damage's location and nature. Since all structures are damaged over time, and significant heritage attributes may be lost forever due to delayed or incomplete rehabilitation, conservation of heritage buildings largely depends on the application of a health monitoring plan.

In a health monitoring plan of a building, building deterioration is the expected event which must be avoided, especially when conducts to the edifice collapse. A structural control plan, part of the health monitoring plan, may be described as the structural monitoring, preparation, intervention and control of the historical building deterioration. It incorporates a diverse group of preservation activities in order to anticipate and avoid the deterioration and failure of the building components. Testing and evaluation of maintenance quality are important at various stages over the life of a structure. For proper health monitoring of civil infrastructure, the specialists have on hand a number of control methods. Control is carried out by a program of requirements and performance levels that the administrators of monumental buildings develop in accordance with the technical regulations.

The health monitoring plan of a building is the file with the changes in the building state, the presence and the number of new features that define a building and the evolution record of the observed parameters, over time. This involves the collecting a specific set or sets of information over time and the analysis of the results in order to detect the changes that occur. Once identified the problem areas, these can be monitored more intensively and, if necessary, can be corrected by measures of strengthening/rehabilitating the building.

The health monitoring activities of historical buildings include:

- data acquisition activities to create a long term structural information database;
- a rigorous procedure in reporting the observations as a record which is the result of the visual inspection and of the measurements processing.

Collecting this information facilitates the identification of recurring problems or of the areas susceptible to damage. The records of historical buildings are generally compiled for one or more of the following reasons:

- to secure an understanding of building's significance, sufficient to prepare a repair plan, or to take decisions related to such a part of the conservation process;
- to document buildings, or parts of the buildings, which may be lost as result of deteriorations;
- to create a permanent information record into an archive for future analyses and decisions.

Table 1. Health monitoring procedures and the importance of their results.

No.	Health monitoring objectives	The importance of the results
1	Building structure	To determine the deterioration of structural elements.
2	Building stability	To determine if the building or parts of it are moving.
3	Building safety	To determine public safety measures in case of emergencies (fire, water, earthquakes, riots, demonstrations).
4	Building maintenance techniques	To determine if the maintenance techniques or their lack have adverse impact on the conservation of building's materials and values.
5	Building materials	To determine the location and the quantity of erosion/ deterioration.
6	Building multiple information data: temperature, relative humidity, dew point, vapour pressure, ultra violet radiation and moisture content	To gather data on various environmental conditions.
7	Building environmental seismic activity	To determine if the conditions are in the limits of the established requirements.

In Table 1 are presented some examples of health monitoring plan objectives, and the importance of the results obtained through experimentally measured indicators, for heritage buildings. For each objective, skilled personnel and many specific types of equipment are involved, and due to these aspects there are difficulties in reporting the observations and processing the measurements in a unique long term structural information database.

A program of regular inspection helps identifying construction's problems. The control programs should be flexible, thorough, and tailored to the tasks they serve. In addition to the periodic inspections, structural surveys should be made, as necessary, especially after earthquakes, violent storms, landslides or changes in building use. This will help reveal the damages early and to prevent related failures.

The health monitoring method of historical monuments presented in the paper is based on achieving the dynamic identifications of a structure. The structural survey of a historical building must include the analysis of the structural dynamic parameters for a proper diagnosis of building damages and to reveal their root causes. Identifying root causes is essential because, if not corrected, they will continue to deteriorate and accelerate the degradation of the related historical building components. A database of the periodically structural dynamic measurements included in a structural control plan is required for in time and proper interventions during the building's life cycle. Databases can be used in expertise of the strength structures, to calibrate the FEM model used in design, and then to evaluate the influence of rehabilitation on the experimentally determined structural building dynamic parameters.

2. Dynamic identification of historical monuments

2.1. Theoretical background of the experimental modal analysis of a structure

Experimental modal analysis is a non-destructive method on real scale experimentation in order to retrieve information on the realistic behaviour of building structures, or on the elements and their mechanical characteristics design. Modal properties of a structure involving natural frequencies, modal shapes and damping rates are frequently used to monitor the strength structures, in old and new buildings, in order to calibrate finite element models or to detect structural changes or damages occurring in the life cycle of a building due to some exceptional actions, such as earthquake, explosion, fire or impact.

The Frequency Domain Decomposition (FDD) method is known for its operational modal analysis of structures and is based on spectral density functions. FDD method provides a modal decomposition of the vibration modes, and the modal information for each mode can be easily and accurately extracted. The technique is an extension of the traditional method of the basic frequency domain or peak picking technique [2], based on the expression of the structural response according to vibration modes. The spectral matrix is decomposed into a set of functions of power auto- and cross- spectral density, corresponding to a single degree of the systems freedom pattern. The method simplifies the user interaction because he has to consider only one frequency domain function - the singular value plot of the spectral density matrix.

Constant dynamic characteristics analysis of linear structures [2, 3] allows the use of particular solutions in the form of equation (1):

$$y(t) = \sum_{r=1}^{n} \emptyset_r \{x(t)\}_r = x_1(t)\phi_1 + x_2(t)\phi_2 + x_3(t)\phi_3 + \cdots + x_n(t)\phi_n \quad (1)$$

The power spectral density matrix of the response, $[G_{yy}(j\omega)]$, expresses the link between the known input x(t) and the measured response y(t), and can be expressed by the equation (2):

$$[G_{yy}(j\omega)] = \overline{[H(j\omega)]} \cdot [G_{xx}(j\omega] \cdot [H(j\omega)]^T \quad (2)$$

where:

- $[G_{xx}(j\omega)]$ - matrix of power spectral density (PSD) of the entry with (r x r) size. Assuming that the input is given only by the white noise, the input matrix $[G_{xx}(j\omega)]$ is constant, equation (3):

$$[G_{xx}(j\omega)] = [C] \quad (3)$$

- r is the number of inputs;
- $[G_{yy}(j\omega)]$ - matrix of power spectral density of the response with (m x m) size;
- m is the number of responses;
- $[H(j\omega)]$ – matrix of frequency response function (FRF) with (m x r) size;
- '$\overline{[\quad]}$' - complex conjugate of the matrix;
- '$[\quad]^T$' - transposed matrix.

In the frequency domain decomposition method (FDD), the estimation of power spectral density matrix $[G_{yy}(j\omega)]$is made for each frequency f_k, k corresponding to a peak in the fast Fourier transforms (FFT). The FFT operates by decomposing an *n* point time domain signal into *n* time domain signals, each composed of a single point. Then one must calculate the *n* frequency spectra corresponding to these *n* time domain signals, and the *n* spectra are synthesized into a single frequency spectrum. The power spectral density matrix $[G_{yy}(j\omega)]$ is expressed in eqation (4):

$$[G_{yy}(j\omega)]_k = \begin{bmatrix} PSD_{11}(j\omega) & CSD_{1n}(j\omega) \\ CSD_{n1}(j\omega) & PSD_{nn}(j\omega) \end{bmatrix}_k \quad (4)$$

where:

- *PSD (jω)* – the power auto-spectral density;
- *CSD (jω)* – the cross-spectral density;
- *n* - number of measuring channels.

Using the matrix of characteristic vectors and characteristic values one can obtain the expression of the output power spectral density, Using matrix of characteristic vectors and characteristic values allow expression of the output power spectral density, $[G_{yy}(j\omega)]$, as it is in equation (5):

$$[G_{yy}(j\omega)] = [V][S][V]^H = v_1 s_1 v_1^H + v_2 s_2 v_2^H + \cdots + v_n s_n v_n^H \quad (5)$$

where:

- *[V]* - matrix of characteristic vectors;
- *[S]* - matrix of characteristic values.

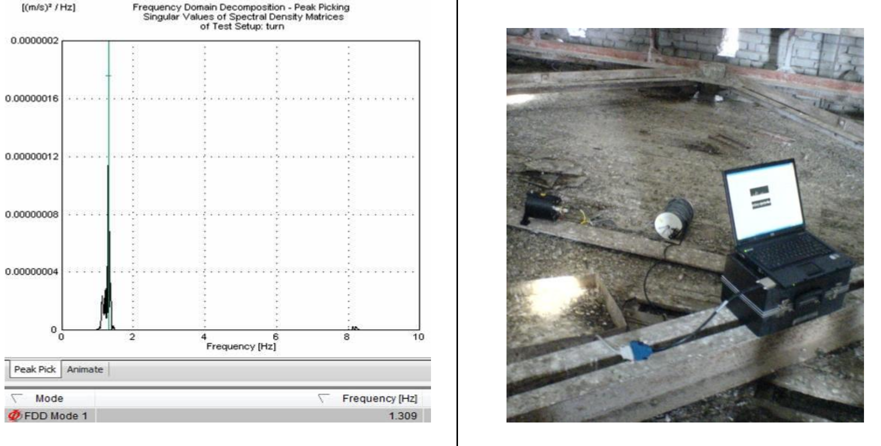
Basically, for each peak *k* we can determine a set of characteristic values and characteristic vectors corresponding to the number of measuring channels - *n*. Since part of the peaks does not correspond to the vibration modes of the structure (which may be an unknown source of external excitation) we must verify the orthogonality using the modal assurance criterion (MAC) [3]. The modal assurance criterion is defined as a constant - the degree of linearity of the two reference modal vectors [4]:

$$MAC\left(\phi_i^A \phi_i^B\right) = \frac{\left|\left\{\phi_i^A\right\}^T \left\{\phi_i^B\right\}\right|^2}{\left\{\phi_i^A\right\}^T \left\{\phi_i^B\right\}\left\{\phi_i^A\right\}^T \left\{\phi_i^B\right\}} \quad (6)$$

where ϕ_i^A and ϕ_i^B are the modal vectors.

The experimentally determined modal vectors are normalized so that the diagonal terms of the mass matrix are unitary. To the modal assurance criterion is assigned the value ‘0’ when there is no correlation between two modal vectors, and the value ‘1’ if there is a perfect correlation between them [3].

The dynamic parameters are identified through an experimental modal analysis using modal software packages (e.g. ARTeMIS Extractor). The software is based on the Frequency Domain Decomposition (FDD) method, and the vibration modes are identified from the measured data.



(a) (b)

Figure 2. (a) Dynamic identification through FDD technique, (b) Overall view of the testing procedure.

Figure 2 presents the frequency domain obtained by the experimentally modal analysis for the tower of the historical monument ‘Palace of Culture’ [1]. The dynamic characteristics were recorded by sensors disposed in the building. The acquired information was computed using the ARTeMIS Extractor software, based on the structure response. The analyses show the vibration modes and the natural frequencies for the structure.

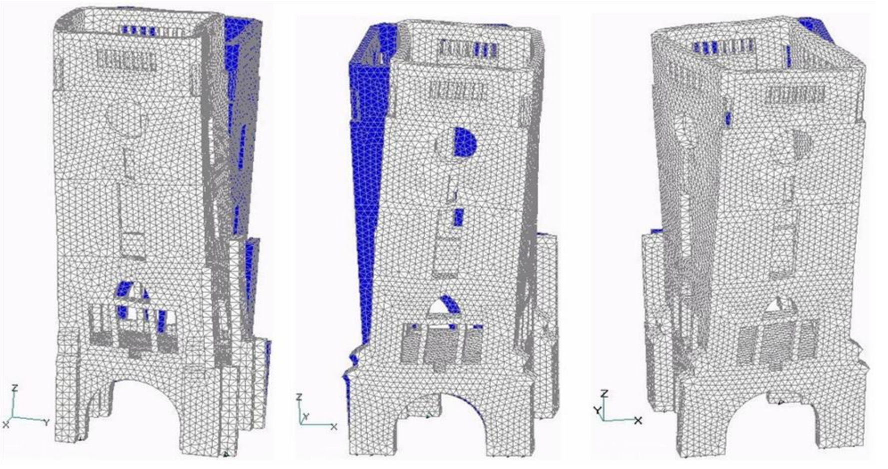
The experimental modal analysis can be extended to the whole structure. The structural systems have a large number of natural frequencies. When the structural system vibrates freely, its movement describes a certain configuration or a modal shape. Each natural frequency has associated its own modal shape. Using sensors disposed in the building structure and configured to generate files with acceleration record for a period of time, there are determined the natural frequencies, respectively the corresponding periods of the vibration modes. The analysis of the signals typically relies on Fourier analysis. The resulting transfer function will show the natural frequencies which can be estimated from the measurements.

2.2. Theoretical background of the analytical modal analysis of a structure

The analytical modal analysis refers to the calculation method used to determine the modal frequencies and shapes of the structures, and the individual responses to a given operation mode. Finite element method (FEM) is a method commonly used to perform structural analysis because, like in other calculations using FEM, the analyzed object may have arbitrary shape and the calculation results are acceptable. From the modal analysis are resulting analytical equations, which were observed in typical systems. The physical interpretation of the characteristic values and characteristic vectors which result from solving the system is that they represent the modal frequencies and the corresponding modal shapes. The modal frequency of a system is dependent only on the stiffness of the structure and the mass which participates with the structure (including self-weight). It is not dependent on the load function.

In finite element analysis, the structural system is modeled by a set of appropriate finite elements interconnected at nodes. The elements have geometrical characteristics (such as thickness or depth, and width) and physical properties (such as density, Young's modulus, shear modulus and Poisson's ratio).

FEM structural analysis follows the virtual work principle or the minimum total potential energy principle. The direct stiffness method is the most common implementation of the finite element method (FEM). The direct stiffness method, also known as the displacement method or matrix stiffness method makes use of the members' stiffness relations for computing member forces and displacements in structures. In order to apply the method, the system must be modelled as a set of simple, idealized elements interconnected at the nodes. The material stiffness properties of these elements are then, through matrix mathematics, compiled into a single matrix equation which governs the behaviour of the entire idealized structure. The vector of the equivalent nodal forces is obtained by summing the elements load vectors, and the system stiffness matrix is obtained by summing the elements stiffness matrices.



f_1 = 1.24Hz f_2 = 1.37Hz f_3 = 1.91Hz

Figure 3. Modal shapes for the clock tower from the Palace of Culture.

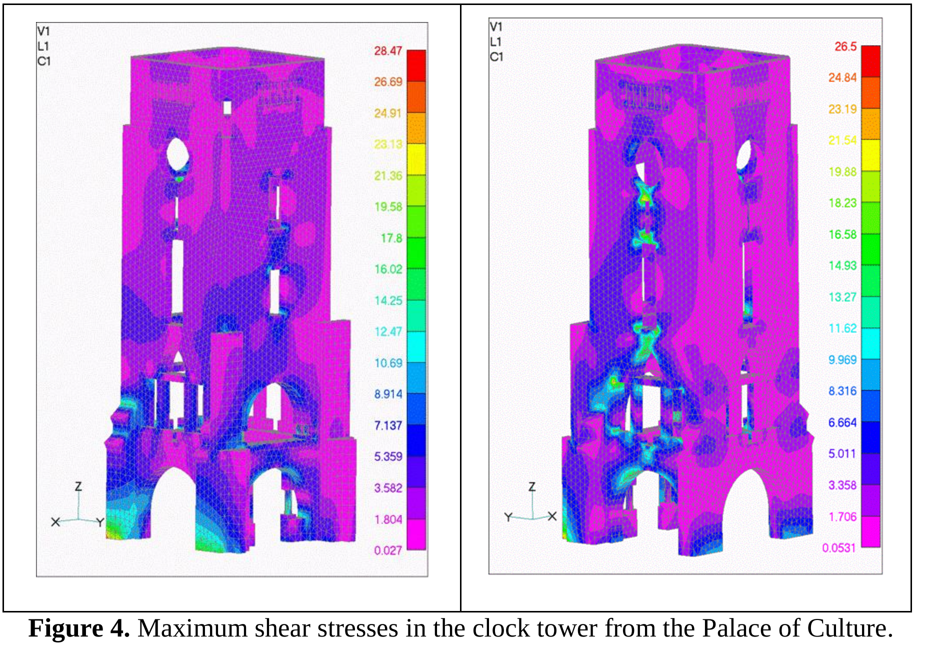


Figure 4. Maximum shear stresses in the clock tower from the Palace of Culture.

The elements stiffness matrices express the property of the structural members. In general, elastic modulus is not the same as stiffness. The elasticity modulus is a property of the material. Stiffness, on the other hand, is a property of the solid body dependent on material and on the shape and boundary conditions. Stiffness is evaluated using the cros-sectional geometrical parameters (area or the polar moment of inertia), the material elastic properties (Young's modulus or the shear modulus of the material), and an integer depending on the boundary conditions. The axial stiffness for an element in tension or compression, *k*, is a function of the cross-sectional area (*A*), the elastic modulus (*E* or Young's modulus), and the length of the element (*L*). Similarly, the rotational stiffness, *k*, is a function of the polar moment of inertia (I_p), an integer depending on the boundary conditions (*n*), and the shear modulus of the material (*G*).

The basic requirements for the strength and the stability of a historical building structure are checked by creating a FEM model, using the complex structure survey with geometrical and material inputs, that represent as accurate as possible the real situation. The structure unknown modal frequencies and modal shapes or other parameters (displacements and internal forces or stresses) can then be determined and used to identify deviations in the design performance values.

The analytical modal analysis of the Clock Tower from Palace of Culture presented in Figures 3 and 4 [1], shows that the degradations were produced by the load combination with earthquake. Due to the specified load combination, the maximum shear stresses and modal shapes maps have identified the position of stress concentrations with structural degradation observed in the building. Nastran software was used for the finite element analysis.

2.3. Dynamic identification of historical monuments

Concerns regarding the engineering techniques for dynamic identification of a structure appeared about five decades ago [5], and were widened in the last years due to the development of the technical possibilities [4]. With the conventional non-destructive methods based on ultrasound, radar waves and other local determinations can be made only the material identification [6], and in order to be used one need access to accurate data about the degraded area. The method based on measuring the dynamic characteristics can be used on a global scale and does not require information on degraded areas.

The dynamic identification of a structure means to establish relationships between excitation (induced vibrations) and the dynamic characteristics of the structure and to quantify the causes of their values variation. By measuring the structure dynamic parameters produced by the induced vibration one can obtain quite precise estimations of the changes in the dynamic behaviour of the structure which are due to possible degradations. High accuracy results are obtained if the excitation is of white noise type, the structure is of reduced damping and the vibration modes are geometrically orthogonal [2]. Specifically, the accepted discrepancies in the frequency domaine between the experimental test and FEM analysis must be less than 10%, and if they are outside the limit it means that there are degradations in the structure.

The accumulation of degradation in building strength structures amends the modal properties of a structure, usually an increasing in damping and a decrease in stiffness due to material properties. These modification induced in a structure are reflected by the material properties (Young' modulus, shear modulus) or by the integer depending on the boundary conditions. A comparative analysis of experimental and theoretical results highlights or allows identifying degraded areas characterised by: the decrease of physical material properties, reduced cross sectional sizes, the modification of joint types between elements and between elements and the ground (boundary conditions).

Subsequent FEM analysis developed up to the values of natural frequencies obtained in experimental measurements, has as result changes of the structural system parameters. The changes allow to identify the local degradations caused by: internal cracks, material alterations, rupture of elements, settlements or over limits displacements.

In the case of historical monument evaluation, it is necessary to calibrate the FEM model using an inverse method in order to identify the changes in the structural system. Calibration is an intervention on a FEM model, which modifies the structure and material characteristics, to predict the real structural behaviour when the structure or material can not be defined in the FEM model as having ideal physical and mechanical properties, due to a hidden local structural degradation. The process of model calibration involves reconciling the differences between the results of the experimental test and the numerical analysis. This process requires advanced methods and models in order to: assess the shortcomings of the model, to assess the importance of the parameters, to assess the higher modes, to have accurate information about modal displacements, and to calculate the necessary changes. The model calibration uses a selection approach based on the parameter range, nonlinear optimization to minimize the error between the experimental test and the numerical analysis, and multiple FEM models to bound the system response and to assess the probability of finding a reconciling solution in the frequency response functions as parameters are varied.

The modal analysis used to evaluate the global structural behaviour, allowing to estimate the modal parameters and to detect local damages must be followed by statistical analysis in order to evaluate the environmental effects [7]. This combination of research activities is a step in the health monitoring plan for a historical monument. During the building's life is necessary to have programmable steps multiplied by the extraordinary events.

For the clock tower, the comparison of modal frequencies of the FEA model with the experimentally measured frequencies [1] highlighted a maximum difference of about 5%, resulting in measured natural frequencies slightly higher than the frequencies of the finite element calculation model. The measured frequency of the first mode (1.31 Hz) is very close to that resulting from the computational model (1.24 Hz). The conclusion is that the dynamic behaviour of the building FEA model is similar to that resulting from the measurements. The degradations visually identified on the structure are found in the concentration of stresses due to the seismic action. The experimental measurements clearly indicate [1] that the FEA model of clock tower, made using a selection approach based on a real parameters range, describes the actual behaviour of the structure.

3. Conclusions

Historical monuments degrade over time due to material alteration or to accidental actions. Eliminating the degradation phenomenon means strengthening interventions, which if made at long intervals involve huge financial resources. Therefore, in order to decrease the costs, close health monitoring is required at short intervals. To be effective, a standard method of collecting data and a standard format for reporting is required. From the structural point of view, health monitoring activities of a historical monument are effective if they provide data and information to enable a rapid assessment at low costs and they do not cause local degradation during the measurement.

The development of policies for the preservation of built heritage must be centred on two important issues: the damage identification at the earliest possible stage and the long-term commitment. Visual inspection and non-destructive tests done at regular intervals are methods that can meet these requirements.

The dynamic identification is a non-destructive testing method based on the changes of dynamic parameters: natural frequencies, modal shapes and damping coefficients. The identification method based on dynamic parameters defining the structure is attractive because it is easy to perform and does not involve complex equipment, but, as a long-term investigation method requires accurate and stable acquisition systems.

Dynamic identification provides reliable data on the actual condition of a structure and allows to asses the potential degradation caused by extraordinary events such as earthquakes, impact, winds, or landslides. The method involves a repeated collection of sets of the building's natural frequencies and modal shapes over time and an introspective analysis of the results in order to detect the changes that are occurring.

The collection of this information facilitates the identification of structural elements and materials susceptible to damage. A technical description at day and the evolution of a building can be achieved by using this valuable method. Comparing measurements from data sets collected over long periods of time, allows continuous verification of the integrity and safety of the building. Once identified, the problem areas can be monitored more intensively and, where appropriate, management action taken.

The periodic structural dynamic measurements can be integrated into a structural control plan for in time and proper interventions during building's life cycle. A database of the measurements included in the technical building record is required.

Dynamic measurements, scheduled on the life cycle of the building, enable real-time identification of degradation, and therefore, vulnerability assessment and to take the appropriate decisions.

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