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Barely visible impact damage in scaled composite laminates: Experiments and numerical simulations

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ABSTRACT

This paper investigates the effect of size and complexity of composite structures on the formation of low-velocity impact damage via experimental tests and numerical modelling. The ASTM standard low-velocity impact test and a scaled-up version of the test were conducted. A novel numerical technique is presented that combines 3D solid and thin 2D shell elements for modelling different domains to achieve a high level of fidelity locally under the impact location, whilst achieving good computational efficiency for large structures. Together with the experimental studies at the different scales, the predictive capability of the numerical models was systematically validated. This modelling method demonstrated an advanced computational efficiency without compromising predictive accuracy. The models are applied to a case study of low-velocity impact of a large-scale stringer-stiffened panel, showing this modelling approach to be suitable for predicating low-velocity impact damage and structural response of laminated composites over a range of sizes and complexities.

1. Introduction

Polymer matrix composite materials are being widely and increasingly used in aerospace structures. Despite their superior properties, such as high specific stiffness and strength, over conventional metal alloys, they are susceptible to low-velocity impact, especially for laminated carbon fibre epoxy composites. Different to isotropic materials, laminated composites under transverse loadings easily result in Barely Visible Impact Damage (BVID), the extent of which is not clearly visible from the surface but causes debilitating internal damage. BVID can be caused by runway debris during aircraft take-off and landing or by dropped tools during manufacturing. If the impact velocity is as low as the case of the latter scenario, impact damage is usually dominated by the resin or matrix properties, without the fibre failure. Matrix cracking occurs as the first damage mode at intra-ply locations due to intralaminar shear and tension and acts as a precursor to delamination. Usually driven by interlaminar shear, delaminations occur between plies and are prone to propagate under in-plane compressive loading, which could eventually lead to catastrophic failure of the structure. Delamination is therefore one of the most critical factors limiting design. As laminated composites are used in structures at various locations, the impact damage mechanisms and extent of which, in relation to different size and complexity of the boundary conditions of the structures, is not able to be accurately quantified through the commonly used standard small-coupon experiments (e.g. ASTM-D7136, Boeing BSS-7260, Airbus AITM-1.0010, etc.). It is important to understand the low-velocity impact damage behaviour of composites under the different boundary conditions resulting from such structural applications. This is largely approached by expensive testing regimes, but accurate high-fidelity numerical modelling has a role to play in understanding the various scales and complexities, which could significantly reduce cost and time [1].

Numerous studies in the literature have focused on modelling standard impact events and predicting impact damage using Finite Element Analysis (FEA). By combining Continuum Damage Mechanics (CDM) at the ply level and Cohesive Zone Modelling (CZM) at interlaminar regions, the degradation behaviour of plies and delaminations induced by low-velocity impact of laminated composites can be captured [2–11]. Adopting CZM only at both intra- and interlaminar levels are also often found in the literature, especially for modelling the interactions between matrix cracks and delaminations of laminated composite under tension, open-hole tension, notched tension and transverse loading [12–20], where damage and degradation within the plies is modelled by cohesive elements placed along the fibre directions, instead of using CDM approach. The full CZM method has been applied to previous studies of laminated composite under static indentation [14,21] and is here implemented further in a dynamic impact environment to investigate the

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robustness of the modelling approaches developed thus far and extend it to large scale structures.

Numerical models with implementation of either CDM or CZM require considerable computational cost for cases where the laminates have complex stacking sequences and when the dynamic effects are not negligible. The high computational cost and long run times make such FEA models less attractive for impact damage analysis for large and complex composite structures. With the difference in numerical efficiency between 3D solid and thin shell elements for modelling composites, finite element techniques combining different element types in different regions of a composite structure become one of the obvious solutions. In cases such as laminates under point loading or with a geometric discontinuity like a pre-crack, the potential damage locations can be approximated or derived from small-coupon tests in advance, allowing regions with and without damage to be modelled separately, with different element types, in order to reduce cost without losing basic accuracy. Even with a single element type, different mesh schemes at different regions lead to significant improvement in efficiency. Riccio et al. [22,23] and Caputo et al. [24,25] used solid elements throughout in a model to capture the low-velocity impact damage of laminated composite; contact was used to tie the fine-mesh detailed local domain and coarse mesh global domain. This application was later developed for predicting impact damage in an all-composite wing-box structure [26], and numerical predictions coincided well with experimental data. Approaches, involving solid-shell coupling techniques or similar, have been investigated by numerous researchers for various applications; for example, a mesh superposition technique developed by Gigliotti and Pinho [27], Sellitto et al. [28,29] for a non-matched mesh coupling techniques, Ledentsov et al. [30] for applications of sheet metal forming simulation, Krueger *et al*[31–34]. in studying composite structures with delaminations, Cho and Kim [35] in investigating bifurcation buckling behaviour of delaminated composites, and Davila and Johnson [36] in predicting compressive strength of dropped-ply laminates. Both computational efficiency and accurate prediction were demonstrated by these studies. Few of the studies in the literature have systematically investigated the effectiveness of global-local modelling approaches for low-velocity impact with fully solid (i.e. accurate but computational heavy) models, combined with experiment results as the structural dimensions and complexity increases.

A high-fidelity numerical modelling strategy, first developed and validated in a previous study on quasi-static indentation [14], is here applied to the case of low-velocity impact. To evaluate the scalability of such modelling techniques for various sizes and boundary conditions of composite structures, impact tests were performed on laminates with two in-plane sizes (i.e. the standard ASTM-D7136 size [26] and a scaled up version of this test). In order to model the larger scale a mesh coupling technique is introduced to combine the accuracy of the solid based high fidelity models, with the structural and computational efficiency of shell elements. This modelling technique was then further applied to a stringer stiffened skin panel as a full structural application example.

2. Specimen preparation and experiments

Low velocity impact (LVI) tests were designed and then carried out using an Instron Dynatup 9250 HV drop-weight impact tower. During impact testing, the impact force and displacement were measured by a single accelerometer inside the tup, and the measured data is automatically processed by a 4 kHz filter of the console software to reduce the noise and oscillations. All laminates tested in this work were manufactured from Hexcel's IM7/8552 unidirectional carbon fibre pre-preg sheet and fabricated by hand lay-up and autoclave. Two laminate stacking sequences were used; single-ply laminates with a $[45°/0°/90°/-45°]_{4S}$ layup and blocked-ply laminates with a $[45°_2/0°_2/90°_2/-45°_2]_{2S}$ layup. These are designated as Sublaminate-scaled (Ss) and Ply-blocked scaled (Ps) laminates, respectively. Both types of laminates have a nominal thickness of ~ 4 mm.

The specimen geometry was based on the ASTM D7136 standard [26]. Baseline specimens that exactly followed the standard were cut to 100 mm × 150 mm for both Ss and Ps laminates and then submitted to low-velocity impact test, with various impact energies. Large-scale (Ls) specimens, using only the Ps stacking sequence, were cut to 200 mm × 300 mm and tested at various impact energies and impact locations. To accommodate the Ls laminate in the standard impact testing equipment, a new supporting structure was designed and manufactured. The opening dimensions of the larger supporting window were directly scaled up, giving an opening of 250 mm × 150 mm, based on double the standard opening (i.e. 125 mm × 75 mm), however the impactor with diameter of 16 mm was used for both test conditions. The testing configurations are listed in Table 1, and Fig. 1 shows the standard and large supporting windows.

In order to be consistent with the previous quasi-static indentation study [14], the impact energies used were controlled to only result in matrix cracks and delaminations, without the occurrence of fibre breakage and perforation. For each post-impact laminate, the projected delamination area was inspected by ultrasonic C-scanning. In addition, X-ray Computed Tomography (CT) scanning was also performed on selected standard specimens.

To investigate the effect of the impact location, and hence boundary conditions, on damage and structural response, central and offset impact tests were conducted on the Ls specimens. Fig. 2 illustrates the configurations of central impact on the standard plates (i.e. the Ps and Ss cases) and the two offset impacts on the Ls plate. Three impact tests were performed on each Ls plate, one at each location, denoted as the central impact (C-Imp), longitudinal direction offset impact (L-Imp) and the width direction offset impact (W-Imp). The impact energies used were 12 J, 5 J and 12 J, respectively. The effect of boundary conditions on damage extent was expected to be significant for the W-Imp case, so the lowest impact energy was used for this case (i.e. 5 J) to avoid interaction between delamination and the edges of the plate. Impact locations in Ls plates were designed to be sufficiently far apart so as to avoid interactions between secondary and pre-existing impact damage.

3. Modelling techniques

3.1. High-fidelity solid (3D) model

The high-fidelity 3D models used in this study were similar to those developed in the previous quasi-static indentation study [14], in that the same composite laminate model and boundary conditions were used, but here the load was applied dynamically. FE models

Table 1
Configurations of the standard (Ps and Ss cases) and large laminates tested and size of the support openings.

Specimen		Specimen size (mm)	Supporting window opening (mm)	Stacking sequence	Effective ply thickness (mm)	Number of plies
Standard plates	Ply-blocked scaling (Ps)	150 × 100	125 × 75	$[45°_2/0°_2/90°_2/-45°_2]_{2S}$	0.25	16
	Sublaminate scaling (Ss)			$[45°/0°/90°/-45°]_{4S}$	0.125	32
Large scale laminate (Ls)		300 × 200	250 × 150	$[45°_2/0°_2/90°_2/-45°_2]_{2S}$	0.25	16