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Damage assessment in a sandwich panel based on full-field vibration measurements

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Different studies have demonstrated that vibration characteristics are sensitive to debonding in composite structures. Nevertheless, one of the main restrictions of vibration measurements is the number of degrees of freedom that can be acquired simultaneously, which restricts the size of the damage that can be identified. Recent studies have shown that it is possible to use high-speed three-dimensional (3-D) digital image correlation (DIC) techniques for full-field vibration measurements. With this technique, it is possible to take measurements at thousands of points on the surface of a structure with a single snapshot. The present article investigates the application of full-field vibration measurements in the debonding assessment of an aluminium honeycomb sandwich panel. Experimental data from an aluminium honeycomb panel containing different damage scenarios is acquired by a high-speed 3-D DIC system; four methodologies to compute damage indices are evaluated: mode shape curvatures, uniform load surface, modal strain energy and gapped smoothing.

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1. Introduction

Sandwich structures typically consist of thin face sheets or skins and a lightweight thicker core sandwiched between the skins to obtain a structure with superior bending stiffness. The concept of sandwich structures is common in nature; for example, the branches of a tree or the bones in skeletons are examples of sandwich structures with foam-like core materials. The high stiffness and strength at a minimum weight make sandwich structures attractive for use in applications where weight saving is critical. Consequently, in recent years, the applications of sandwich structures have been rapidly increasing and range from satellites, spacecraft, aircraft, ships, automobiles, rail cars, wind energy systems and bridge construction [1].

Nevertheless, despite their advantages, sandwich structures can experience imperfect bonding or debonding between the skins and core because of manufacturing defects or impact loads. Debonding in a sandwich structure may severely degrade its mechanical properties, which can cause catastrophic failure of the overall structure. Therefore, even though making the structure as light as possible without sacrificing strength is a fundamental requirement in aircraft design, the application of sandwich structures remains limited to secondary (non-critical) components [2].

To improve both safety and functionality of these systems, structural damage assessment methodologies can be implemented. The purpose of these methodologies is to detect and characterize damage at the earliest possible stage and to estimate how much time remains before maintenance is required, the structure fails, or the structure becomes no longer usable.

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Damage assessment has a tremendous potential for safety and/or economic benefits; it reduces maintenance costs and increases structural safety and reliability.

Non-destructive inspection (NDI) techniques are frequently used to detect damage in sandwich structures. Some of the techniques used for in-service inspections are visual, tap testing, mechanical impedance, shearography, ultrasonic and thermography inspections [3–5]. Heida and Platenkamp [5] from the Netherlands Aerospace Centre (NLR) investigated different NDI techniques for in-service evaluation of composite aerospace structures. Commercially available NDI equipment was tested to identify impact, delamination and disbond damage in three composite aerospace structures. The results showed that only ultrasonic inspection was able to detect and quantify disbond damage, but the limitations were its small field of view and the requirement to use a couplant. A similar conclusion was reached by Hsu [4] in a large-scale experiment organized by the Sandia Laboratories to evaluate different NDI techniques for honeycomb sandwich structures; it was found that air-coupled ultrasound was the best technique among those investigated. Nevertheless, regardless of the number of NDI techniques available to inspect sandwich panels, some challenges remain [6]:

- the detection of defects/damage in thick sandwich structures remains limited,
- it is generally not possible to detect far-side defects with one-sided inspection methods,
- during inspections, it may be difficult to distinguish between damage and hidden features of the structure, and
- there is insufficient knowledge about the sensitivity and reliability of NDI when applied to sandwich composites.

In addition, NDI techniques are time-consuming, need prior knowledge of the damage location and require access to the portion of the structure being inspected, which can be impractical in some cases.

1.1. Vibration-based damage assessment

A global technique called vibration-based damage assessment has been expanding rapidly in recent years [7]. The basic idea is that vibrational characteristics such as natural frequencies, mode shapes, damping and frequency response functions are functions of the physical properties of a structure. Thus, changes to the material and/or its geometric properties owing to damage will cause detectable changes in its vibrational characteristics.

Different studies have demonstrated that vibrational characteristics are sensitive to debonding in sandwich structures. The first numerical investigation was performed by Jiang et al. [8] who modelled debonded honeycomb structures with a commercial finite element software. Their results showed that natural frequencies are sensitive indicators to the presence of debonding. The finite-element method was also used by Burlayenko et al. [9,10] to study the influence of skin/core debonding on the vibrations of honeycomb panels, concluding that the size of the debonded zone reduces the natural frequencies and creates a discontinuity in the mode shapes. Similar conclusions were found in the experimental and theoretical/numerical investigations of Kim and Hwang [11] and Lou et al. [12], where it was concluded that natural frequencies decrease because of a loss of stiffness caused by local damage and that vibration modes show local deformation in the damaged region. On the other hand, the experimental study performed by Shahdin et al. [13] showed that the damping ratio is a more sensitive parameter for damage detection than the natural frequencies, although it is much harder to estimate. Meruane at al [14,15]. demonstrated that it is possible to identify debonding in honeycomb sandwich panels using the changes in natural frequencies and mode shapes.

Vibration-based damage assessment methods are classified as model-based or non-model based. Model-based methods are particularly useful for predicting system response to new loading conditions and/or new system configurations. Nevertheless, the performance of a model-based damage assessment algorithm relies on the quality of the structure's numerical model. If the numerical model is not accurate, it becomes difficult to distinguish between numerical errors and actual changes owing to damage. On the hand, non-model-based methods detect damage by comparing the measurements from the damaged and undamaged structures with no need of a numerical model.

Many response parameters have been used in non-model damage assessment and include natural frequencies [16], spatial correlation of mode shapes [17], mode shape curvatures [18], modal flexibility and its derivatives [19,20] and modal strain energy (MSE) [21]. Most have been developed for one-dimensional (1-D) structures such as beams, frames, and truss structures, while only a few studies have investigated damage assessment of two-dimensional (2-D) (plate-like) structures. Cornwell et al. [22] were the first to use strain energy in a damage localization method for plate-like structures. The damage index was computed using the strain energy of a plate in the damaged and undamaged states. The method was validated using numerical simulations and with experimental data of an aluminium plate with saw cuts. Lin et al. [23] investigated the identification of damage in plate-like structures using a strain mode technique derived from the Rayleigh–Ritz approach. The authors proposed two damage indices, the bending moment index and the residual strain mode shape index. Their results showed that the bending moment is more sensitive than the strain mode shape, but the detection depends on the damage location, whereas the residual strain mode shape detects damage accurately independent of the location. Wu and Law [24] developed a damage localization method for plate structures based on changes in the uniform load-surface (ULS) curvature. ULS is defined as the deflection vector of a structure under a uniform load. The method was validated with numerical data of different plates, and damage was introduced as a localized stiffness reduction. In a later work, Wu and Law [25] proposed a model-based damage assessment algorithm that also used changes in the ULS curvature. The inverse problem was modelled

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