Composite Structures 108 (2014) 267–276

Contents lists available at ScienceDirect

Composite Structures

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

Impact damage identification in composite laminates using vibration testing

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ARTICLE INFO

Article history:
Available online 25 September 2013

Keywords:
Composite laminates
Damage identification
Low-velocity impact
Non-destructive evaluation
Experimental modal analysis
Compression after impact

ABSTRACT

Due to the problems arising from impact damage in composite laminates, there is a need to develop fast, accurate, cost-effective and non-destructive testing methods to identify this type of damage at an early stage and thus enhance the service life of composite structures. This paper presents the results of an extensive experimental campaign conducted to investigate the feasibility of using vibration-based methods to identify damages sustained by composite laminates due to low-velocity impacts. The experimental programme included an evaluation of impact damage resistance and tolerance according to ASTM test methods, characterisation of induced damage by ultrasonic testing and quantification of the effects on the vibration response. The damage identification involved the detection, localisation, quantification and estimation of the remaining bearing capacity. Four damage indicators based on modal parameters were assessed by comparing pristine and damaged states. The results allowed for conclusions to be drawn regarding the capability and suitability of each damage indicator, including its ability to detect impact-induced damage, its precision in determining the location of damage, its sensitivity regarding damage extent and pertinent correlations with residual bearing capacity.

1. Introduction

Laminated composite materials offer engineers advantages that are especially appealing for structural applications; however, underlying problems arising from impact damage have greatly hindered their widespread application, particularly in structures prone to impacts during service. The susceptibility of laminated composites to impact damage is due to the material's lack of plastic deformation, low interlaminar strength and laminated construction to reduce the anisotropic nature of the plies Reid and Zho [1].

The damage induced by a low-velocity impact is a mixture of three main failure modes: matrix cracking, delamination and fibre breakage, among which delamination the most severe because it may severely degrade the stiffness and strength of composite structures. The situation has been proved critical when the damaged surface of an impact point is not representative of the internal damage induced, commonly referred to as barely visible impact damage (BVID), leading to a collapse under unacceptable compressive load levels Hodgkinson [2]. For these reasons, the development of fast, accurate, cost-effective and non-destructive testing (NDT) methods is required to identify this type of damage at an early stage and thus enhance the service life of composite structures.

Over the years, due to the significance of this problem, several non-destructive damage assessment techniques have been used for impact damage detection in composites, including acoustic emission, radiography, shearography, thermography and ultrasonics, whose development continue to date Aymerich and Meili [3], Schilling et al. [4], Růžek et al. [5], De Rosa et al. [6], Hung et al. [7], De Angelis et al. [8], Goidescu et al. [9], and Bull et al. [10]. An overview of the advantages and disadvantages of some of the currently available NDT methods are presented in Garnier et al. [11]. All of these NDT methods have allowed for considerable progress in the structural integrity assessment of composite components. However, almost all of these techniques require that the vicinity of the damage site be known in advance and that the damaged region of the structure being inspected is readily accessible. It should be noted that some of the techniques are also impractical for applications under in-service conditions, thus requiring withdrawing the component or structure being assessed from service Doebling et al. [12]. In addition, these techniques provide local information and no indication of residual structural performance.

Over the past three decades, numerous researchers have devoted their efforts to developing so-called vibration-based NDT methods Doebling et al. [12, Sohn et al. [13], Carden [14], Yan

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http://dx.doi.org/10.1016/j.compstruct.2013.09.025

et al. [15], Fan and Qiao [16] and Kim et al. [17]. The principle underlying these methods is that a vibration response depends on the physical properties of a structure (mass, damping and stiffness); therefore, changes that occur in physical properties due to damage can result in detectable variations in the vibration response, which can serve as an indicator of structural integrity Doebling et al. [12]. A considerable number of contributions in the field of vibration-based NDT have been made – Doebling et al. [12], Sohn et al. [13], Carden [14], Yan et al. [15], Fan and Qiao [16]. These methods can be broadly classified into two approaches: model-based methods, i.e., methods that require numerical models, and response-based methods, i.e., methods that use only experimental data to identify damage. The second approach includes methods based on the time domain, frequency domain and modal domain, the last of which has received the most attention Fan and Qiao [16], Kim et al. [17], Radzieński et al. [18]. With respect to this group, one can find in the literature modal parameter-based damage identification methods, such as natural frequency-based methods, mode shape-based methods and curvature mode shape-based methods, among others. Another type of damage-identification method common in the open literature Carden [14] defines four levels of damage identification: determination of the presence of damage in a structure (Level 1), determination of the geometric location of damage (Level 2), quantification of the severity of damage (Level 3) and prediction of the remaining service life of a structure (Level 4). Detailed reviews on vibration-based NDT methods for structural damage identification can be found in Doebling et al. [12], Sohn et al. [13], Carden [14], Yan et al. [15], Fan and Qiao [16].

The concept of using vibration-based NDT as the basis for damage identification in laminated composites is not a new one. Experimental evidence has shown that the presence of delamination changes the strength as well as the vibration response of composite structures Zou et al. [19] and Della and Shu [20]. Using this approach, numerous researchers have reported analytical, numerical and experimental results regarding the effect of delamination on the vibrational response of laminated composites Zou et al. [19], Della and Shu [20], Polimeno and Meo [21], Aymerich and Staszewski [22], Ooijevaar et al. [23], Wei et al. [24], Kessler et al. [25], Yam [26], Frieden et al. [27], Fan and Qiao [28], Niemann et al. [29], Araújo dos Santos et al. [30] and Frieden et al. [31]. Due to the complexity of the physical phenomena involved, the analytical formulations proposed are restricted to particular cases Della and Shu [20]. On the other hand, the effectiveness of the model-based methods is dependent on the accuracy of the numerical model used. This fact is of utmost importance in impact damage detection in laminated composites because induced damage is a complex mixture of multiple failure modes interacting with each other Pérez et al. [32].

Several response-based methods have been proposed in the literature as alternatives or supplements to the model-based methods Polimeno and Meo [21], Aymerich and Staszewski [22], Ooijevaar et al. [23]. To date, the majority of these studies have focused on measuring the vibration response before and after damaging a composite, analysing the data in both the frequency and modal domains. These studies provide a basic understanding of the influence of damage -especially delaminations- on vibration response and seek to demonstrate the feasibility of using measurable changes in vibrational characteristics to identify damage in laminated composites. However, the sensitivity and measurability of shifts in vibration response due to induced damage is a point of controversy among many researchers Kim et al. [17], Wei et al. [24] and Kessler et al. [25]. It is also notable that a large number of experimental works are based on the analysis of the influence of an isolated, artificially induced damage Ooijevaar et al. [23], Wei et al. [24], Kessler et al. [25], Yam [26]. It is common practice to induce delamination by inserting a polyimide film before consolidating a composite specimen in an autoclave. By doing so, the influence of other failure modes induced during the impact event, such as fibre breakage, is not considered. Despite the extensive studies of vibration analysis on damaged laminated composites, the literature reviewed concentrates primarily on Levels 1 and 2 of damage identification Polimeno and Meo [21], Aymerich and Staszewski [22], Ooijevaar et al. [23], Wei et al. [24], Kessler et al. [25], Frieden et al. [27], Fan and Qiao [28] and Niemann et al. [29], i.e., detection and localisation, respectively, whereas the quantification of damage and estimation of the residual bearing capacity are in a relatively immature stage.

The aim of the present study was to investigate the feasibility of using vibration-based methods to identify damages on composite laminates resulting from low-velocity impacts. In contrast with previous publications addressing the detection of damage in composites, the present work focussed on real damage induced by low-velocity impacts and sought to address the four levels of identification mentioned previously. This paper mainly presents the results of an extensive experimental campaign carried out on a set of 48 carbon fibre-reinforced composite laminated specimens. Composite coupons were manufactured, and the impact damage resistance and tolerance were evaluated using ASTM standard test methods. The effect of impact-induced damage on the vibration response was analysed in terms of four damage indicators computed from modal parameters. The results allowed for conclusions to be drawn regarding the capability and suitability of each damage indicator presented to identify impact damage.

In the following section, the mechanical background of the experimental modal analysis performed for modal parameter estimation and the damage indicators that will be assessed are briefly presented. Section three discusses the methodology and details of the experimental test procedures. The results are discussed in section four. Finally, the conclusions of the study are presented in the last section.

2. Theoretical background

2.1. Identification of modal parameters

The proposed methods for damage identification examine modal domain data through modal analysis, in which time domain data are mapped onto the frequency domain. The modal parameters are then extracted from the so-called frequency response functions (FRFs). The structural response $\mathbf{X}(\omega)$ is directly related to the system forcing function $\mathbf{F}(\omega)$ through the quantity $\mathbf{H}(\omega)$ as follows:

$$\mathbf{H}(\omega) = \frac{\mathbf{X}(\omega)}{\mathbf{F}(\omega)} \tag{1}$$

where $\mathbf{X}(\omega)$ and $\mathbf{F}(\omega)$ are the n-vectors of Fourier transformed responses and force inputs, respectively, ω is the frequency variable and $\mathbf{H}(\omega)$ is the FRF $n \times n$ matrix, where n is the number of test degrees-of-freedom (DoFs) of the structure. To estimate the modal parameters from FRF measurements, a curve-fitting method is used. Assuming that stationarity, linearity and reciprocity are valid for a test structure, the FRF matrix can be analytically represented in terms of the modal parameters of the structure.[1] Each FRF matrix component can be written in partial fraction form as follows:

$$H(\omega)_{pq} = \sum_{i=1}^{m} \left(\frac{Q_i \phi_i \phi_i^t}{j\omega - \lambda_i} + \frac{Q_i^* \phi_i \phi_i^t}{j\omega - \lambda_i^*} \right) \tag{2}$$

[1] The formulations used are thoroughly described in references Piersol and Paez [33] and will not be elaborated here except for the main aspects, which are briefly described subsequently.