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Paper Number: **1006**

Title: Experimental Study of Laminated Composites Containing Manufacturing Defects Under Combined Stress States

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ABSTRACT

Manufacturing defects are known to cause a knock-down in the mechanical properties of composite materials. These knock-downs are however usually only tested in simple stress states and not the more complex loading as found in real structural applications. Here a modified Arcan test fixture has been designed and manufactured to apply interlaminar shear in combination with through thickness compression to carbon fibre/epoxy composite laminates. The fixture is designed to accommodate a 30 × 30 mm size specimen and allows the ratio of interlaminar shear to through-thickness compression applied to the specimen to be varied by altering the angle of the fixture. The material used in this study is the Hexply® IM7/8552 and the ply stacking sequence of the laminates is $[+45_2/90_2/-45_2/0_2]_{3S}$, giving a nominal specimen thickness of 6 mm. The study included pristine specimens as well as specimens with an artificially embedded out-of-plane wrinkle defect which was generated by inserting a precise pattern of narrow pre-preg strips with 90° orientation across the width of the laminate during lay-up, which during cure merged with adjacent 90° plies in the stack. This experimental study has investigated failure stresses and failure modes for both pristine and wrinkle defect specimens, tested over a range of interlaminar shear to through thickness compression stress ratios.

INTRODUCTION

The use of composite materials is increasing in a number of industries such as aerospace and automotive. This is mainly because of the advantages composite materials provide in terms of weight reduction, energy absorption capacity and the ability to tailor stiffness in safety-critical regions etc. However, the use of composites in thick sections requires an understanding of mechanical response and failure under more complex loadings as found in real structural applications. In these applications

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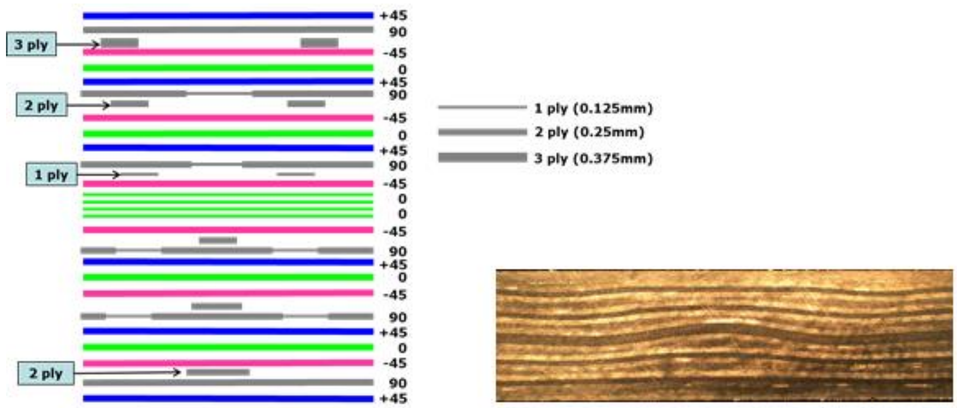
interlaminar failure is a weak link and therefore a serious concern in the design and manufacture of joints as well as in the response to impact events. Even if delamination does not directly lead to catastrophic failure, it can contribute to loss in structural integrity through reduced resistance to buckling [1]. Another key challenge is that the overall failure of a structure is significantly influenced by the presence of manufacturing defects under mechanical loading [2, 3]. These defects act as sites of potential failure initiation in composite laminates and hence reduce their load bearing capacity. Therefore, it is necessary to accurately estimate the role of defects on the mechanical performance of composite structures in order to have a damage tolerant design. The most commonly found defects include voidage/porosity, in and out-of-plane fibre misalignment, local variations in fibre-volume fraction, fibre-resin debonds, etc [4]. Out-of-plane misalignment of fibres is a type of defect also known as "wrinkling" [5] and this is commonly found in thick section components or curved composite parts as a localised band of wavy fibres through-the-thickness. A number of mechanisms have been suggested in the literature for the formation of wrinkles [3, 6, 7]. Geometric parameters such as amplitude, wavelength and waviness angle [8] are used to quantify the severity of the wrinkle.

In this study a test method has been developed to determine the interlaminar shear strength of a continuous fibre-reinforced composite laminate containing a wrinkle defect, when a through-thickness compressive load is applied simultaneously. A modified Arcan test fixture has been developed for this purpose which allows the ratio of interlaminar shear to through-thickness compression stress to be varied over a wide range.

EXPERIMENTAL TECHNIQUE

PRISTINE AND WRINKLE COUPON MANUFACTURE

Large sheets of Hexcel's IM7/8552 with 0.125 mm nominal cured ply thickness were doubled up and consolidated under vacuum prior to cutting the required ply shapes, effectively producing a cured ply thickness of 0.25 mm. The pristine laminates comprised 24 plies producing a nominal cured laminate thickness of 6 mm. Laminates were produced by hand lay-up in clean room conditions with vacuum consolidation applied to the lay-up stack at least every 4 plies. The completed quasi-isotropic (QI) ply stack, $[+45_2/90_2/-45_2/0_2]_{3S}$ was vacuum bagged and autoclave cured according to the manufacturers specified cure schedule. Aluminium upper and lower tooling was used in the autoclave cure process. A laminate with an embedded out-of-plane fibre wrinkle was manufactured in a similar manner except that additional strips of 90° pre-preg were incorporated into the lay-up in a precise pattern to force wrinkle formation. These 90° strips were always placed adjacent to an existing 90° ply in the stack. The frequency of vacuum consolidation during lay-up was increased in order to minimise porosity in the end product. A schematic of the lay-up along with a microscope image of the typical wrinkle resulting from this technique is shown in Figure 1a. An upper tool plate made of 8 mm thick aluminium was used during curing to overcome the uneven thickness profile which would otherwise result from the inclusion of the additional 90° material in the laminate. Figure 1b shows a side-on view of the central section of the lay-up where the wrinkle was deliberately generated. The average of the measured waviness angles for these specimens was 9.9°.



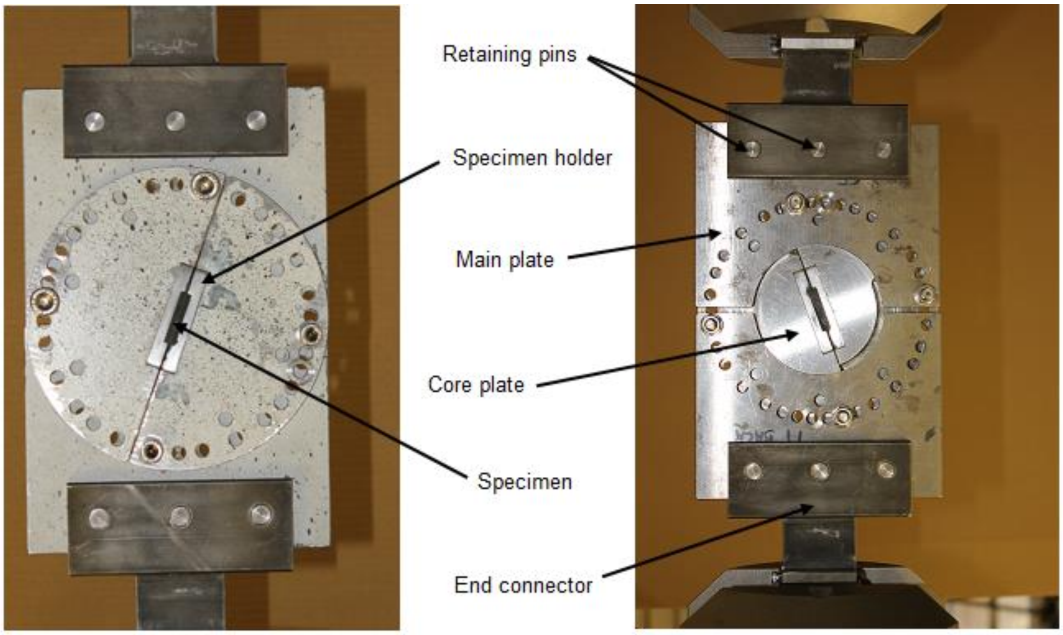
(a) (b)

Figure 1: (a) Pattern of insertion of 90° strips for the creation of wrinkle specimens, and (b) side view of a cured and finished specimen.

The cured laminates were subsequently trimmed on a diamond saw and test specimens 30 mm long by 30 mm wide were extracted – specimens with an embedded wrinkle were cut so that the wrinkle was located at the centre of the specimen length. Cut specimens were stored in a desiccator until the time of testing. All the tests described herein have been performed at ambient laboratory conditions.

TEST PROCEDURE

A modified Arcan test fixture has been developed which allows the ratio of interlaminar shear to through-thickness compression stress to be varied over a wide range, as shown in Figure 2. The test fixture has two removable specimen holders into which the specimen is bonded prior to test. Specimens were bonded into the specimen holder using a two-part epoxy paste adhesive, Araldite® 2015. The gap between the two holders (either side of the specimen) was filled with a 1 mm thick PTFE sheet during bonding to prevent spread of the adhesive into this region (see Figure 3). All surfaces to be bonded were degreased, grit blasted and degreased again prior to bonding in order to achieve the maximum bond strength. The specimen holder/specimen pre-assembly was bolted between the two semi-circular core plates of the test fixture using four M5 cap head screws tightened to maximum allowable torque (10 N·m) using a suitable torque wrench. The core plates were then bolted to the main plate plus end connector assemblies at the required test angle using four M8 cap head screws also tightened to maximum allowable torque (45 N·m). During initial trials of the test fixture the retaining pins holding the end connectors to the main plates were a push fit but these were subsequently modified to a rigid, permanent fit to minimise 'play' in the fixture.



(a) (b)

Figure 2. Modified Arcan test fixture installed in Instron 8801 test machine (20° angle from vertical) (a) front view and (b) rear view.

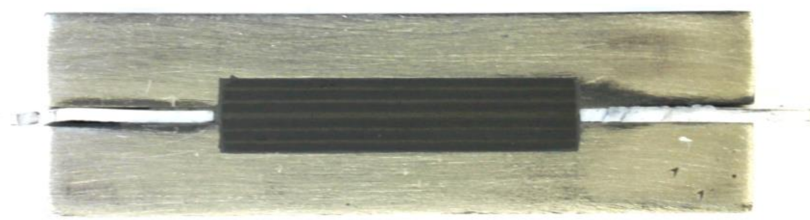
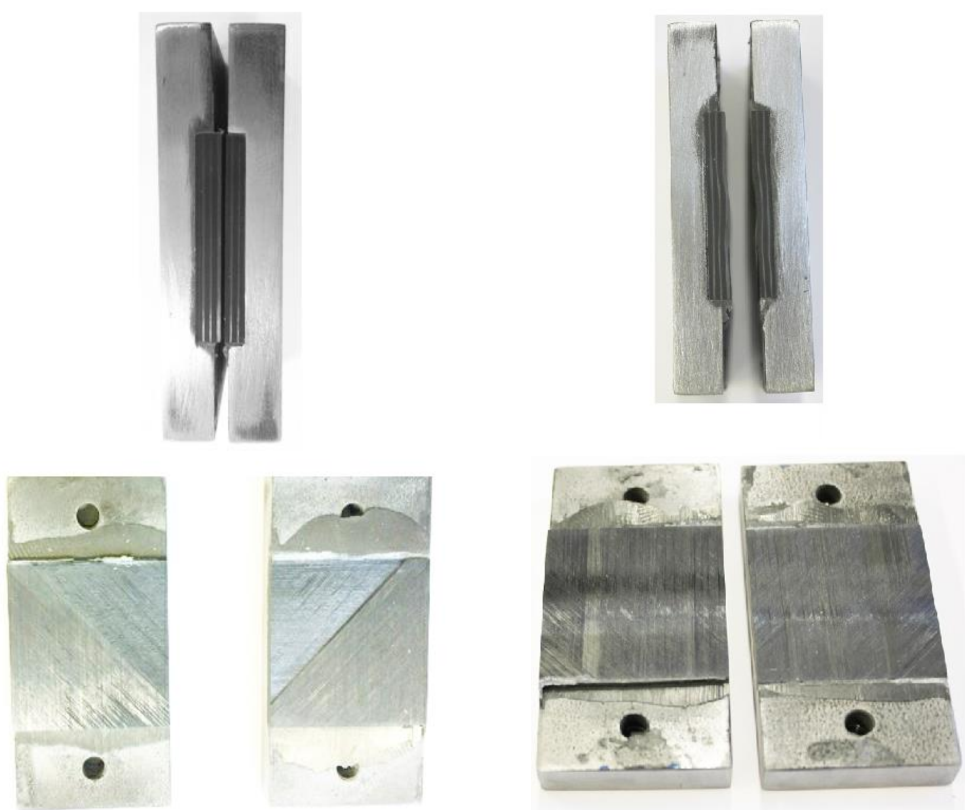


Figure 3. Pristine specimen bonded into a pair of specimen holders with PTFE in place.

The complete fixture plus specimen assembly was then installed in the grips of the test machine, making sure that it was accurately aligned. The fixture design facilitates its use in a variety of standard testing machines provided that the test machine grips are capable of accommodating the end connector dimensions, i.e. 12 mm thickness and 50 mm width. Tests were performed on a 100 kN capacity Instron servo-hydraulic test machine (model 8801), fitted with hydraulic grips. The test machine actuator was driven under displacement control in compression at a rate of 0.2 mm/min until catastrophic failure of the specimen occurred. Load and displacement data were recorded continuously via the test machine's computerised control system.

RESULTS AND DISCUSSIONS

A minimum of two repeats were tested for both the baseline defect-free (pristine) configuration and wrinkle configuration. Two loading angles, 4° and 20°, were selected to provide different ratios of interlaminar shear and through thickness compression. The load-displacement curves were predominantly linear up to failure which was always catastrophic and accompanied by an audible noise. The fracture surfaces of representative pristine and wrinkle specimens tested at the 4° angle are compared in Figure 4. The loci of failure were very similar in both cases (pristine and wrinkle) and were very close to the 0° plies at the centre line. A summary of the mean failure loads (and coefficients of variation) is shown in Table I. Assuming a completely rigid fixture, the through thickness compression and interlaminar shear stresses were resolved based on the angle of the fixture and are presented in Table II. The 4° and 20° angles resulted in ratios τ_{13}/σ_{33} of 14.3 and 2.7, respectively.



(a) (b)

Figure 4 Failure surfaces of pristine (a) and defect (b) specimens tested at 4° angle (failure loads 44.7 kN and 42.8 kN respectively).

The two loading angles were then analysed separately. For the 4° case it was found that the introduction of a wrinkle slightly reduced the mean failure load (±CV) from 42.50±3.94 kN (pristine) to 41.06±6.08 kN (wrinkle); however this was well within experimental scatter. For the 20° case the mean failure loads (±CV) were 54.94±11.58 kN for pristine specimens and 57.93±5.57 kN for wrinkle specimens. Again, the introduction of a wrinkle defect did not cause significant changes in the failure load considering the experimental scatter. This result was not initially anticipated, as compressive strength reductions of about 33.5%-36% have been reported for quasi-isotropic and cross-ply laminates due to wrinkle defects [4, 8].

This lack of sensitivity to ply waviness in the modified Arcan test can be attributed to two main factors, namely (i) the suppression of delamination from the wrinkle due to the friction-like 'enhancement' of the apparent interlaminar shear strength in the presence of through-thickness compressive stresses, as investigated by Gan *et al*. [8]; and (ii) the fact that, by suppressing delaminations, failure will be driven by free-edge stresses which are not very sensitive to ply waviness. These hypotheses are currently being investigated via a combination of Digital Image Correlation (DIC) data and detailed Finite Element (FE) analysis.

Table I. Mean failure loads and coefficients of variation (CV) for pristine and wrinkle specimens.

Test No	**Specimen type**	**Test angle**	**Mean failure load (kN)**	**Test Repeats**	**CV (%)**
1	Pristine	4°	-42.50	3	3.94
2	Wrinkle	4°	-41.06	2	6.08
3	Pristine	20°	-54.94	4	11.58
4	Wrinkle	20°	-57.93	2	5.57

Table II. Mean through-thickness compressive and shear stresses for pristine and wrinkle specimens tested at two different angles (4° and 20°).

Test No	**Specimen type**	**Test angle**	**Mean through-thickness compressive stress (MPa)**	**Mean interlaminar shear stress (MPa)**
1	Pristine	4°	3.29	47.11
2	Wrinkle	4°	3.18	45.51
3	Pristine	20°	20.88	57.67
4	Wrinkle	20°	22.01	60.49

If pristine and wrinkle specimens are bundled together and the two load cases (4° and 20°) compared, it becomes clear that compressive through-thickness stresses increase the apparent interlaminar shear strength considerably. This effect was studied in depth by Gan et al. [9] using a biaxial testing machine. Following their analysis, the enhanced through-thickness shear strength, S^*_{13}, is assumed to vary linearly with the though-thickness direct stress, σ_{33}, i.e.

$$S^*_{13} = S_{13} - \eta \sigma_{33} \tag{1}$$

where η is a friction-like material parameter and S_{13} is the through-thickness shear strength in the absence of compression. By adopting this assumption, a linear regression over the entire dataset of pristine and wrinkle specimens gives S_{13}=43.67 kN and η=0.71. Alternatively, if the linear regression is done over the pristine data only, then the coefficients become S_{13} = 44.25 kN and η=0.65.

Koerber *et al.* [10] conducted biaxial tests on the same material system using off-axis tests on unidirectional laminates, therefore studying different combinations of in-plane compression σ_{22} and in-plane shear τ_{12}. If the material is assumed transversely isotropic, then their results can be compared with the Arcan test results via 'failure envelopes' as shown in Figure 5.

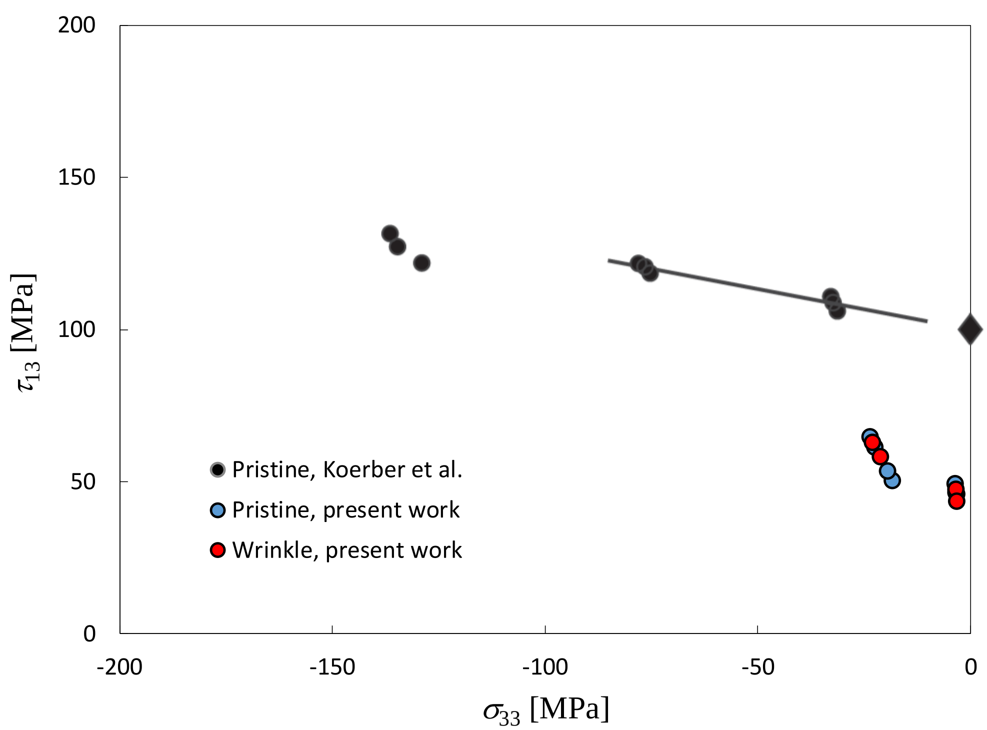


Figure 5: Failure envelopes for Arcan tests and the data from Koerber *et al.* [10] assuming transverse isotropy.

The considerably lower strengths observed with the Arcan tests are attributed to the fact that a *quasi-isotropic* layup was used here in contrast with the *unidirectional* layup used by Koerber *et al* [10]. A quasi-isotropic layup will result in the generation of thermal residual stresses (after the high-temperature autoclave cure) and free-edge stresses due to the stiffness mismatch between plies of different orientations. The presence of very high free-edge stresses, caused by the superposition of thermal residual stresses and mechanical loading, is also believed to be responsible for the negligible differences between pristine and wrinkle specimens in Figure 5. However, the Arcan test data and the results by Koerber *et al* [10]. show a similar trend of higher interlaminar shear strength with transverse compression which supports the assumption of a friction-like enhancement effect as described by equation (1).

CONCLUDING REMARKS

A modified Arcan fixture has been developed for the testing of composites containing out-of-plane ply waviness (wrinkling) defects under combinations of interlaminar shear and through-thickness compressive stresses. The ratio of through-thickness compression to shear loading is controlled by the angle of the specimen with respect to the cross-head movement. Pristine specimens as well as specimens containing controlled wrinkle defects were tested at 4° and 20° angles which resulted in ratios τ_{13}/σ_{33} of 14.3 and 2.7, respectively. The interlaminar shear strength was found to be strongly influenced by through-thickness compression, in agreement with previous work reported in the literature. However, the presence of ply wrinkling did not affect the measured interlaminar shear strength significantly. This suggests that the compressive loading suppresses any delamination arising from the defect and high free-edge stresses, which are not strongly influenced by the presence of ply waviness, have an influence on the overall failure. Digital Image Correlation (DIC) and 3D Finite Element analysis are currently being used to interpret these results further.

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