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A multi-mode approach for multi-directional damage detection in frame structures

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ABSTRACT

Due to their three-dimensional nature, damages have different effects on each vibration mode of a frame structure, depending on the direction of deflection of its structural elements. In this study, a Multi-mode Multi-directional Damage Index (MMDI) method is proposed to benefit from the recognition of the multi-directional effects of damages in order to reduce damage detection errors. The novelty of the method resides in the use of specifically developed modal combination factors for the identification of the vibration modes more relevant to the damage detection and for the assessment of the directionality of the damage effects. The detection capability of the MMDI method is experimentally investigated on a bridge testbed consisting of a two-column moment resisting frame. Individual and combined damages are simulated into columns and beams of the testbed through steel parts removal. The dynamic characteristics of the system in its undamaged and damaged configurations are identified upon ambient-like accelerations from a low dense sensor network. The effectiveness of the MMDI method is assessed for its ability of identifying damages without any pre-selection of vibration modes. The accuracy of the damage assessment is measured through four indicators targeting identification, false detection, localization, and severity estimation of the damages.

1. Introduction

Structures undergo inevitable degradation and damaging during their service life due to a variety of factors including material aging, wear, and accidental events, such as earthquakes. Due to the high socio-economic impacts that structural issues may have on bridges, timely detection of evolutionary degradation patterns is a key aspect for maintaining the transportation infrastructure within allowable functionality and safety levels. The remote and timely identification of structural damages through Structural Health Monitoring (SHM) emerged in the past years as a valuable alternative to visual inspections in overseeing the infrastructure's degradation process via non-destructive sensing and data analysis.

Since the early 1980s, great efforts have been spent in investigating and enhancing the damage detection performance of vibration based SHM systems, as extensively described in [1]. Due to their robustness in terms of localization and quantification properties Damage Index (DI) methods based on modal strain are amongst the most suitable methods for SHM of flexible structures, such as bridges [2]. The accuracy of these methods depends on the choice of appropriate vibrations modes, which are inherently affected by any given damage with different levels of severity, as shown in [3] for a continuous beam and in [4] for a two-span reinforced concrete deck. The majority of the experimental studies on DI methods focus on simplified damage scenarios and base the damage recognition on a number of vibration modes in a predominant direction, which is considered to be the most suitable for the damage detection (e.g. modes in vertical direction for damages in arches and beams). However, deterioration and damaging are three-dimensional in nature, with multi-directional effects on the dynamic characteristics of a structure. When multiple 3D vibration modes are used, damage indices may significantly differ in the distinct directions of deflection of each individual vibration mode. The consequent redundancy and discrepancy in results add complexity to the blind interpretation of the DI measures, as shown in [5] for a 3D structural frame, for which damage severity indicators, false positives, and missing detections significantly differ in the two lateral directions of vibrations. The unavoidable multi-directional damage effects on flexible plates was addressed by [6] that proposed the use of DI methods based on generalized strain energy to account for double curvature deflections. This approach was

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proved effective for locating damages, but left some unresolved issues, including lack of clarity about the mechanism of characterizing damage, and susceptibility to noise, as described in [7,8]. A similar modal strain energy approach was used by [9] to detect and estimate the severity of multi-directional damages in 3D frame structures. By dividing the modal strain energy of each structural member into two parts, associated with its axial and transverse coordinates, two vibration modes in mutually orthogonal directions were combined to complement information for damage localization from individual modes. The authors recommended further research to improve the severity estimating capability. A cross-modal severity index was introduced by [10] to address this issue. The index combines strain energy from vibration modes of the undamaged and damaged structure into a multi-modal damage severity measure for each damage previously located through other methods. In a recent review [11] of strain energy DI methods, the issue associated with severity estimation of complex damage patterns is emphasized for further studies.

This study addresses the identification of three-dimensional damages by introducing a Multi-mode Multi-directional Damage Index (MMDI) method. This methods consists of a unified approach for the localization and severity estimation of multi-directional effects of damages in beam and column elements of structural frames. The proposed formulation was developed to complement an existing DI method based on modal strain [12,13], but can be applied to any similar DI approach relying on location and severity indicators. The formulation combines damage indices from individual modes into a multi-mode damage indicator and a directionality vector that associates a direction to the stiffness losses caused by the damage. By combining damage indices from all the available vibration modes, the MMDI method obviates the need for pre-selection of vibration modes to identify damages in specific elements and/or directions.

Experimental testing in laboratory-controlled conditions were used to assess the accuracy of the method on a testbed, consisting of a shake-table assembly of a two-column steel bridge model with removable parts for damage simulation. The choice of a bridge structure is motivated by the constant need for improved damage identification procedures for the large number of worldwide bridge SHM programs currently in place [14–18]. At this development stage, laboratory scale tests were preferred over full-scale tests on real bridges to limit environmental effects commonly encountered during in-situ investigations [19–21]. The use of a 3D bridge model allowed simulation of replicable and concurrent damages in a variety of structural elements, thereby overcoming the inherent limitations of tests on separate bridge components such as individual beams [22], plate-girder decks [23], and flat slabs [24]. The damage detection followed an output-only system identification of the bridge structure triggered by low intensity sparse acceleration data recorded on the testbed. The damage identification capability of the MMDI method is quantified and compared to results from individual modes in terms of four accuracy indicators, evaluated for five different damage scenarios.

2. Damage identification

The DI method was originally introduced in [12,13] and was specifically developed to localize and quantify damages in structural bridge components, as well as in seismic response modification devices such as isolators and energy dissipators. The method was compared to similar DI methods in terms of accuracy by means of numerical simulations. In this study, a formulation is added in order to extend the method to multi-directional damage estimates from multiple 3D vibration modes. The method requires an arbitrary subdivision of the structure into sub-elements not necessarily corresponding to physical components. The damage localization and severity estimation is based on the damage-induced variations in modal strain for each sub-element.

2.1. Individual modes approach

The DI method [13] relies on a localization parameter that compares the modal strain energy variation of the jth sub-element with respect to a kth sub-element for the generic ith mode:

$$\beta_{i,jk} = \frac{\int_{L_j} \varepsilon^{*2} dl}{\int_{L_j} \varepsilon^{2} dl} \cdot \frac{\int_{L_k} \varepsilon^{2} dl}{\int_{L_k} \varepsilon^{*2} dl} \tag{1}$$

where L is the sub-element length, and ε, ε^* are the generic modal strain terms (i.e. modal curvature for flexural elements), in undamaged and damaged conditions, respectively. The parameter defined in Eq. (1) relates the status of a generic sub-element to the condition of every other element. Since damage is associated with local increments in modal strain, a numerical value of $\beta_{i,jk} > 1$ indicates damage in the ith sub-element, while $\beta_{i,jk} < 1$ indicates damage in the kth sub-element. A normalized damage localization term is further defined for the jth element as:

$$\beta_{i,j} = \frac{\beta_{i,jk}}{\beta_{i,k_{\min}}} \geqslant 1 \tag{2}$$

where $\beta_{i,k_{\min}}$ is the minimum value of the localization parameter $\beta_{i,jk}$ of Eq. (1).

The statistical significance criterion described in [13] is used to identify the locations of damage through the definition of the damage localization index:

$$Z_{i,j} = \frac{\beta_{i,j} - \bar{\beta}_i}{\sigma_{i,\beta}} \tag{3}$$

where the parameters $\bar{\beta}_i$ and $\sigma_{i,\beta}$ are the mean and the standard deviation of $\beta_{i,j}$, respectively. Based on the ith vibration mode, the jth sub-element of a structure is considered damaged if the index $Z_{i,j}$ exceeds a pre-determined threshold, which identifies a given confidence level. In this study, a damaged condition is recognized in the generic jth sub-element by a value $Z_{i,j} > 1.28$, corresponding to a one-tailed test at 90% confidence level.

The method provides an estimate of the severity of the damage through the index $\alpha_{i,j}$ that represents the fractional change in stiffness of the jth element:

$$\alpha_{i,j} = (\beta_{i,j})^{-0.5} - 1 \quad \alpha_{i,j} \geqslant -1 \tag{4}$$

For each vibration mode, the fractional change in stiffness is associated with type and direction of the strain measure used in Eq. (1). For flexural elements, for instance, the severity index $\alpha_{i,j}$ quantifies flexural stiffness reductions in the same direction in which the modal curvature is gathered.

When multiple vibration modes are used, a set of damage localization and severity indices are determined for each mode. For 3D mode shapes, the indices refer to damage effects in the direction of the modal deflection of each sub-element. Since the effects of any damage are generally anisotropic in nature, damage indices may significantly differ between different directions, causing difficult interpretation of the results of the DI method.

2.2. MMDI approach

The purpose of the proposed MMDI approach is to combine mono-directional damage indices from individual modes, into multi-mode indices that are representative of the multi-directional nature of the damage. With this aim, the generic ith