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Interaction of inter- and intralaminar damage in scaled quasi-static indentation tests: Part 1 – Experiments

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ABSTRACT

The evaluation of the predictive capabilities of models proposed in the literature for laminated composites calls for experimental testing providing detailed results of both the global and local response in terms of degradation mechanisms, such as delamination, transverse cracking and fibre breaking. Scaled tests, in which one or more characteristic dimensions are modified, allow variation of the different mechanisms. In this paper, a unique series of scaled indentation tests are performed on quasi-isotropic composite plates, and a detailed assessment of the damage evolution is carried out through non-destructive techniques, including ultrasonic C-scan and X-ray Computed Tomography (CT). Four different configurations are tested, presenting changes in both in-plane dimensions and fully three dimensional scaled cases. The latter are performed with sublaminate and ply scaling to show the effect of ply thickness on response. A detailed set of results for both global behaviour and the damage evolution is provided to demonstrate the mechanisms controlling behaviour and to create a reference set of data for model validation. The scaling effects observed are also discussed making use of simplified analytical models.

1. Introduction

In the last decade, the increased use of laminated composites in advanced structural applications has required the development of a wide variety of modelling strategies for the description of composite materials and structures. The validation of the predictive capabilities of such models for damage becomes a real challenge, which needs to be addressed if these strategies are to be introduced in industrial practice.

In order to be used for virtual structural testing, that is for numerical simulations dedicated to the design of laminated structures, a model must be able a priori to predict structural failures in a wide range of complex loading cases. A first task is to define the degradation mechanisms that are involved. Structural failure originates from two main mechanisms: fibres breaking within the plies or delamination between plies. However, other subcritical degradations may play an important role in the final failure. In particular, intralaminar cracks, generally appearing at relatively low stress levels, have been shown to act as initiators for delamination [1–3] or to reduce stress concentrations associated with holes and notches to delay fibre failure [4]. Depending on the relative importance of each mechanism, the final failure scenario and the associated load may change significantly. Thus, tests chosen for validation of the models should highlight the different interactions between the following main degradation mechanisms: intralaminar cracks, delamination and fibre fracture.

A simple way of disrupting the failure sequence between these elementary degradation mechanisms, and thus of exploring a wide variety of failure scenarios with little or no change in the experimental setup, is the use of scaled tests. The principle is to perform a series of experiments using the same setup but varying the characteristic geometrical parameters, such as ply thickness or in-plane dimensions of the sample as well as the dimensions of the experimental apparatus. As the degradation mechanisms do not depend in the same way on these characteristic parameters, a modification can change the failure scenario for the same experimental setup.

This idea has already been applied, for example, to open-hole tensile tests on quasi-isotropic laminates [5]. A wide range of laminates made of the same material and stacking sequences was tested. The tests have shown that a simple change in the ply thickness led to a dramatic difference in the failure scenario, from fibre-dominated to delamination-dominated failure. Furthermore, the variation of strength with in-plane dimensions followed an opposite trend in the case of each failure scenario. This

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experimental work was used both by the authors and by other research groups [6–10] as a basis for validation of different proposed models.

The objective of this work is to apply the idea of scaled tests e.g. [11,12] to a quasi-static indentation test configuration with close similarities to the low-velocity impact test of the ASTM D7136 standard [13] in terms of test configurations and damage mechanisms involved. Many works on low-velocity impact and static indentation test presented in the literature generally focus on a single simple geometry and do not emphasise the acquisition of comprehensive results in terms of damage evolution prior to final failure. In this paper, the authors provide extensive results for scaled indentation tests which highlight the fundamental controlling mechanisms. These are then used to validate numerical models in part 2 of this study. The experiments are also documented in sufficient detail in order to provide a reference for model validation for other researchers.

In [14], low-velocity impacts are defined as impacts in which the contact time between the impactor and the plate is long enough to allow all wave reflections from the boundaries. The relation between deflection and impact load approach those of a purely static loading case [15]. In terms of validation, however, low-velocity impact tests do not allow one to observe the succession and evolution of the degradation mechanisms within the plate, since the plate can only be inspected upon the completion of impact testing. For this reason, a number of researchers have turned their attention to static indentation tests. These tests have been demonstrated to give similar global behaviour and damage states as low-velocity impact tests [16–19]. Since they are static tests, they can be easily interrupted at different stages to observe the damage evolution within the plate. Fig. 1 shows X-ray images comparing two identical composite laminates having a similar projected delamination area induced by quasi-static indentation and dynamic low-velocity impact. No obvious difference can be detected in terms of damage morphology.

Extensive studies can be found in the literature involving experimental results for low-velocity impact or static indentation tests on laminated composites. A few of these works are reviewed here, to illustrate the existing results and to motivate the proposed experiments in this work. In the experiments described in the literature, the plate is often a circular or a rectangular shape; it is either clamped between two fixtures or simply supported on a steel window (see Section 2.1 for more details). In most cases, quasi-isotropic lay-ups are considered [19–22], while some works deal with cross-ply $[0_n/90_m]_S$ or $[0_n/45_m]_S$ stacking sequences [23,24]. The results reported are varied but can be classified into two main categories. On one hand, some papers explore the scaling effect as defined before [22,25,26], but in this case exhaustive experimental data on all the degradation mechanisms are not given, with results generally being limited to the global responses or overall damage extent [24,27]. On the other hand, there are studies focusing on a specific feature of the response, such as the delamination threshold [28,29] or the local indentation effect

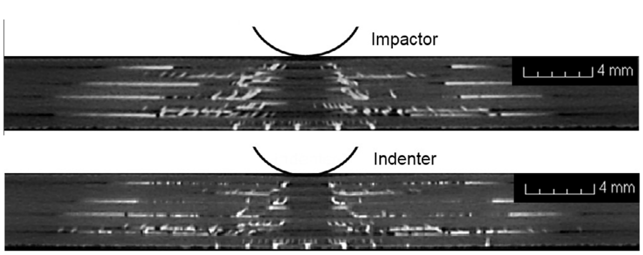

Fig. 1. X-ray images of cross-section of two identical Ps laminates (Ply-blocked scaling) comparing damage extent caused by dynamic low-velocity impact (upper) and quasi-static indentation (lower).

[21,30]. However, papers reporting complete results in terms of global response and damage evolution together are rare, and mostly concentrate on a single lay-up and material configuration. Since both the experimental parameters and the available information on the plate response vary largely from one paper to another, it is difficult to draw conclusions on the scaling effects in these types of test.

As shown in Fig. 2, in terms of global response in most of the described tests, the plate experiences three loading stages during transverse out-of-plane loading. The response involves different damage mechanisms, and the transition of each stage is associated with one or multiple significant load drops. At the beginning, Stage I shows an elastic response, however nonlinear behaviour appears, which can be attributed to local indentation effects, matrix cracking and geometrical nonlinearity. When the load reaches a critical value F_C indicating delamination onset, a large load drop occurs, followed by the response with degraded global stiffness ($K_{II} < K_I$) in Stage II. With propagation of the underlying delamination in Stage II, the degree of nonlinearity increases, with multiple delaminations, and eventually leads to fibre failure at the bottom and top of the specimen as the load increases in Stage III [19,24,27,30], after which complete penetration will take place, which was not considered in this study.

In this work, the objective is to obtain a detailed description of the evolution of the damage during static indentation. Scaled static indentation tests are performed and non-destructive inspection techniques are used to evaluate the damage scenarios within the plates at different load levels.

2. Experimental method

2.1. Definition of the test cases

Different configurations are used in the literature for low-velocity impact and quasi-static indentation tests, ranging from circular to rectangular specimens, which are either fully clamped or simply supported [31,32]. In the aerospace industry, an accepted test configuration is a rectangular 150 × 100 mm specimen, simply supported on a 125 × 75 mm window with four rubber-tipped clamps, as per the ASTM D7136 standard [13]. This configuration is used and scaled in this work, and a schematic of it is presented in Fig. 3.

Similarly to the open-hole tensile tests studied in [1], in this paper the focus is on two types of scaling: in-plane scaling and thickness scaling. In order to keep reasonably-sized specimens, the original 150 × 100 mm plate, support window and indenter are downscaled by a factor of two to obtain the Reference

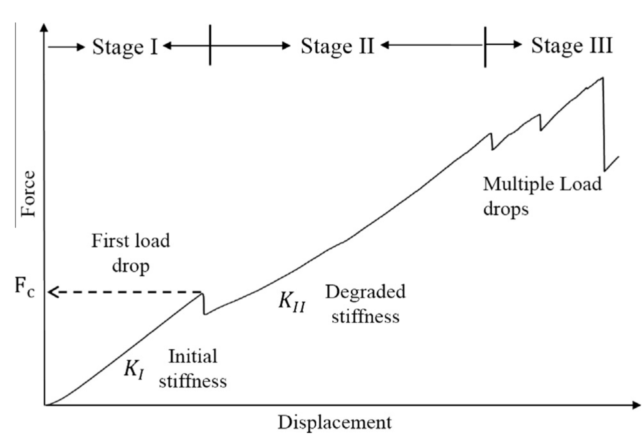

Fig. 2. Schematic of load–displacement curve of typical quasi-static indentation test on quasi-isotropic composite plate.