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Global methodology for damage detection and localization in civil engineering structures

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ABSTRACT

The Structural Health Monitoring (SHM) in civil engineering faces several challenges. The main issue lies in defining a reliable and precise methodology of damage detection and localization in order to allow preventive maintenance or to enable the definition of repair actions. In this paper, a new methodology of SHM is proposed. Using Vibration-Based Damage Detection Methods (VBDDM), a damage detection and localization algorithm is elaborated and tested on a Finite Element Model (FEM) of an existing building. In a first case, the damage is introduced artificially by a local reduction of stiffness, while in the second case, the damage is calculated according to a real seismic signal from the italian L'Aquila earthquake. The advantages and disadvantages of each dynamic monitoring technique are discussed and the usefulness of the algorithm is highlighted.

1. Introduction

The monitoring and the assessment of structures, in order to ensure human and material safety, is a very important issue in civil engineering. There are several methods to evaluate the damage such as radiography, ultrasound or dynamic behaviour analysis. These techniques are called non-destructive methods or SHM techniques. The identification of the damage can be classified into 4 levels: Level 1: Detection of the damage, level 2: Localization of the damage, level 3: Quantification of the damage and level 4: Evolution of the damage [1]. SHM methods can be subdivided into two groups: local and global methods. Local methods concern small structures, and are mainly applied in the aeronautics and automotive fields. They are very efficient and very expensive [2]. Whereas, global methods concern large structures and are based on the study of their dynamic behaviour. They are also called Vibration-Based Damage Detection Methods (VBDDM) [3,4]. Methods used in civil engineering are usually global methods [5]. When structures are damaged, their rigidity decreases as their damping increases. This results in a modification of the dynamic characteristics such as reduction of eigenfrequencies and modification of mode shapes. These changes are related to a modification in the physical properties. Thus, the monitoring of the dynamic characteristics of a structure between an initial state (undamaged state) and a final state (damaged state), represents a method of performance evaluation. This includes mostly the eigenfrequencies method (level 1), the Modal Assurance Criterion (MAC) (level 1), the Mode Shape Curvature (MSCM) method (level 2), the Curvature Damage Factor (CDF) (level 2) and the flexibility method (level 2) [6,7]. Nonetheless, these techniques have several limitations. Over the last few years, the main issue has been the definition of a complete and precise monitoring methodology. Several studies worked on developing better sensors, improving signal-processing, applying existing techniques or developing new techniques [8]. However, the problem still lies in obtaining a good identification of dynamic characteristics and accurate correlation between their variations, the appearance of the damage and its location. This article presents a new methodology that simplifies the monitoring of civil engineering structures based on the methods mentioned above. By applying these methods following a precise order and taking into account the sensitivity, the simplicity and the SHM level of each method, a new detection and localization algorithm is defined. The goal of defining such an algorithm is to facilitate the implementation and integration of SHM techniques into permanent and independent monitoring system. The algorithm is evaluated on a numerical model of an existing building. The considered model is the 18-story Ophite tower located in Lourdes, France. The tower is permanently instrumented with 24-channel system and an acquisition station [9]. The numerical model was calibrated using the modal parameters (eigen frequencies, modes shapes and damping) identified in previous works [10]. Two cases of damage are considered. In the first case, the damage is introduced in the numerical model artificially by a local reduction of

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Young's modulus (first scenario: 50% of local reduction, second scenario: 25% of local reduction). In the second case, the damage is introduced by a true seismic signal in a nonlinear structural finite element model of the Ophite tower. The purpose of this algorithm is to locate the damaged floor.

2. Damage detection and localization methods

Here in, we present the detection and localization methods. These techniques are usually applied separately according to desired SHM level. This list is not exhaustive but it represents methods commonly used in civil engineering. The implementation, advantages and disadvantages of each method are detailed.

2.1. Damage detection methods

2.1.1. Eigenfrequencies method

During the damaging event, the physical properties of a structure undergo a change inducing a modification of the modal characteristics, particularly, a fall of the eigenfrequencies [11]. Thus, the monitoring of the eigenfrequencies presents a simple method of SHM of mechanical and civil engineering structure [12]. It is easy to implement and is very sensitive to the damage [6]. Widely used, it reflects the behaviour of the structure in its entirety and only satisfies the first level of SHM since no indication of the sensors position is required for its implementation [13]. Eigenfrequencies method can be computed as follows [14]:

$$\Delta f = f_i^u - f_i^d \tag{1}$$

with f denotes the eigenfrequency, i denotes the i^{th} mode, u the undamaged state and d the damaged state. Variations of the eigenfrequencies depend on the position of the damage and its severity. In fact, the more severe the damage is, the greater the frequency drop is. For some modes, the damage placed on maxima of the mode shape curvature will produce the highest variations while, damage placed on inflection points of the mode shape curvature will not produce variations in eigenfrequency. For other locations of damage, the frequency shift will be proportional with the mode shape curvature of the vibration mode at that location [15]. In real life situations, the major disadvantage of this method is that damages are detected only when the shift of frequencies is of 5% or more. Shifts lower than 5% can be explained by phenomena not related to any damage such as hygrothermal effects [16]. The MAC method may be an alternative since it uses spacial informations (i.e. the mode shapes).

2.1.2. Modal Assurance Criterion (MAC) method

The MAC method is based on the comparison of two measurement series in order to define the correlation between them [17]. The mode shapes are affected by damages and their variations denote the presence of an anomaly in the structure. Thus, by applying the MAC criterion on the mode shapes of healthy and damaged structure, damages are detected in case of an incomplete correlation between them [18]. The MAC criterion is a matrix defined by Eq. (2) and the value of its component varies between 0 and 1. MAC_{jk} takes the value 1 if the correlation is complete and takes the value 0 if there is no correlation at all. In this matrix, the most interesting values are those of the diagonal. They reflect the correlation between the mode shapes of the same mode. Any diagonal value less than 1 can be interpreted as a damage indication [19].

$$MAC_{j,k} = \frac{\left(\sum_{i=1}^{n} [\psi_u]_i^j [\psi_d]_i^k\right)^2}{\sum_{i=1}^{n} ([\psi_u]_i^j)^2 ([\psi_d]_i^k)^2} \tag{2}$$

where $[\psi_u]$ and $[\psi_d]$ denote respectively the mode shapes of the undamaged and the damaged structure. $MAC_{j,k}$ factor indicates the degree of correlation between the j^{th} and the k^{th} mode and n is the number of measurement nodes.

For low severity damage, corresponding to eigenfrequencies shift less than 5%, the MAC method indicates damage in higher order modes. These modes are more sensitive to the damage and are difficult to identify in real life situations [20]. Moreover, experimentally, in the case of two series of measurements on the same structure's state, the estimation of the mode shapes is not precise and the correlation is not complete. Several methods of Operational Modal Analysis (OMA) exist and allow the experimental identification of mode shapes such as Frequency Domain Decomposition (FDD) algorithm [21]. In the literature, the FDD algorithm is applied around a resonance peak in the Power Spectral Density (PSD) that represents an eigenfrequency. The mode shape is therefore calculated around this peak and MAC is used as a comparison criterion with mode shape computed from the analytical model. It is admitted that a good identification of mode shape is given for any diagonal value greater than 0.8 around the peak. This limit value is called the MAC rejection level [22]. Therefore, it would be necessary for the diagonal values to be less than 0.8 for damage to be detected with confidence.

2.2. Damage localization methods

2.2.1. Mode Shape Curvature Method (MSCM)

This technique is based on the relationship between the mode shape curvatures and the flexural stiffness.

$$\psi''(x) = \frac{M(x)}{EI} \tag{3}$$

where $\psi''(x)$ denotes the mode shape curvature at location x, $M(x)$ is the bending moment and EI is the flexural rigidity. According to Eq. (3), it can be seen that when the structure is damaged, its Young's modulus varies inducing a variation of the mode shape curvatures [7]. MSCM may be defined as the absolute difference in curvatures of the undamaged and the damaged state. It is computed as follows [23]:

$$\Delta\psi_i'' = |\psi_{i,u}'' - \psi_{i,d}''| \tag{4}$$

with ψ_i'' denotes the mode shape curvature vector of the i^{th} mode, u and d denote respectively the healthy and the damaged structure. It is admitted that the local increase in the curvature occurs when the stiffness is locally reduced (i.e. local damage) [24]. Curvatures can be computed using the central-difference formulas [25]:

$$\psi_{i,j}'' = \frac{\psi_{i+1,j} - 2\psi_{i,j} + \psi_{i-1,j}}{h^2} \tag{5}$$

where h is a constant distance that separates two consecutive nodes [26]. $\psi_{i,j}$ is the mode shape component of the i^{th} coordinate at the j^{th} mode.

2.2.2. Curvature Damage Factor (CDF)

CDF method is derived from MSCM. The main idea of this technique is to average the variations of mode shape curvatures at a given coordinate j with respect to the number of considered modes. The use of several modes enables the detection of damages affecting mode shapes other than that of the fundamental mode and reduces the weight of misleading informations [27]. This method is computed as follows:

$$CDF = \frac{\sum_{i=1}^{N} |\psi_{i,j}''^{u} - \psi_{i,j}''^{d}|}{N} \tag{6}$$

where N is the total number of modes.

The accuracy of detection and localization depends on the number of measurement nodes. In other words, the more complete the description of the mode shape is, the more accurate the localization of the damaged area is [28].

2.2.3. Flexibility method

The presence of damage induces stiffness decrease and flexibility