EXPERIMENTAL INVESTIGATION OF LOW-VELOCITY IMPACT DAMAGE IN PSEUDO-DUCTILE COMPOSITE LAMINATES CONTAINING PLY WEAKENING

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Abstract
The damage resistance of a composite laminate configuration, which exhibits a pseudo-ductile stress-strain curve under tensile loading, was investigated. Pseudo-ductility was achieved by weakening some of the 0° plies in the laminate stacking sequence, by means of equally spaced, discontinuous cuts perpendicular to the fibres. Plies containing fibre cuts were embedded within 0° plies, in order to promote delamination onset from the ply cuts and propagation along the 0° fibre direction. This damage mechanism was demonstrated to cause a pseudo-ductile response in both unidirectional and multidirectional specimens in tension. Low-velocity impact tests were performed on specimens containing the cut fibres and on baseline specimens, with the same stacking sequence. Results showed a similar response to an impact event and a similar extent of damage in the baseline specimens and in the specimens containing ply weakening. It can be concluded that the strategy to achieve pseudo-ductility in composite laminates through discontinuous cuts perpendicular to the 0° fibre preserves the damage resistance of the material to a low-velocity impact event.

1. Introduction

Carbon fibre reinforced polymer matrix composites are characterised by brittle, catastrophic failure, which greatly limits the efficiency of their application in safety critical structures. In recent years, research has focused on the development of novel composite configurations, which have a pseudo-ductile stress-strain curve, which mimics that of metals, resulting in a more gradual failure under tensile loading [1-4]. In one approach, studies have shown that such a behaviour can be achieved by introducing designed ply weakening in some of the 0° plies in a laminate. In [5], a pseudo-ductile response under tensile loading was obtained by cutting the fibres in the two plies at the midplane in unidirectional specimens, resulting in a stacking sequence $[0/0_c/0_c/0]$, where the subscript 'c' indicates plies with cut fibres. The fibre cuts were perpendicular to the 0° fibres and extended across the entire width of the specimen. Multiple cuts were equally spaced along the specimen length. Fibre cuts in the two adjacent plies were aligned, in order to promote delamination at the $0/0_c$ interface, between the cut ply and the pristine 0° ply. The damage mechanism obtained is described in detail in [5] for unidirectional laminates under tension.

In a subsequent study [6], the ply weakening method was modified, in order to reduce the amount of discontinuous 0° fibres and increase the initial stiffness of the laminate. Instead of cutting the fibres in the 0° plies across the entire width of the specimen, 5-mm cuts were introduced, perpendicular to the 0° fibre direction, and separated by 5 mm of continuous fibres. These lines of discontinuous fibre cuts were repeated along the length of the specimen, as previously done in [5]. Similar to [5], unidirectional specimens with a stacking sequence $[0/0_p/0_p/0]$ were tested, where the subscript 'p' indicated 'perforated' plies with 5-mm fibre cuts. A pseudo-ductile response was obtained in the perforated unidirectional specimens [6]. The study extended the results to 0-dominated multidirectional stacking sequences obtained by positioning a $0/0_p/0_p/0$ ply block at the midplane. The stacking sequence investigated in [6] was $[90/+45/-45/0/0_p]_s$. The same damage mechanism observed in the unidirectional stacking sequence was successfully promoted in specimens having this multidirectional stacking sequence and a pseudo-ductile stress-strain response under tensile load was obtained [6].

Previous studies mainly focused on the tensile behaviour of the material [5-6]. However, if pseudo-ductile composites are to be used in real composite structures, the question arises as to how the weakening in the 0° plies in a laminate would influence its behaviour in the event of a low-velocity impact event, and the residual compression strength. The work presented here is aimed at evaluating the performances of pre-weakened pseudo-ductile composite laminates under low-velocity impact, and the consequent compression-after-impact response.

2. Experimentation

2.1. Ply Weakening Configuration

Low-velocity impact tests and compression after impact tests were performed on specimens made from a composite laminate configuration, which has recently been demonstrated to exhibit a pseudo-ductile behaviour, when loaded in tension [6]. The material configuration used contains ply weakening in some of the 0° plies in the specimen stacking sequence. The ply weakening strategy tested in [6] was used here, to investigate the impact behaviour of a composite laminate containing cut fibres. Ply weakening in the 0_p plies was obtained by means of 5-mm-long discontinuous 'perforations', in a direction perpendicular to the 0° fibres, in some of the 0° plies in the specimen stacking sequence. The perforations were cut in the prepreg using a laser milling technique, which allowed a fine control of the length and position of the fibre cuts. A 5-mm-long space of intact fibres was left between consecutive perforations across the width of the specimen. This pattern was repeated over the entire width of the 0_p plies. Multiple lines of perforations were cut along the length of the specimen, spaced by 10 mm. All the lines of perforations were aligned in the specimen width direction, in order to leave continuous 0° fibres between neighbouring perforations. This perforation pattern was chosen according to the analytical model presented in [5], which predicts delamination and debonding of the bundles of cut fibres from the surrounding material, when the laminate is loaded in tension. A sketch of a perforated 0° ply for an impact specimen in shown in Fig. 1.

The stacking sequence selected for the impact specimens contains $[0/0_p/0_p/0]$ ply blocks (where 0_p indicates plies containing ply weakening) similar to those tested in [6]. The presence of these ply blocks is required to achieve the pseudo-ductile behaviour in tension, since it allows delamination growth from the onset at the location of the perforations, along the 0° fibre direction at the $0/0_p$ interface. Perforations in adjacent 0° plies were aligned through the thickness. The $[0/0_p/0_p/0]$ ply blocks were included in a multidirectional stacking sequence, similar to the pseudo-ductile multidirectional stacking sequence investigated in [6]. In order to have a specimen thickness and layup similar to that used in standard impact tests [7], a 30-ply stacking sequence was employed, resulting in a specimen thickness of 5.40 mm. The stacking sequence of the impact specimens was $[(+45/90/-45/0/0_p)_s]_3$.

2.2. Specimens Materials and Manufacturing

Specimens were made using Hexply® M21/35%/198/T800s carbon fibre/epoxy prepreg with a nominal cured ply thickness of 0.18 mm. The required perforations were cut in the 0_p plies using a laser technique and inspected in a stereo microscope, in order to verify that the fibres were cut through the entire thickness of the prepreg. Four alignment holes were cut in each ply of the stacking sequence. A layup plate fitted with four pins was used during the layup, in order to assure the alignment of the perforations in adjacent plies. The panels were cured in an autoclave, according to the curing cycle recommended by the material manufacturer.

Specimens were cut out of the panels using a waterjet cutter, to control the positions of the perforations in the specimens. Specimens were ground to the final dimensions. Specimens were nominally 150 mm long (in the 0° fibre direction) and 100 mm wide (in the 90° fibre direction) [7], with an average cured thickness of 5.40 mm. The perforations close to the specimen edges were nominally at a distance of 2.5 mm from the edge, in the specimen width direction, and at a distance of 5.0 mm from the edge, in the specimen length direction.

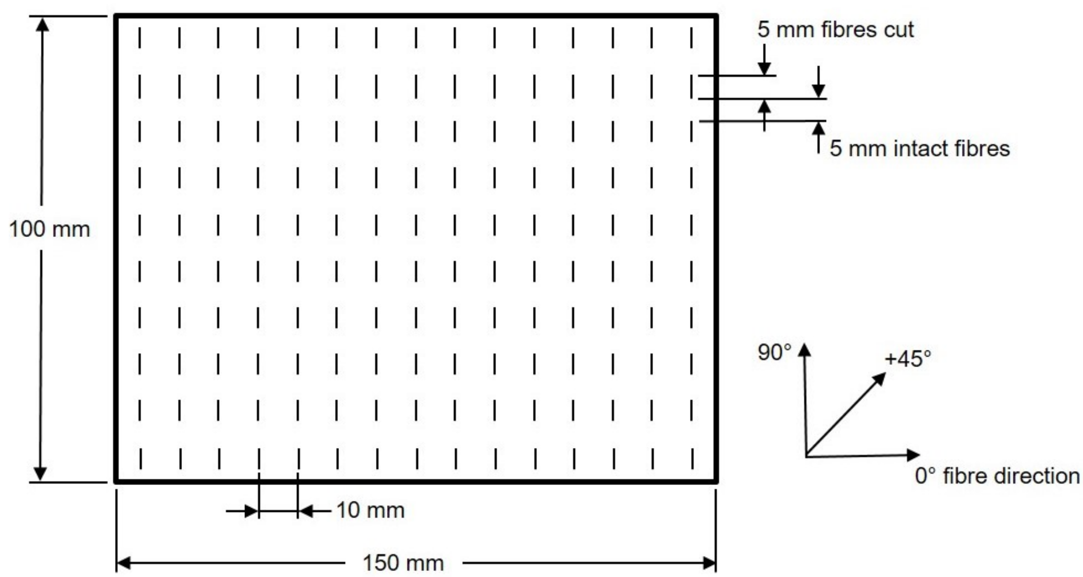

Figure 1. Schematic representation of the plan view of a perforated 0_p ply.

2.2. Test Procedure and Inspection Methods

Low-velocity impact tests were conducted at an impact energy of 12 J. Tests were performed using an Instron CEAST34 drop weight impact tower, equipped with a 16 mm hemispherical tup. Tests were conducted according to the ASTM D7136 Standard Test Method [7]. A picture frame test fixture was used for the impact tests. The test fixture has a 125 mm × 75 mm rectangular test window, as required by the standard [7], but provides uniform boundary conditions around the boundary of the test window.

Tests were conducted on specimens containing the ply perforations described above, and on baseline specimens, having the same stacking sequence but without ply weakening, for comparison. Two specimens were tested for each configuration.

After impact tests, specimens were inspected by an ultrasonic C-scan equipped with a 10 MHz probe. Both faces of the specimen were scanned to detect the morphology of the impact damage.

Compression after impact tests were performed according to the ASTM D7137 Standard Test Method [8]. Specimens were equipped with four strain gages, to monitor the strain during the compression tests. The non-impact face of the specimen was painted with a speckle pattern and monitored during the test using a GOM Digital Image Correlation system (DIC).

3. Results

Fig. 2 shows a graph of the contact force recorded during the test as a function of time, for the duration of the contact between the impactor and the specimen. Tests were very repeatable for each specimen configuration, therefore only one curve for each type is represented in the figure, for clarity. Fig.2 shows that the contact force does not change significantly in the specimen containing ply perforations, compared to the baseline specimen. This result is encouraging because it shows that the resistance of the laminate to a low-velocity impact event is not degraded by the presence of the ply perforations. The maximum contact force in Fig. 2 was 8.43 kN for the baseline specimen and 8.48 kN in the specimens with ply perforations.

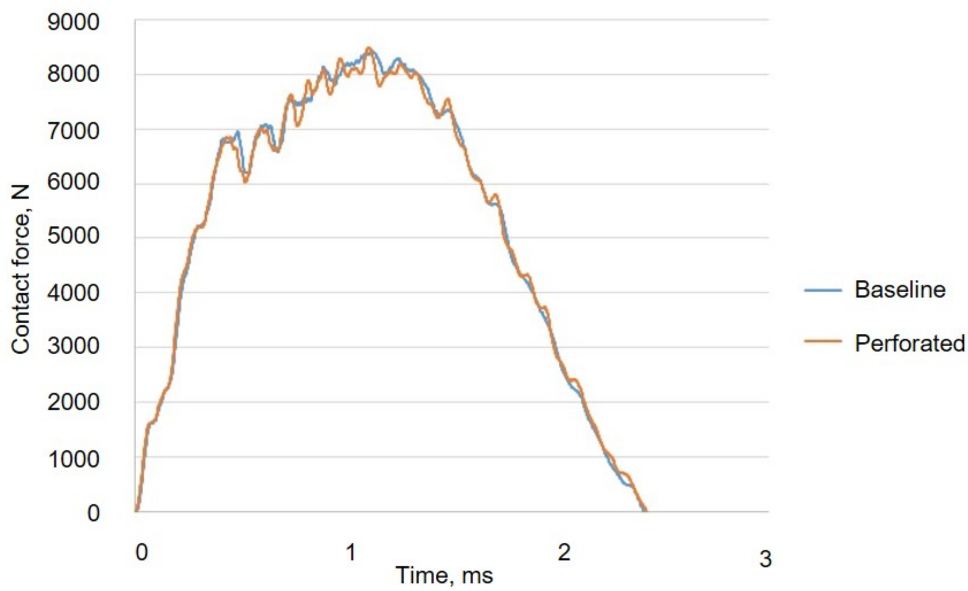

Figure 2. Impact force as a function of time during the impact event for a representative baseline specimen and a representative specimen containing ply perforations.

Fig. 3 shows Time of Flight C-scan images of the impact surface (Figs. 3a and 3b) and of the non-impact surface (Figs. 3c and 3d) of a baseline specimen without ply weakening (Figs. 3a and 3c) and a specimen containing ply perforations (Figs. 3b and 3d). Fibre orientations and the nominal locations of the perforations in the 0_p plies are indicated in the figure. The images show a 50 mm × 50 mm area surrounding the impact damage.

The maximum size of the delaminated area visible in the C-scan images was measured along the 0, 90, -45 and +45 degree fibre directions. In all the specimens tested, in all the direction measured, the delaminated area measured in the C-scan image of the non-impact surface of the specimen was greater than that measured on the C-scan image of the impact surface. Results are summarised in Fig. 4 for all the specimens tested. Fig. 4 shows the maximum delamination size measured for each specimen along each direction (0, 90, -45 and +45 fibre orientation). In the figure, specimens without perforations have a label starting with 'SP_' and are represented by solid colour bars, while specimens containing

5-mm-long perforations/5-mm continuous fibres have a name starting in ‘S55_’ and are represented by bars filled with inclined coloured lines.

The mean value of the size of delamination produced by a 12 J impact for the specimens without perforations was 33.9 mm along 0° fibre direction, 27.7 mm along the 90° fibre direction, 26.9 mm along the -45° fibre direction and 24.1 mm along the +45° fibre direction. For the specimen containing ply perforations, the mean value of the delamination size was 34.9 mm along 0° fibre direction, 28.5 mm along the 90° fibre direction, 28.3 mm along the -45° fibre direction and 24.6 mm along the +45° fibre direction. The impact-induced delaminations in the specimens containing ply perforations were between 0.5 mm and 1.4 mm larger than in the baseline specimens, without ply perforations. Therefore, it can be concluded that the ply weakening method proposed in [6] and tested here offers the advantage of a pseudo-ductile tensile response [6], and, at the same time, does not degrade the impact resistance of the laminate.

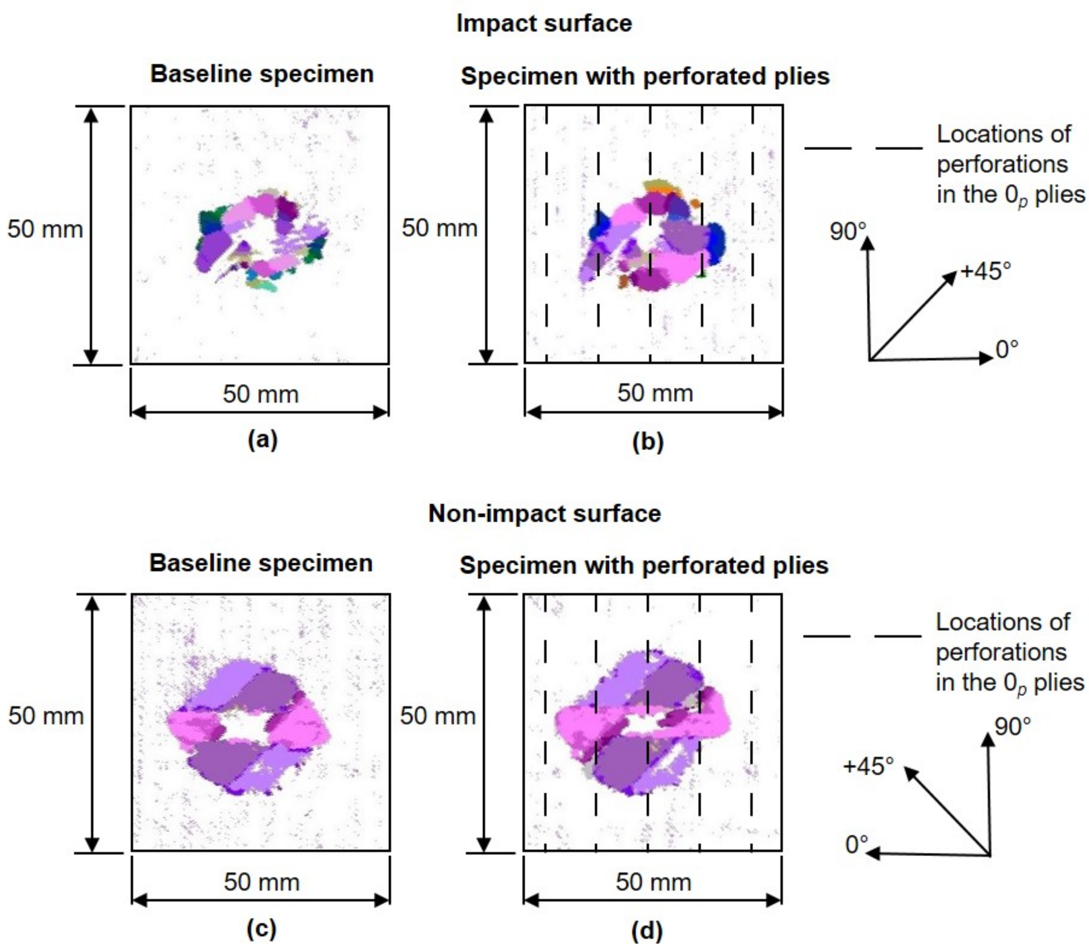

Figure 3. C-scan images of the impact surface of a baseline specimen (a) and a specimen containing ply perforations (b) and of the non-impact face of a baseline specimen (c) and a specimen containing ply perforations (d).

3. Conclusions

Low-velocity impact tests were performed on specimens made of a pseudo-ductile composite laminate configuration. The pseudo-ductile tensile response had been achieved by discontinuous cuts perpendicular to the 0° fibre in some of the plies in the stacking sequence [6]. Low-velocity impact tests were performed at an impact energy of 12 J on specimens containing fibre cuts and on baseline specimens made from the same stacking sequence and without cut fibres.

It was found that the contact force recorded during the impact event did not significantly change in the specimens containing fibre cuts, compared to the baseline specimens. The impact damage in the specimens was detected by ultrasonic C-scan of both surfaces of the specimens. Results show that the extension of damage in the specimen containing fibre cuts is comparable to that obtained in the baseline specimens. Therefore it can be concluded that the ply weakening method proposed in [6] to achieve pseudo-ductility by means of discontinuous fibre cuts does not affect the resistance of the composite laminate to low-velocity impact damage. This result is particularly relevant for practical applications of a composite material made pseudo-ductile by means of weakening of the 0° plies to real structures, such as aeronautics structures, which are likely to be subjected to low-velocity impact events. The compression-after-impact performance of the specimens containing fibre cuts is currently being investigated.

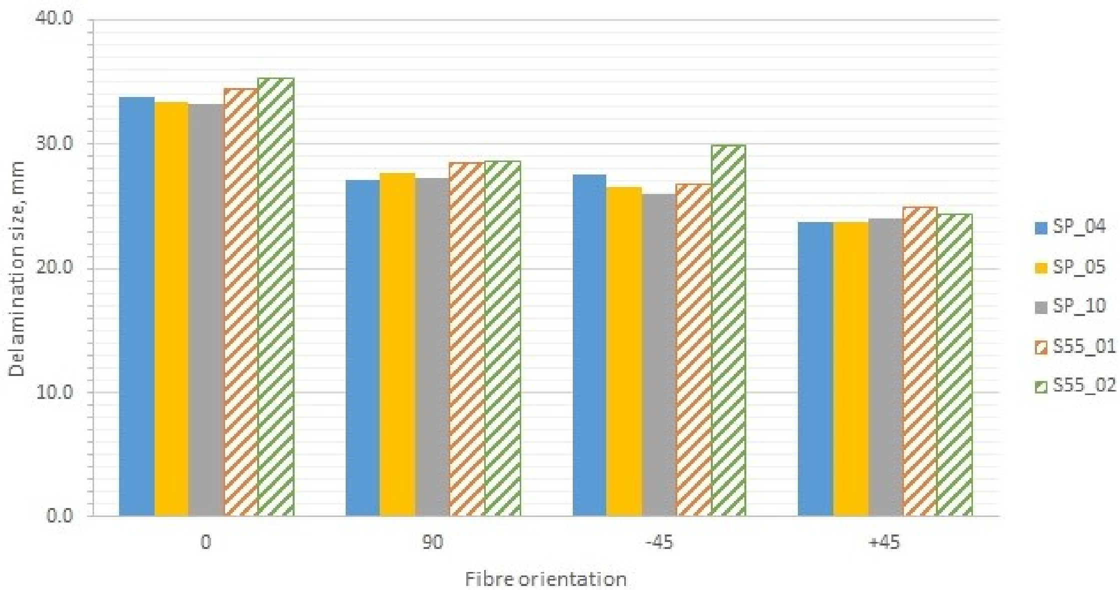

Figure 4. Maximum size of delamination measured along the 0, 90, -45 and +45 fibre orientation in C-scan images of the non-impact face of all the specimen tested. 'SP_' represents specimens without perforations, 'S55_' represents specimens containing 5-mm-long perforations/5-mm continuous fibres.

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