SIMULATION OF PROCESS INDUCED DEFECTS IN RESIN TRANSFER MOULDED WOVEN CARBON FIBRE LAMINATES AND THEIR EFFECT ON MECHANICAL BEHAVIOUR

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ABSTRACT: With increasing usage of composites in primary structural applications and the drive towards efficient manufacturing routes like RTM there is a need to review the defect acceptance criteria. Amongst other manufacturing induced defects, distortion in the fibres in the form of waviness, become significant when loaded in compression. Also associated with any disorientation in the fibre tow path is the accumulation of resin rich pockets. In this work both in-plane and out-of-plane fibre waviness, and resin rich layers on the surface were simulated in flat panels. It was found that the presence of fibre waviness caused a significant reduction of up to 35.2 % in the compression strength. The failure initiated where the fibre misalignment was the greatest. In the case of resin rich regions the failure did not initiate from the resin rich layer itself. Instead the initiation of delamination was found to occur at a region demarking the deformed and the undeformed layers. The reduction in tensile strength was 32%.

KEYWORDS: Resin transfer moulding; fibre wrinkling; fibre folding; resin rich layer; compression; delamination;

INTRODUCTION

Resin transfer moulding offers a means of producing a high volume of parts at low cost. With the increasing shift of focus towards efficient manufacturing methods there is a growing emphasis on using RTM in the aerospace industry for manufacture of primary structure components. For such specialised applications many manufacturing deviations come under scrutiny and an understanding of the defects and their effect becomes essential. Issues like void generation, fibre wrinkling, folding, resin richness, complexities around 3-D geometrical features and their effect on mechanical performance are now of relevance in the industry [1-4]. Waviness in fibres is a manufacturing defect that can be induced in the manufacturing step depending on the process used. For example waviness could occur in filament wound tubes [5], or in the inner radii of L sections cured in a female mould due to corner consolidation. In the RTM process also there is a possibility of waviness induced in the preforming operation. Generally waviness can be either in-plane or out-of planes and can be defined by the ratio of the amplitude of the wave to its wavelength. The wavelength can vary from short to large distances and when deviations in fibre paths occur the space between the distorted fibre path is taken up by the matrix leading to resin rich regions. Thus defects of waviness and resin rich regions could co-exist. Waviness in either form becomes an important issue when parts are subjected to compression [4]. Composites are known to be inherently weaker in compression than in tension, Rosen [6] derived a relationship, between the compressive strength and the shear modulus of the matrix of a composite with initially straight fibres which buckle in phase but this gives values that are far too high. When fibre waviness is taken into account the predicted strength values are reduced considerably [7, 8]. When unidirectional composites containing wavy fibres are compressed the misaligned fibres (with respect to the loading axis) are subjected to shear loading. The load when the shear stress exceeds the interlaminar shear strength of the composite is an upper bound on failure and it has been found by many that the failure occurs where the fibre misalignment is greatest [9,10]. Thus in the present work an attempt is made to simulate some of these defects in simple flat laminates and look at the initiation of failure in these samples. The effects on mechanical performance are reported. Also tensile tests were carried out on specimen with resin rich regions to study the effect on damage initiation.

MATERIALS AND SPECIMEN PREPARATION

All the test laminates were made using dry carbon fibre, 5-harness satin woven fabric and RTM 6 epoxy resin both supplied by Hexcel UK. In our work the 0 degree direction of the woven cloth is considered to be the warp direction and the weft fibres therefore are the 90 direction. A resin transfer moulding facility developed at the University of Bristol was used to make the Carbon-epoxy flat laminates. The tool is comprised of a fixed cavity formed between the top and bottom plate with a spacing of 4.2 mm. A stacking sequence of $((\pm45),(0/90))_{3s}$ was used to make specimens with and without defects. 12 layers of dry fabric were cut to the required size and stacked together to form the preform. After loading the mould, the top and bottom plates were closed and the assembly of platens was then heated to 120 deg C and the cavity with the preform was evacuated to 1000 mbar. Resin was injected into the mould at 3.5 bars pressure and after completion of the filling process the mould was then heated to its cure temperature of 180 deg C and held at this temperature for two hours. From the cured laminate test specimens were cut to the required size using a diamond disc cutter. The edges of the specimen were then polished to get a smooth surface.

Simulation of defects:

Localised kinking of fibres can occur during manufacture when the process step induces axial compression on the fibres. This buckling of the fibres can either be in-plane or out of plane depending on the local constraining conditions. Thus the difference between folding and wrinkling is very fine and often difficult to distinguish.

Wrinkling in this test programme is defined as that in which in-plane deviations of the fibre tows occur. The wrinkled plies were the sub surface plies (layer number 2, 4 and 6 from the top) and were the primary load carrying (0/90) plies.This was done on only one side to simulate a real life situation where not necessarily all plies will be wrinkled at a particular location. They were simulated in the middle of the gauge section and constituted 25% of the total ply count. The extent of wrinkles was limited to a length of 16 mm and they were distorted in-plane by three tow widths, or approximately 7 mm. This resulted in a localised fibre disorientation of about 30 deg as can be seen in Figure 1. To get wrinkles in the fabric the areas outside the desired 16 mm length were shear deformed against one another in the in-plane direction, by a specified amount of three tow widths. While doing the lay up it was ensured that all the wrinkled plies are wrinkled in the same direction and made to fall at a coincident location with respect to the centre of the gauge length.

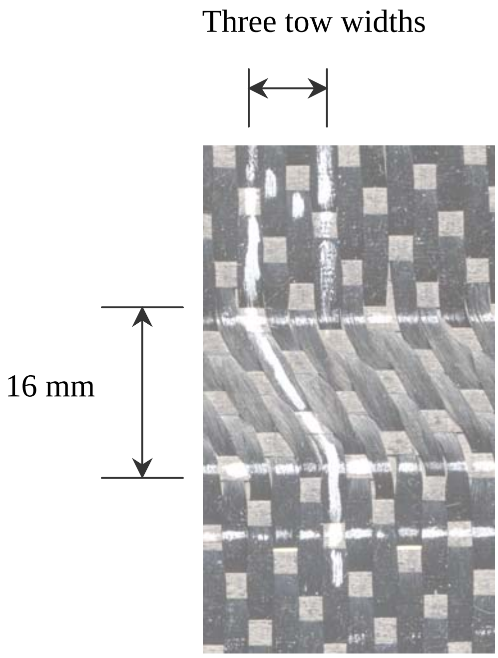


Figure 1. Picture showing in-plane fibre tow distortion in simulating wrinkling of fabric.

Folding of the fibres in the test samples is defined as out-of-plane fibre distortion, and was simulated on 100% of the plies in the through thickness direction (i.e. the entire stack of plies $[(\pm45),(0/90))_{3s}]$) by crimping the preform in the through thickness direction. For doing this, a preforming tool was made. This consisted of arranging precured carbon fibre rods spaced 8 mm apart on one side of the preforming tool while two rods were placed on the opposite side so as to fall in the centre of the span between the rods on the opposite side. The entire assembly was then heated to the preforming temperature of 150 deg C. After a specified time of 20 minutes the pressure was released and the preform taken out and allowed to cool. Due to the manufacturing difficulties some variation in the fold parameters was seen. Thus fibre folding was simulated in the gauge section with a wavelength between 7 and 8.5 mm and amplitude of about 0.6 mm, as shown in Figure 2. The distortion of the surface fibres was observed to be more than the fibres at the mid plane. The measured angular deviation observed at the centre of the laminate was found to be in the range 18 to 29 degrees.

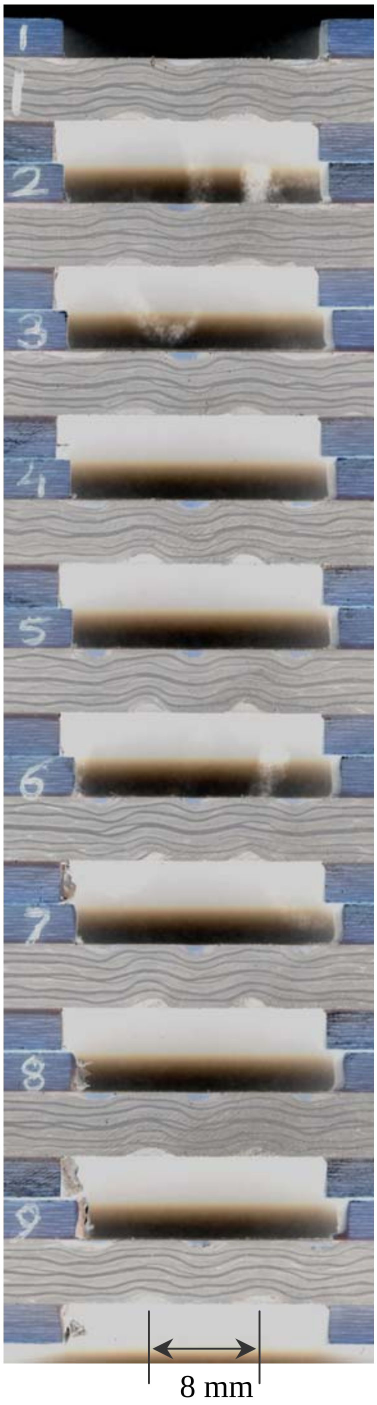


Figure 2. Out of plane fibre distortion simulating fabric folding .
(Picture in negative to show clarity in fibre distortion).

Resin richness: These are regions especially around corner radii, where a layer of resin is often found to be accumulated. These regions of resin richness form locally when the fibres get compacted to one side more than they would normally at other places. To simulate the resin rich layer within the flat specimen a forming tool of the desired resin rich geometry was fabricated. The preform stack with the forming tool was then placed in a vacuum bag. The entire assembly was then subjected to the preforming operation as described above. Using this method and after a few trials a successful resin rich zone of up to 12 mm long and 0.6 -0.7 mm depth was achieved as shown in Figure 3.

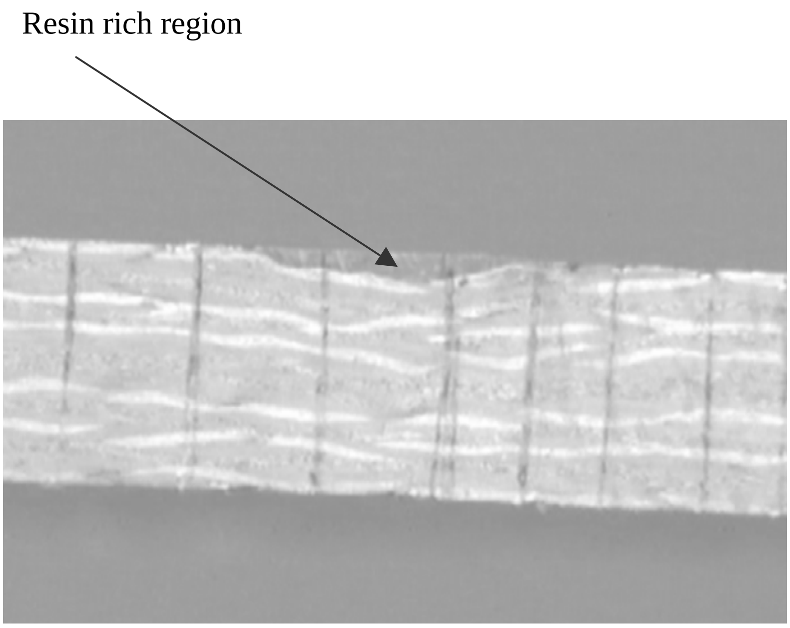


Figure 3. Resin richness simulated on the top surface of the specimen

Specimen preparation:
From the resin rich test panel, tensile test specimens were cut to dimensions 25 mm wide and 250 mm long (with a grip length of 60 mm), and emery paper of grit size 100 was used between the specimen and the jaws of the test machine to grip the samples at either ends. For the ply waviness studies, compression tests were carried out using the Imperial College Standard Test (ICST) rig. Compression specimens of 100 mm length and 10 mm width were cut from the laminates and end tabs of length 40 mm were bonded on both sides at both ends giving a gauge section of 20 mm. All specimens were tested in an Instron machine under displacement control at a crosshead speed of 0.5 mm/minute. The failure stresses are calculated based on the nominal ply thickness of 0.36 mm to compare with other data. For a 12 plied laminate the total thickness was 4.32 mm, compared with actual thicknesses ranging between 4.20 and 4.28 mm.

RESULTS AND DISCUSSION

When the specimens with no defects were loaded in tension they showed an increasing stress-strain response till failure and there was some evidence of delamination close to the failure stress. The delamination was observed to occur at the interface between the weft fibres and the resin rich pockets formed at the spaces corresponding to the crimps in the fabric weave. When these samples were loaded in compression the failure was sudden with fracture running through the entire thickness of the sample. The compressive failure stress was 492 MPa, 21% lower than the tensile failure stress of 625 MPa.

Fibre wrinkling:

During the compression test, the edge was observed carefully and delamination cracks were observed to appear within the wrinkled layer region. Closer examination revealed that the cracks relate to the interface between the outer most angle plies and the adjacent wrinkled layers (0/90), Figure 4. Possibly the location of the cracks corresponds to a place where the fibre tows of the wrinkled layer are cut where they meet the edge of the sample. The initiation stress was found from observation of the specimen edge during the test to be about 319 MPa and

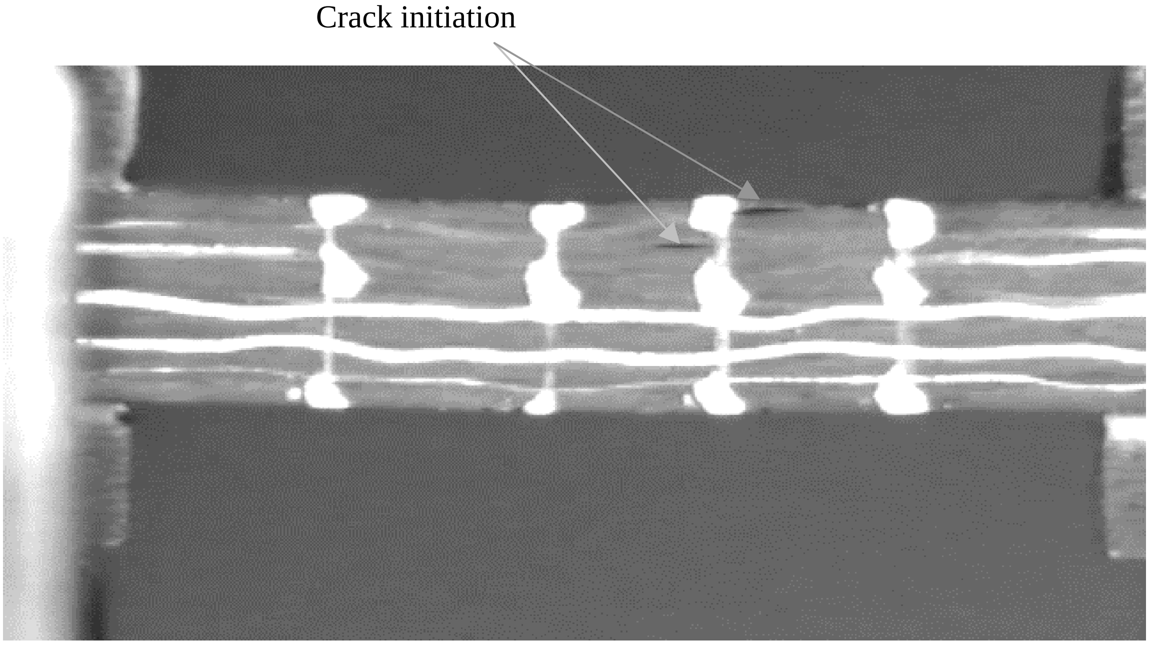


Figure 4. Picture showing the initiation of delamination at the interface of the wrinkled and angle plies in the specimen. (Note the white dots are marked on the specimen edge to monitor strains during the test)

the failure stress 370 MPa, which is 35.2 % lower than the failure stress of 492 MPa obtained from pristine laminates. The localised angular distortion of the wrinkled fibres (in-plane) is about 30 deg from the nominal fibre axis, which will significantly affect the stiffness properties locally and together with its asymmetric location will lead to bending of the specimen. Therefore delamination occurs early between the interface of the angle and axial plies within the wrinkled region. The wrinkling is uniform in all the specimens and initiation is from a specific feature i.e. the interaction of the local fibre tow path and the specimen edge, which probably explains the small scatter, with a c.v. of about 5 %.

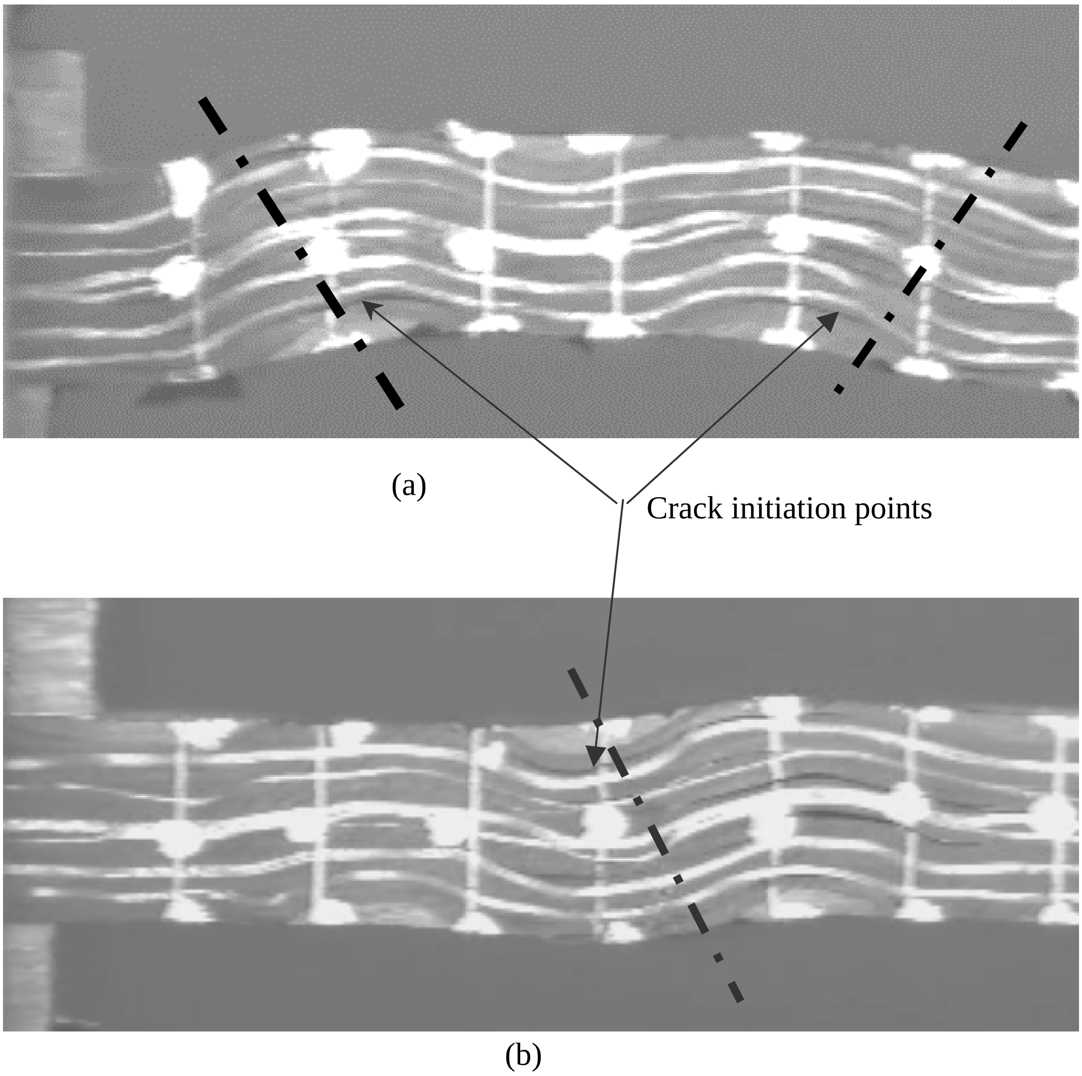


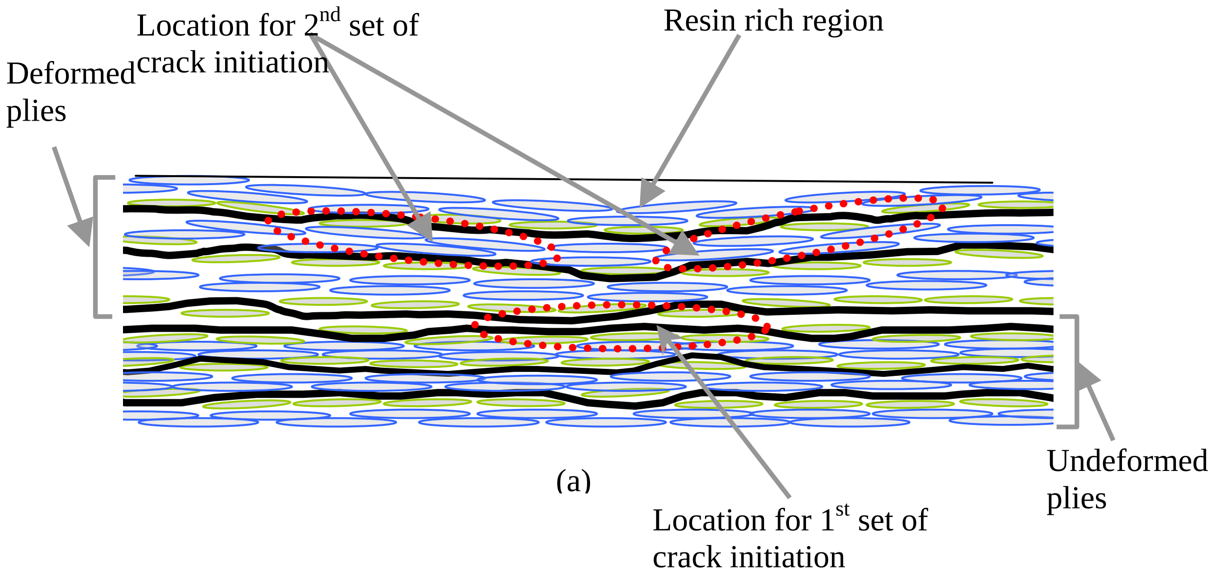
Figure 5. Different types of failure pattern observed in the samples (a) with delamination initiation at two locations and (b) with one initiation location. The dashed line denotes the general plane of failure corresponding to maximum fibre misalignment.

Fibre folding:

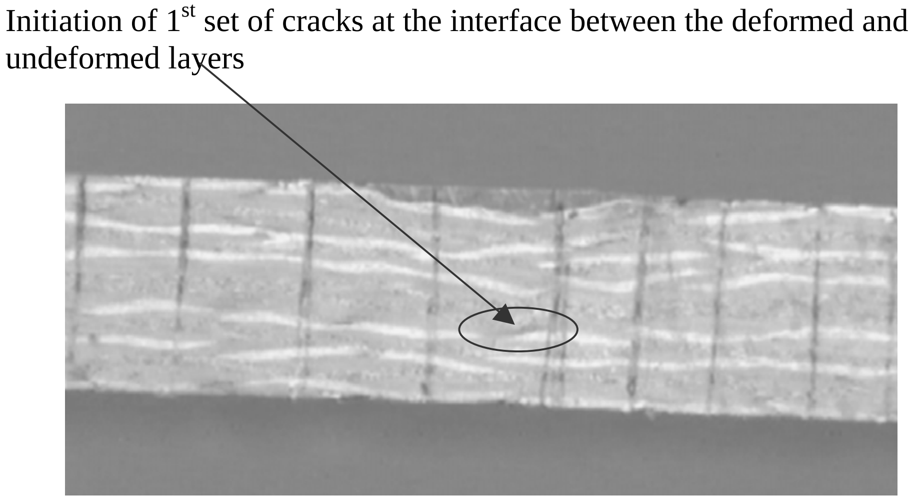
When the specimens were tested in compression, prior to reaching the peak load there was a discernable slope change in the load-deflection plot and at this point the specimen showed substantial cracks /delamination initiation between the surface and the subsurface plies, as shown in Figure 5 (a) & (b) resulting in sudden out of plane buckling of the specimen. At this juncture there was a significant drop in load and with increasing displacements, more delamination cracks began to appear and grow. The specimen edge was carefully monitored during the test and from the visual observations the stress corresponding to the damage initiation was found out to be about 138 MPa and was closely followed by the specimen failure at about 140 MPa. Thus the damage initiation stress is about 72% lower than the base line data of 492 MPa for the pristine laminate. It was also seen that there was not much time interval between the appearance of the first crack and the final failure. The fibre folding from the manufacturing process showed a slight variation in the degree of folds, Figure 2. In specimens where the fold was uniform throughout the gauge section the failure initiated simultaneously from the transition between the straight fibres and the fibres with folds located at both ends of the gauge section. Also since there were three folds in the gauge section the two outer folds were in phase with each other and this facilitated the out of plane displacement of the entire central section in unison, Figure 5(a). This kind of failure occurred at an early stage and the central gauge section was found to displace laterally thereby registering a lower failure initiation stress of about 111 MPa. In specimens with non uniformly distributed folds or varying fold geometry, Figure 5 (b) the failure occurred at the place where the severity of the fold was greatest. Usually it was observed that the most severely folded fibres lay closer to one of the supported ends and a higher initiation stress of about 163 MPa was recorded. The difference in the two failure types observed explains the large scatter (c.v. of 21%) in the data. In all these cases the failure could be attributed to shear induced delamination initiation at the sub surface ply as indicated in the Figures 5 (a) and (b).

Resin richness:

As a result of manufacturing variabilities the resin rich layer thickness varied between 0.6 mm and 0.7 mm. It may be recalled that the resin rich layer was created using a preforming tool on one side. As a result, there was deformation of the plies that was greatest at the surface and negligible beyond the mid plane, Figure 6 (a). These samples were tested in tension with six samples in this category. No failures were observed in the resin rich regions. The initiation of the 1st set of cracks appeared at the interface between the deformed and undeformed fibres which roughly corresponds to the mid plane, Figure 6 (a) & (b), with no failure in the resin region. The initiation stress for the delamination of about 300 MPa is 46.9% lower than the baseline samples. Soon after, a 2nd set of cracks appeared at 305 MPa within the deformed region, at the interface between one of the sub-surface angle plies and the adjacent axial plies, Figure 6 (b). The volume fraction is estimated to be about 68% in the region below the resin–rich layer, provoking early delamination. Many such delamination cracks appear in the vicinity of the resin rich region, causing the deformed plies to separate and straighten up at about 389 MPa. The specimens fail completely at about 428 MPa, and the reduction in strength is 32 %.



(a)



(b)

Figure 6. Schematic diagram (a) with picture showing initiation of delamination in (b) at the interface between the straight and deformed layers and subsequent propagation

CONCLUSION

- Wrinkling of the 0 degree fibres by approx 30 degrees in-plane in one half of a quasi-isotropic laminate reduced the compressive strength by about 35 %. Damage initiated at a stress 35.2% below that of the pristine specimens, with small cracks where the wrinkled plies were cut at the edge.

- When all the fibres are folded by approximately 29 degrees out-of-plane, the compressive strength is reduced by 71.5 %, with damage initiating just before failure.
- Failure in this case occurs at the place where the deviation in the fibre angle is greatest, believed to be controlled by the local interlaminar shear strength of the misaligned layers.
- For specimens with a resin rich layer on one surface loaded in tension no failure was observed in the resin rich region. Failure initiated primarily as delamination cracks in the region demarcating the straight fibres and the sub surface layers which were deformed as a result of the way the resin rich regions were formed.
- Damage in this case initiated at 46.9% below the pristine samples. Due to the asymmetric location of the resin rich region across the mid plane, bending was induced, with a reduction in ultimate tensile strength of about 32 %.

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REFERENCES

1. Piggott, M.R. The effect of fibre waviness on the mechanical properties of unidirectional fibre composites: A review, Compos Sci & Technol (1995) 53: 201-205
2. Mrse, A.M. and Piggot, M.R. Compressive properties of unidirectional carbon-fibre laminates: I A compact flexure beam for compression testing, Compos Sci & Technol (1993) 46: 213-217
3. Mrse, A.M. and Piggot, M.R. Compressive properties of unidirectional carbon-fibre laminates: I, The effect of unintentional and intentional fibre misalignment, Compos Sci & Technol (1993) 46: 219-227
4. Hale, R.D. and Villa, M. Influence of opposing wave nesting in compression-loaded composites, J Comp Mater. (2003) 37(13): 1149-1166.
5. Hsiao, H.M. and Daniel, I.M. Elastic properties of composites with fibre waviness, Compos Part A, (1996) 27A: 931-941
6. Rosen, B.W. Mechanisms of composite strengthening Chapter 3, Fibre Composite Materials. ASM (1965).
7. Davis, J.G. jr Compressive strength of fibre reinforced composites materials, Composite Reliability, (1975) ASTM STP 580, 364-377.
8. Hahn, H.T. and Williams J.G. Compression failure mechanisms in unidirectional composites, Composite Materials: Testing and Design (1986) Seventh Conference, ASTM STP 893, 115-139
9. Adams, D.OH and Bell, S. J. Compression strength reductions in composite laminates due to multiple-layer waviness, Compos Sci & Technol (1995) 53: 207-212.
10. Wisnom, M.R. Analysis of shear instability in compression due to fibre waviness, J Rein. Plast. and Compos. (1993) 12: 1171-1189.