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Curvature rate approach to the evaluation of the stiffness distribution in plate-like structures

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ABSTRACT

A procedure for identifying the bending stiffness distribution in plate-like structures is presented. The algorithm is based on the correlation between a parameter called curvature increased factor (CIF) and the bending stiffness of the plate, *D*. Accurate correlation can be achieved only by considering the effect of the redistribution of internal forces and moments due to the damage on the curvature distribution. In order to achieve this goal, the study offers an iterative procedure, which eliminates the effect of the moment redistribution from the CIF and eventually correlates accurately between CIF and D. The curvature rate is evaluated from the displacement mode shape using a 2D smoothing technique. The procedure takes into account the presence of random errors and the limited number of measured nodes. The procedure's effectiveness, reliability, and range of applicability are demonstrated using numerical examples.

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1. Introduction

Vibration-based non-destructive damage identification assessment has been attracting growing interest over the past two decades. The basic idea of the non-destructive global dynamic methods is that the modal parameters (natural frequencies, mode shapes, and modal damping) are functions of the physical properties of the structure (mass, stiffness, and boundary conditions), so that changes in the latter make for changes in the former, i.e. in the modal properties.

Significant research works have been conducted and reported on in this field, and hence it would be almost impossible to cite them all here. Many such works focused on one-way (unidirectional, 1D) structures, such as beams, frames, and truss structures. Significantly fewer studies have been conducted and reported on regarding two-dimensional (2D) plate-like structures.

Since damage typically consists of local phenomena, its effect on the lower displacement mode shape in the global measured response of the structure may be insignificant. Curvature rate and strain mode shapes, on the other hand, are more sensitive to local damage [1] and so they were used extensively to locate damage primarily in continuous 1D structures. In order to apply this concept to plate-like structures, the accurate estimation of the strain or curvature mode shape should be considered, as well as the effect of the redistribution of internal forces and moments on the curvature distribution.

Cornwell et al. [2] expanded the strain energy method, originally developed for beam-like structures, to plate-like structures. This method is based on the assumption that damage is located primarily at a single sub-region in which the strain energy changes, while the fractional energy in undamaged sub-regions remains relatively constant. The curvature is

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evaluated using the finite difference method, assuming that the modal displacements are given at each node in the structural model. Lee and Shin [3] proposed a damage identification algorithm based on modal data from the intact (or undamaged) structure and on the frequency response function (FRF) data (instead of the modal data) from the damaged structure. Chen and Bicanic [4] presented a damage identification procedure for continuous structures that uses natural frequencies and mode shapes in the context of an optimization technique. These researchers handled the problem of incomplete modal information by expanding the modal information of the damaged plate using the Gauss–Newton Least Squares method. Based on the local characteristic of the strain mode shape, Li et al. [5] proposed a strain mode technique for determining damage parameters of plate structures, and evaluates the coefficient of the strain mode shape using the Rayleigh–Ritz approach. Yam at el. [6] investigated the sensitivity of static and dynamic parameters to damage in plate structures. The static analysis was based on the out-of-plane deflection and its slope and curvature, based on an FEM model. In the dynamic analyses, the damaged parameters were correlated to the curvature mode shape and to the strain frequency response function. Choi [7] extended and improved Choi and Stubb's method [8], and presented two improved methods: one using the variation in the compliance distortion and the other using the variation in the modal strain energy. Choi et al. [9] also proposed an identification procedure based on variations in the distribution of the plate's modal compliance due to damage. Wu and Law [10] proposed a damage identification procedure based on changes in the uniform load surface. Curvature rates were evaluated using three methods: The central difference method, the Chebyshev polynomial approximation, and the gapped smoothing technique, which requires only modal information from the damaged state. Wu and Law [11] also studied the sensitivity of two dimensional curvatures of a uniform load surface to the stiffness parameter in each element, and applied their method to the identification of cracks in thin plates using an anisotropic damage model [12]. Since the gapped smoothing method is based on modal information from the damaged state only, Yoon et al. [13] extended it to 2D plate-like structures. Kannappan and Shankar [14] proposed an identification procedure based on variations in natural frequencies and strain energy, which can be calculated from discrete values of the deflection mode shapes. Bayissa and Haritos [15] derived the spectral strain energy from the moment and the power spectral densities of the curvature responses, and later on [16] extended their method and proposed the mean square value of the bending moment response's power spectral density as a damage indicator.

All the studies surveyed above have demonstrated some level of success. However, there is no existing publication on a systematic and quantitative procedure that overcomes a series of fundamental obstacles in the measurements and their translation into structural quantities. Among these obstacles the critical are the following ones: (a) the measurement uncertainty and the inadequate test data, such as consideration to realistic random error of the simulated modal information; (b) the limited number of mode shapes and the limited number of measured points along the structure; and (c) the case where the availability of the modal information is limited to the damaged structure. These three issues must be considered in the identification procedure, especially when the measured data (usually displacement) is translated to curvature or strain distribution. For the case of statically indeterminate structure, such as plate-like structures, additional critical obstacle needs to be overcome: (d) the consideration to the redistribution of the internal forces and moments due to damage. This issue must be considered in order to obtain an accurate correlation between the measured quantities and the structural damage. All these issues have not been fully and systematically addressed in the documentary found in the open literature and surveyed above, and are faced in this paper. The presence of measurement noise has been addressed by few studies, Ref. [3,9–11,15], some of them (Refs. [3,10,11,15]) also considered the limited number of measurements points. Several studies (Refs. [4,16]) considered the limited number of measurements points but used analytical mode shapes. Nevertheless all of them used tens of measured points in the reduced model. Such a large number of sensors is somewhat less practical when realistic experiments are considered. The limited number of mode shapes dictated by assuming that only several lower mode shapes are available in the identification procedure has been investigated in Refs. [4,6,7,9,11,14]. Consideration that the modal information is available only from the damaged structure has been reported only in Refs. [5,13], however both works did not consider other issues such as the uncertainty of the measurements and the limited modal information. It is seen that none of the above studies considered all fourth obstacles at once, and practically the fourth one – consideration to the redistribution of the internal forces and moments due to damage.

The objective of this paper is to face the above challenges for plate like structures. First, by using a new post-processing procedure – a 2D optimal smoothing technique, which evaluates the curvature rate from a given set of modal displacements, assuming that the dynamic response is acquired by placing sensors in a rectangular grid. Opposed to the works surveyed above (Refs. [2,4–7,13,14]), this post-processing technique takes into consideration the inherent limitation of the measured data, namely the limited number and location of the measured modal displacements and the possibility of noises and measurement inaccuracies. Note that Refs. [3,10,11,15] did consider these issues, however all of them used tens of modal measurements in the identification procedure. The procedure developed here aims to use a much smaller numbers of sensors as input.

The study proposes using the curvature increased factor (CIF) as a sensitive and effective indicator for the bending stiffness distribution of two-dimensional plate-like structures. Specifically, the CIF is derived from the change of the curvature of a specific section and is divided by the curvature of the same section in the undamaged state. The concept of the CIF was used previously in Ref. [17] for static measurement of 1D reinforced concrete beam using distributed fiber optic measurement. In Ref. [17] the CIF was defined as an integrative smoothed 1D parameter whereas here the CIF is evaluated for each direction directly from the modal curvature. In statically determinate structures, the CIF is related directly to the bending stiffness of a specific section. However, for statically indeterminate structures Ref. [18], such as plate-like structures,

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