Engineering Structures 167 (2018) 549–566

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Output-only damage detection in buildings using proportional modal flexibility-based deflections in unknown mass scenarios

Giacomo Bernagozzi[a,*], Suparno Mukhopadhyay[b], Raimondo Betti[c], Luca Landi[a], Pier Paolo Diotallevi[a]

[a] Department DICAM, University of Bologna, Bologna, Italy
[b] Department of Civil Engineering, Indian Institute of Technology, Kanpur, India
[c] Department of Civil Engineering and Engineering Mechanics, Columbia University, NY, USA

ARTICLE INFO

Keywords:
Structural health monitoring
Damage detection
Modal flexibility matrix
Modal flexibility-based deflection
Building structure

ABSTRACT

Methods based on the evaluation of structural deflections from experimental modal flexibility matrices are important tools in vibration-based damage detection, especially for building structures. Modal flexibility matrices, however, can not be directly estimated when dealing with output-only vibration data (e.g. in the important case of structures tested under ambient vibrations). One can use an a-priori estimate of the mass matrix of the structure or the added mass method to obtain the modal normalization constants needed to assemble the flexibility matrix, but these operations can be challenging for real-life civil structures. To address this problem, a modal flexibility-based approach for output-only damage detection and localization in building structures that can be applied with minimal or no a-priori information on the structural masses is proposed in this paper. This approach is also able to deal with the general case in which mass modifications, e.g. due to operational variability in structures, are present before and after damage. The approach is based on the estimation (directly from output-only data) of modal flexibility-based deflections of building structures that are proportional with respect to the corresponding true deflections. From analytical investigations it was found that the missing scaling factor between the two deflections can be made theoretically equal to the total mass of the structure, as proposed in the paper. Then, interstory drifts evaluated from the proportional deflections are used for damage detection and localization according to two proposed strategies. The first strategy can be applied with minimal a-priori information on the masses (i.e. using a parameter that quantifies an eventual relative modification of the total mass of the structure before and after damage). The second one is a more advantageous strategy that can be applied from output-only data without any a-priori information on the masses, even in the case in which the masses are varied before and after damage. The effectiveness of the proposed approach was demonstrated using both numerical simulations and experimental vibration tests on frame building structures.

1. Introduction

Detecting damage in structures starting from vibration measurements is one of the main goals of the emerging field of Structural Health Monitoring (SHM) [1]. This approach for SHM can be applied to civil, mechanical, and aerospace structures. Especially in civil engineering, the process of data acquisition is usually performed during the normal operating conditions of structures tested under ambient vibrations. The mechanical and dynamic characteristics of a structure are in general altered when the structure experiences damage, and damage detection techniques [1,2] thus aim to obtain information on such changes starting from the vibration measurements. Civil structures, such as bridges or building structures, subjected to ambient vibration monitoring can also experience changing operational and environmental conditions (the former can be associated, for example, to mass modifications due to the variability of the payloads, while the latter can be associated to temperature variations) [1,3]. Such changes are not related to a damaged state, but they in general affect the dynamics of the system (e.g. the modal properties). It is thus important to ensure that the indices used for damage detection are not sensitive to such changes [1].

Methods based on the evaluation of structural deflections starting from modal flexibility are important tools in vibration-based damage detection. These methods belong to the more general class of the methods based on modal flexibility [4–16], and they have been developed and applied for damage detection and localization in bridges

* Corresponding author.
E-mail address: giacomo.bernagozzi2@unibo.it (G. Bernagozzi).

https://doi.org/10.1016/j.engstruct.2018.04.036
Received 28 February 2018; Accepted 9 April 2018

Nomenclature

DSF	damage sensitive feature
$eMAC_{id}$	error on MAC_{id}
MAC_{id}	Modal Assurance Criterion applied to vectors of interstory drifts
MD_{id}	Mahalanobis distance between vectors of interstory drifts
PFM	proportional flexibility matrix
PSIL	positive shear inspection load

[15–17] or in building structures [4–6]. Experimental modal flexibility matrices of structures can be derived from vibration tests, and the deflections can then be estimated by applying special loads termed "inspection loads" (for example, uniform loads applied at all the measured DOFs). One of the advantages of the methods that adopt modal flexibility-based deflections over the methods that use modal flexibility is that, as shown in [4,5,13], the components of the deflections due to uniform loads are in general less sensitive to experimental and truncation errors derived from modal tests than the components of the modal flexibility matrices. Among different methods based on structural deflections, an effective method for output-only damage detection and localization specifically developed for building structures has been presented in [4]. The modal flexibility-based deflections are calculated using special loads termed positive shear inspection loads (PSIL) [4], and the interstory drifts evaluated from such deflections are considered as damage sensitive features (DSFs) to detect and localize damage. The effectiveness of this method, which is indicated in this paper as PSIL method, was demonstrated, as shown in [4], using a laboratory steel frame structure subjected to output-only vibration tests.

It is important to underline that modal flexibility can be estimated only when mass-normalized mode shapes are available (for example, in forced input-output vibration tests with at least one actuator-sensor pair [18,19]). On the contrary, in ambient vibration tests and output-only identification [20], only arbitrarily-scaled mode shapes can be obtained, and flexibility matrices are thus not readily available [10]. In the output-only case, the mass normalization of the mode shapes can be carried out using the added mass method [21,22] by executing complementary tests. However, as reported in [20], for many civil engineering structures the added mass method might be difficult to be applied in practice, especially in the applications of ambient vibration monitoring. Alternatively, as adopted for example in [4] where the PSIL method for output-only damage detection is presented and verified, an a-priori estimate of the system mass matrix can be used to mass normalize the identified mode shapes.

In the context of the PSIL method it is clear that it can be of interest to have a strategy to obtain the modal flexibility-based deflections that does not require an a-priori estimate of the mass matrix of the structure (or, alternatively, complementary tests based on the added mass method). A similar problem was investigated in the context of another damage detection method - i.e. the Damage Locating Vector (DLV) method [7]. This modal flexibility-based method was originally formulated for the case of input-output data, and then it has been extended to the output-only case using the approaches proposed in [8–11]. These approaches do not aim to find the correct way of scaling (i.e. mass normalize) the mode shapes used to assemble the flexibility matrices, but to obtain flexibility matrices that are proportional to the corresponding true flexibility matrices. To perform this operation the mass matrix of the structure is not required, and the normalization of the mode shapes can be done using a proportional mass matrix estimated directly from the data. Proportional flexibility matrices can then be used for damage detection, since mapping changes in flexibility can be done considering either the true flexibility matrices or the proportional flexibility matrices [8].

In this paper, a modal flexibility-based approach is proposed for output-only damage detection and localization in building structures that can be applied with minimal or no a-priori information on the masses. This approach is based on the theory behind the PSIL method, but it aims to make the damage detection process based on the modal flexibility-based deflections applicable directly from output-only vibration data and independent as much as possible from an a-priori estimate of the mass matrix of the structure. In particular, it is proposed to use the technique defined in [8] to obtain proportional flexibility matrices from output-only data (hereinafter referred to as PFM technique) in the framework of the PSIL method. In this way modal flexibility-based deflections that are proportional to the corresponding true deflections can be directly estimated from the output-only data. Then, two strategies for damage detection and localization are also proposed. The first strategy can be considered as an extension of the PSIL method, and it can be applied from output-only data with minimal a-priori information on the masses (i.e. a parameter that quantifies an eventual relative modification of the total mass of the structure before and after damage is the sole parameter to be known a-priori). The second strategy adopts the same damage sensitive features of the first strategy but different damage metrics, and it can be applied from output-only data without any a-priori information on the masses (even in the case in which the masses are varied before and after damage).

The paper is organized as follows. Section 2 is dedicated to the theoretical background: the main steps of both the PSIL method and the PFM technique are presented. In Section 3, the approach proposed for the estimation of proportional modal flexibility-based deflections of building structures from output-only vibration data is firstly presented. Then, the two above-mentioned strategies for damage detection and localization are introduced. Sections 4 and 5 are dedicated to the verification of the proposed approach, which was conducted using both numerical simulations and experimental vibration tests on frame building structures.

2. Theoretical background

2.1. Damage detection and localization in building structures using modal flexibility-based deflections

The main steps of the Positive Shear Inspection Load (PSIL) method [4] for output-only damage detection in building structures are summarized herein (Fig. 1a). The method has been formulated for structures that can be modeled as plane shear buildings [4], and it can be applied if horizontal acceleration measurements are available at all the stories (i.e. the structures are instrumented at all the DOFs). Starting from the recorded ambient vibration data, any output-only modal identification technique can be applied to estimate the modal parameters of the structure. Then, the modal flexibility matrix of the building structure is determined, and to perform this operation the mass normalization of the mode shapes can be carried out using an a-priori estimate of the system mass matrix [4] or, alternatively, through the added mass method [21,22]. When considering the first situation, as done in [4], the modal flexibility matrices $\boldsymbol{F}_{r\ n\times n}$ can be assembled using the following equation valid for a generic undamped or classically-damped MDOF structure [23]

$$\boldsymbol{F}_r = \boldsymbol{\Psi}_r\boldsymbol{\Lambda}_r^{-1}(\boldsymbol{\Psi}_r^T\mathbf{M}\boldsymbol{\Psi}_r)^{-1}\boldsymbol{\Psi}_r^T \tag{1}$$

where $\boldsymbol{\Psi}_{r\ n\times r}$ is a matrix that contains arbitrarily-scaled real mode shapes, $\boldsymbol{\Lambda}_{r\ r\times r}$ is a matrix with the square of the natural circular frequencies ω_i^2 on the main diagonal, $\boldsymbol{M}_{n\times n}$ is the mass matrix (diagonal for a shear building), n is the total number of the DOFs of the structure (i.e. the number of the stories for a shear building), and r is the number of the modes included in the calculation with $r \le n$. Then, the modal flexibility-based deflection of the building structure is computed as follows