IMPACT RESPONSE OF AUTOMATED FIBRE PLACEMENT ADVANCED PLACED PLY COMPOSITES

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ABSTRACT

This research focuses on the impact response of Automated Fibre Placement Advanced Placed Ply (AP-PLY) laminates. Panels with different internal mesoestructure are subjected to low velocity impact and compression after impact experiments to evaluate their damage tolerance. The development of matrix cracks during impact is observed in-situ by high-speed imagining. The internal architecture of the laminates is found to have a significant influence on their performance. Pseudo-homogeneous mesostructures with through-thickness undulations and individual tows are observed to act as effective crack arrestors, resulting in reduced in-plane delamination and relatively high residual strengths due to the higher resistance to buckling of the sublaminates. However, cross-ply panels exhibit a poor impact performance with large delamination footprints and a drastic loss in residual strength when subjected to 50 J of impact energy. These findings indicate that AFP AP-PLY laminates are appropriate for composite structures with enhanced impact performance, and can replace conventional angle-ply composite laminates in dynamic applications. This technology has the potential to be employed for high-value applications within the transportation industry.

1 INTRODUCTION

The aviation industry is responsible for about 2.1% of global carbon dioxide emissions, therefore the substitution of heavy metal components by advanced lightweight composite structures could reduce aircraft weight, leading to improved fuel efficiency and reduced greenhouse gas emissions. However, the adoption of composite materials in structural applications is currently hindered by their vulnerability to damage from out-of-plane loading. This is a major concern for the design of critical aerospace structures. Conventional angle-ply laminated composites are particularly susceptible to delamination when subjected to low velocity impact, resulting in poor impact tolerance and post-buckling response. Alternative composite architectures, e.g. 3D-wovens, non-crimp fabrics, and z-pinned composites, contain through thickness reinforcements which improve their out-of-plane response. However, the fibre crimp and fibre breakage introduced during the manufacture of these composites negatively impact their undamaged in-plane mechanical properties [1].

A novel preform method known as Advanced Placed Ply preforming (AP-PLY) makes use of Automated Fibre Placement (AFP) technology to produce quasi-woven composites [2,3]. The through-thickness fibre connectivity present in AP-PLY laminates have been shown to improve their impact tolerance in comparison to conventional angle-ply composites, but retain the latter's excellent in-plane strength and stiffness [4,5], even when subjected to high-strain rates, despite the higher number of defects induced by the AFP process.

Until now, research on the mechanical behavior of AP-PLY laminates has mostly focused on examining their in-plane or flexural properties, while there has been limited investigation into their impact response. Nagelsmit conducted a study on the impact response of AP-PLY quasi-isotropic architecture, including low velocity impact response and compression after impact (CAI). These preliminary investigations revealed that the innovative preforming technique could potentially increase the energy absorption capacity of traditional angle-ply laminates, however, it did not identify the mechanisms responsible for these improvements. Previous investigations in analysis of in-plane mechanical response showed a large influence of the internal architecture. In quasi-isotropic laminates, the through-thickness reinforcement acted as crack arrestors, contributing to maintain the structural integrity of the laminate, nevertheless, the strain concentrations at the undulations trigger early damage and catastrophic failure of AP-PLY cross-ply laminates. Considering these findings, the role of the undulations in the impact performance is an open research questions, together with their energy absorption and failure mechanisms as function of the internal architecture. This information is critical to optimise the preforming method of AP-PLY laminates and maximize the energy absorption capacity for future industrial applications.

In this paper, the low velocity impact performance of cross-ply, triaxial, and quasi-isotropic AP-PLY laminates is assessed. The AP-PLY specimens were first subjected to drop-weight tower testing at impact energies of 5, 30 and 50 J. The development of matrix cracks during impact was observed in-situ by high-speed imagining. Internal delamination was inspected using non-destructive ultrasound. The failure modes as function of the internal architecture and layup were characterised. Afterwards, the residual compressive strength of the specimens was determined using compression after impact tests. The difference in failure modes were evaluated as function of the delamination footprint.

2 ADVANCED PLACED PLY CONCEPT

In an AP-PLY laminate, tapes are placed in a predefined pattern to create interlayer fibre connectivity, as illustrated in Figure 1. Instead of placing tapes to form complete plies, as in conventional laminates, the AFP head is modified to place tapes in sets. A tape set is a group of tapes with the same fibre orientation, in which each tape is separated from the next by a predefined gap. The size of the gap can be varied but must always be a multiple of the tape width. The gaps left between tapes in a set are later “filled in” by another tape set, but only after tape sets have been placed in all the other desired fibre orientations first.

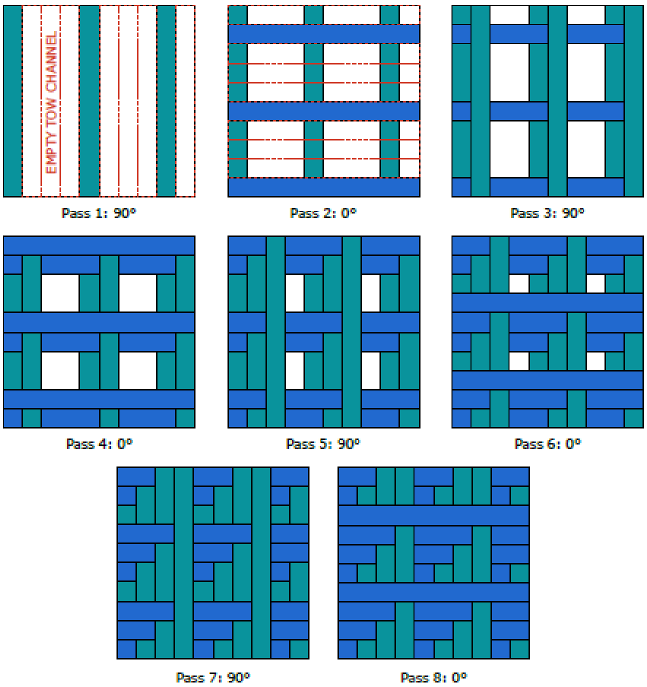

Figure 1. Schematic illustrating the layup process of a cross-ply AP-PLY laminate tape spacing of 3.

AP-PLY laminates are composed of multiple interlaced sublaminates with 3D fibre connectivity. These sublaminates can tailor their mechanical properties through the modification of the internal architecture. Some of the most relevant design parameters stand for: (i) the tow skipping parameter, the number of tow width gaps left between tows placed in the same set, (ii) alternating or series patterns, where tow orientation is changed each time a single tow is placed, resembling helical filament winding, and (iii) totally interwoven concept, where the last tow set from each sublaminate is interlaced with the first layer of the next package.

3 MATERIALS

AP-PLY panels were manufactured by vacuum assisted resin transfer moulding and the fibre preforms were produced using an mTorres AFP machine, see Figure 2. All laminates were produced using Hexcel HiTape UD210 dry tapes impregnated with Hexcel RTM6 resin. Three different panels were manufactured with a cross-ply (XP) $[0°,90°]_{6S}$, triaxial (TRI) $[0°,60°,-60°]_{4S}$, or quasi-isotropic (QI) $[0°, 45°, -45°, 90°]_{3S}$ layup. The quasi-woven AP-PLY architecture was created by leaving a single tow width gap - measuring 12.7 mm - between tows placed in the same pass. The average thickness of each panel was determined to be 5.16±0.02 mm, 5.04±0.07 mm, and 5.15±0.05 mm, for the XP, TRI, and QI configurations, respectively. Planar RVE dimensions for the XP, TRI, and QI laminates measure 25.4 mm x 25.4 mm, 25.4 mm x 29.3 mm, and 25.4 mm x 25.4 mm respectively.

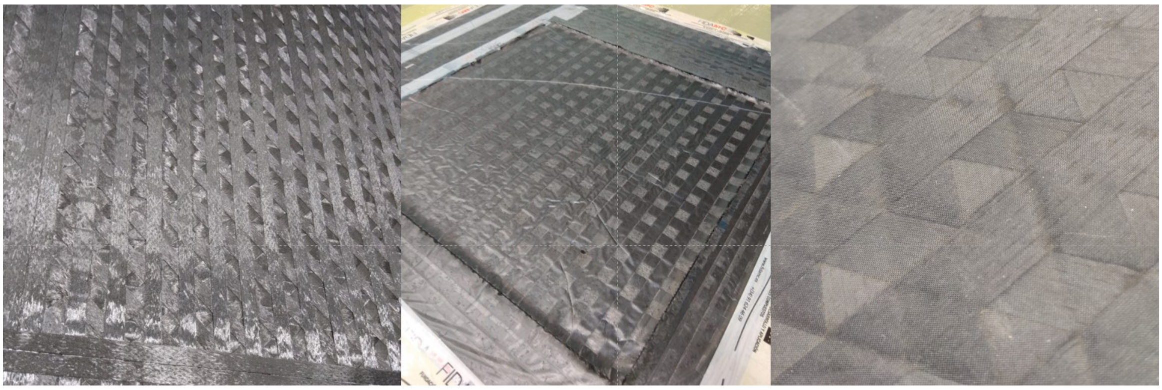

Figure 2. AP-PLY manufacturing process. (a) Dry fibre preform created by AFP, (b) resin transfer moulding and (c) final surface quality.

The quality of the manufactured panels was assessed by Scanning Electron Microscopy (SEM) and CT-Scan, see Figure 3. A relatively high fibre volume fraction was obtained, with no apparent voids. Resin pockets were found between the undulating tapes. Overall, the repeatable architecture resulted in an structured pattern of lower density areas coincident with the tow crossovers, see Figure 3(b).

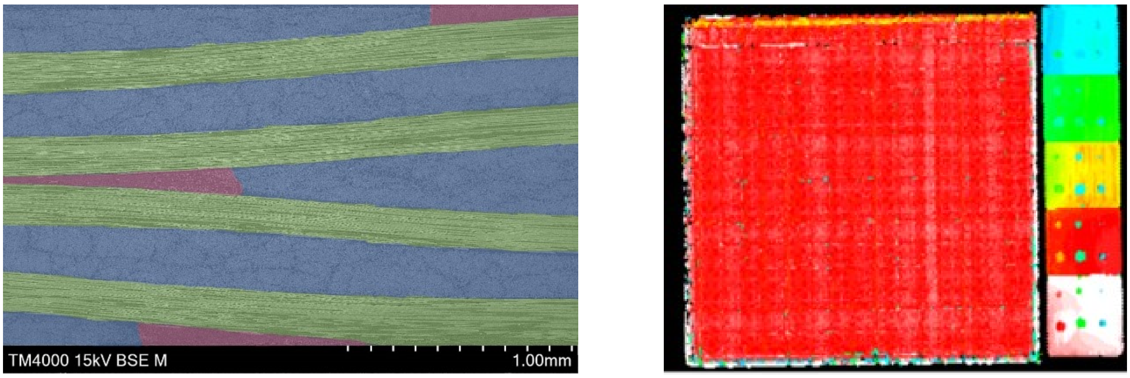

Figure 3. (a) SEM micrographs showing the characteristic tow undulations in green, the perpendicular tows in blue and the resin pockets in red. (b) Preliminary C-Scan measurements and comparison against baseline plates.

4 EXPERIMENTAL TECHNIQUES

Low velocity impact (LVI) testing was conducted in accordance with the ASTM D 7136 standard. Three different energy levels were selected; 5, 30 and 50 J. A 5.85 kg impactor with a 16~mm diameter hemispherical tip was dropped from a height onto each coupon, resulting in up to 4.13 m/s impact velocity. Photron SA-Z 2100K cameras were used to record the back face of the specimens at 20,000 frames per second at a resolution of 1 megapixel. Space constraints in the impact tower precluded recording the back face of the specimens directly, so a mirror, inclined at 45°. 3D Digital Image Correlation was employed to process the imagines and determine the strain field and the out-of-plane displacement of the plates during impact. Laminates were inspected before and after impact through ultrasound non-destructive inspection using an Olympus Omniscan X3 phased array ultrasound device. Amplitude and time-of-flight data were recorded using a 5.0~MHz transducer. Ultrasound data was post-processed using Olympus' OmniPC software and plotted using Python.

The residual compressive strength of the AP-PLY laminates was evaluated through compression after impact (CAI) tests conducted according to the Airbus AITM 1-0010 standard, which is similar to the more commonly used ASTM D 7137 standard. The undamaged in-plane strength of each laminate was characterized by short block compression tests according to an adaptation of the ASTM 1-0008 standard.

5 RESULTS AND DISCUSSION

Figure 4 compares representative force-displacement curves at different energy levels for the cross-ply and triaxial panels. The results of the quasi-isotropic panels were very similar to the triaxial counterparts. The panels presented similar elastic response when impacted at 5 J of energy, with no apparent indentation or damage after impact. Increasing the impact energy progressively increased the deflection, showing a higher stiffness of the TRI and QI panels, with the XP panel exhibiting a larger compliance. The best performance under low velocity impact was exhibited by the TRI and QI laminates. These laminates resulted in higher stiffness, peak load, and damage tolerance. The XP laminate exhausted its maximum load capacity at around 12 kN when impacted at 50 J.

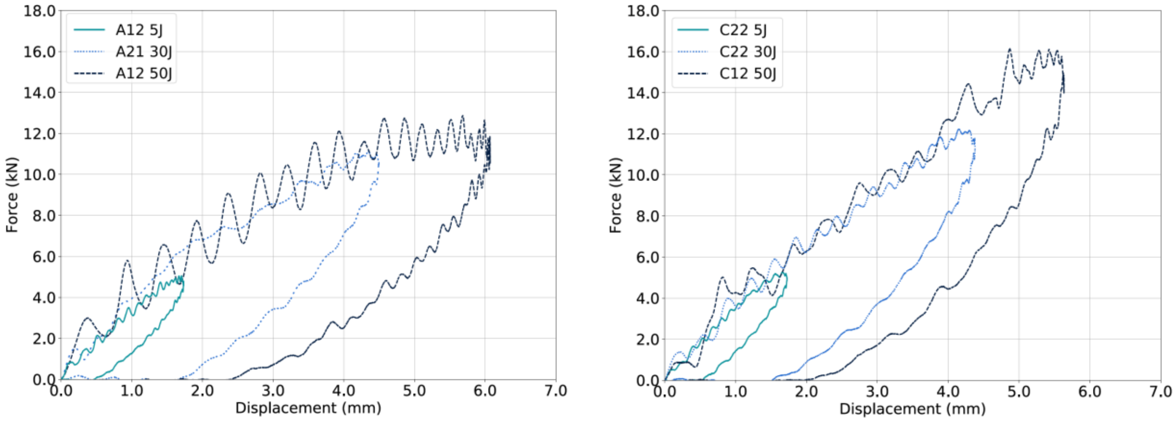

Figure 4. Representative force vs displacement curves at different energy levels for (a) AP-PLY crossply panel and (b) AP-PLY triaxial panel.

The onset and propagation of damage on the rear face of the laminates was analysed in situ with high-speed photography. Figure 5 shows representative out-of-plane deflection of the panels at the peak loads for the highest impact energy of 50 J. Higher deflection was obtained for the XP panel in agreement with the force-displacement curves. Matrix cracks appeared in the rear face of the specimens, with no evidence of fibre splitting of fibre fracture. These cracks formed at the directly impacted tows parallel to the fibres and along the tow boundaries, resulting in tape debonding. Crack propagation away from the impact point was inhibited by the internal architecture of the AP-PLY laminate, since the tow undulations acted as crack arrestors.

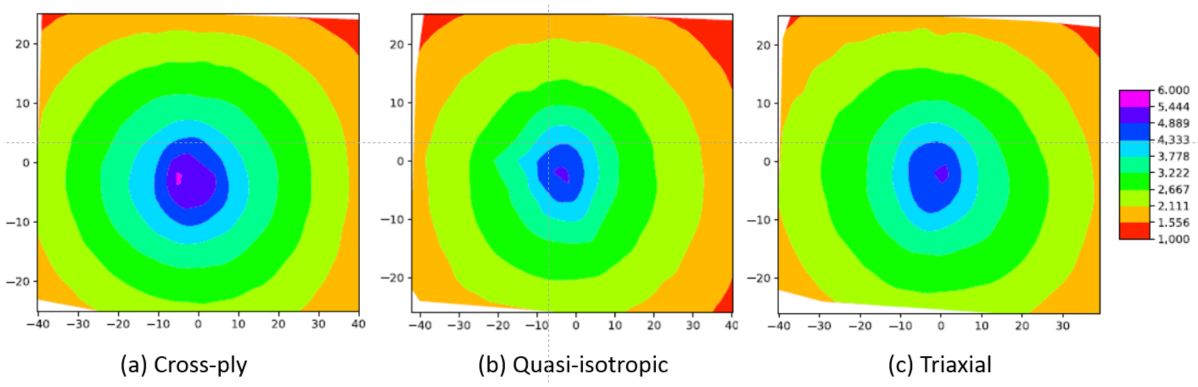

Figure 5. Maximum deflection of the panels at the peak force. Deflection in mm.

C-Scan measurements were employed to assess the internal damage of the specimens. Figure 6 summarises the surface area of the delamination footprint. At 30 J of impact energy all the configurations presented a similar internal delamination and energy dissipation, the discrepancies between the configurations were within the experimental scatter. Increasing the impact energy to 50 J increases the delamination footprint, in particular for the XP panel, which shows a large tendency to delaminate. The shape of the delamination also changed from the original elliptical footprint into a cross-shaped delamination, following the orientations of the perpendicular tows. This correlates with the force-displacement low-velocity impact curves, where it was found this laminate exhausted its maximum load capacity. Since no fibre failure was found, it can be stated that delamination is a catastrophic failure mode of AP-PLY laminates. Difference in propagation of the delamination can be explained by more closely analysing the internal architecture of the AP-PLY laminates. In the XP specimens, a maximum of two layers are interlaced, compared with 3 or 4 interlaced layers in the TRI and QI laminates. Furthermore, the tows that are interlaced in a XP laminate are always orthogonal to one another, while in the TRI and QI laminates, the interface angles between tows vary. As a consequence of their heterogeneity, the larger deflection during impact and the large bending stiffness mismatch between interlacing tows, the XP laminates are more prone to delamination than the TRI or QI laminates at the highest impact energy.

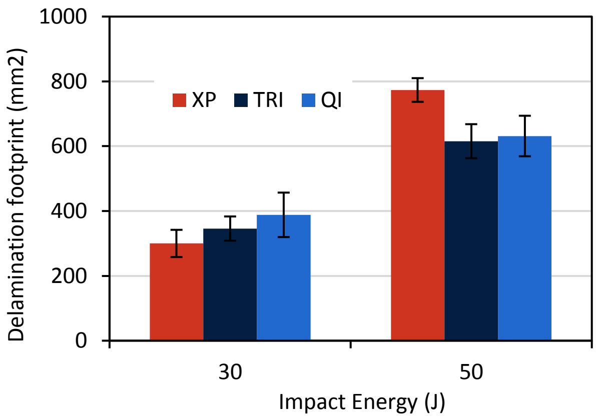

Figure 6. Delamination as function of the impact energy.

In CAI test, the TRI and QI laminates presented similar residual strength, with reductions of 26% and 20.6% respectively after low velocity impact at 50 J. The XP laminate instead presented a drastic loss of 49.1% in residual strength, exhibiting very poor performance. The lower through-thickness reinforcement rate (only every 2 plies) and the higher delamination of the XP laminate resulted in less stable sublaminates, prone to fail through the formation of a global shear band under compression, see Figure 7. The TRI and QI laminates instead had a higher through thickness connectivity (every 3 and 4 plies) and exhibited a more tortuous crack patch that followed, to an extent, the tow boundaries in the laminates. This resulted in increased energy dissipation and residual strength.

Figure. 7. Crack path and cross-section of fracture plane in crossply and quasi-isotropic CAI specimens impacted at 50 J.

6 CONCLUSSIONS

This paper has explored the influence of the stacking sequence in the failure mechanisms of AP-PLY laminates subjected to LVI and CAI. Triaxial and quasi-isotropic panels presented enhanced impact performance in terms of damage tolerance. The through thickness undulations acted as crack arrestors, minimizing the delamination and resulting in low reductions in residual strength after impact. The cross-ply laminates instead exhibited large delaminations since the angle mismatch at tow interfaces induced large intratow shear stresses. This had a detrimental result in their residual strength, with a drastic loss of 49.1% with respect to the original undamaged panel.

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