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Micro-mechanical approach for the vibration analysis of CFRP laminates under impact-induced damage

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Abstract

This paper deals with modeling the effect of low-velocity impact damage upon the vibration response of CFRP laminates through a micro-mechanical description of the induced internal damage. The serial-parallel (SP) continuum approach is used to estimate the map of induced internal damage by considering the micro-structural interaction between the composite constituents and modifying their constitutive performance through a continuum damage formulation. An eigenvalue analysis is then done to determine the modal response of impacted laminates. The validity of the modeling approach to successfully reproduce the vibration response of impacted coupons is assessed through a comparison with an experimental test series conducted on a set of 48 CFRP laminated coupons. The results confirm the ability of the described approach in comparison to competing ones used to reproduce the experimentally observed behaviour.

Keywords: B. Impact behaviour, B. Vibration, C. Micro-mechanics, C. Finite element analysis (FEA)

1. Introduction

Composite laminates are being extensively used in advanced structural applications because of their appealing advantages when being compared to traditional structural materials. Nevertheless, these materials have also shown a susceptibility to impact damage due to lack of plastic deformation, low interlaminar strength and the laminated construction to reduce the anisotropic nature of the plies [1]. Experimental studies consistently indicate that impact-induced damage combines three main failure modes: matrix cracking, delamination and fibre breakage, among which delamination is the most severe because it may severely degrade the stiffness and strength of the composite laminate, thus compromising the residual bearing capacity of the structural component and causing a collapse under unacceptable compressive load levels [2]. For these reasons, over the years, a massive amount of research activity has been devoted to developing non-destructive evaluation techniques to identify this type of damage at an early stage, as well as numerical methodologies that can quantitatively predict the performance and durability of composite structures under impact events.

Among different non-destructive experimental approaches, the so-called vibration-based Non-Destructive Testing (NDT) methods have been shown to be useful tools for damage identification in laminated composites, since, in contrast to other assessment methods, these techniques provide global information, does not necessarily require that the vicinity of the damage site to be known in advance and can be employed under in-service conditions. The overall principle underlying these methods is that vibration response depends on the physical properties of the structure (mass, damping and stiffness); therefore, changes that occur in physical properties due to damage can result in detectable variations in the response, which can serve as an indicator of structural integrity [3]. Based on this phenomenon, a considerable number of contributions in the field have appeared, e.g. [4–14]. These methods can be broadly classified into two approaches: response-based methods that use only experimental data to identify damage, and model-based methods that require numerical models. The experimental approaches have mostly focused on measuring the vibration response before and after damaging the composite, analysing the data in both the frequency and modal domains. On the other hand, the effectiveness of the model-based methods is highly dependent on the accuracy of the numerical model used. This fact is of utmost importance when applied to impact identification in composite laminates because, as stated before, induced damage is a complex mixture of multiple failure modes interacting with each other [15].

The complexity of the failure modeling in composite structures arises from the heterogeneous microstructure of composite materials. This fact represents a departure from the way that conventional materials are modeled and consequently requires unconventional approaches to dealing with them. The different entities involved, i.e. component materials, ply and laminate, span a spectra of length scales that clearly dictates the analysis approach. Over the years, due to the increased computing

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