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EXPERIMENTAL IDENTIFICATION OF ARAMID FIBRES REINFORCED THIN LAMINATES BEHAVIOUR IN COMPRESSIVE STRESS STATES

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ABSTRACT

The overall behaviour in plane stress compressive stress states of thin aramid fibres reinforced laminates is investigated by means of four points bending tests, focusing on non-linearity and failure modes. Test results on woven fabric composites with [0/90], [+/-45] and [45/0/45] stacking sequences are presented. The tensile behaviour and the residual strength of the laminates after the compressive tests are reported for each laminate type. The different roles that aramid fibres yielding, composite shear non-linear response and fibre microbuckling can have on woven fabric Kevlar reinforced laminates response are pointed out.

1. INTRODUCTION

The yielding and the non-linear compressive behaviour of aramid fibres are well reported in the existing literature, and are generally related to the intrinsic fibrillar microstructure of a bare aramid fibre [1,3].
This intrinsic failure mode is related to the low strength of Kevlar reinforced laminates in compression [2] but, as the fibre can experience high strain levels before the final failure, laminates toughness is considerable. As it was shown in [12] the occurrence of the fibres yielding does not imply the complete loss of load carrying capability in aramid reinforced beams and rings in bending stress-strain states.
While this mechanism is peculiar of the aramid fibres, a typical non-linear behaviour of long fibres reinforced composites occurs when matrix and fibre-matrix interface undergoes a shear stress state, as in a tensile or compressive uniaxial test performed on angle ply laminates. This non-linear shear response plays a key role in the instability of compressed fibres embedded in a polymer matrix. This phenomenon, known as microbuckling, is the typical compressive failure mode of carbon reinforced composite materials [13].

The paper reports the results of an experimental campaign aimed to evaluate the influence of all the aforementioned non-linear behaviours and failure modes on the compressive overall response of thin aramid reinforced woven fabric laminates.
The effects of the activation of these inelastic deformation processes on the residual tensile strength after compression are moreover considered.
Unlike carbon fibres it is in fact known that aramid reinforcement can retain remarkably high residual tensile strength after very high compressive strain or even kinking has occurred [2].
Experimental tests were performed on 0/90 and +/-45 homogeneous lay-ups as well as on a 45/0/45 laminate. The specimen typology adopted and the compressive test methodology were based on the four point bending tests on a sandwich specimen, suggested by the ASTM standards [5,6]. The standard is referred to the characterisation of unidirectional polymer matrix composite materials tested in the direction of fibre reinforcement. In this work the test methodology has been applied to woven fabric composite with different fibre alignments, focusing on the identification of the non-linear behaviour modes in the response of the compressed skin.
Capsizing the specimen a tensile test could be performed, with the same test fixture, on the skin previously failed in compression, thus leading to the evaluation of the tensile behaviour and of the residual tensile strength after the compressive failure.
The presented experimental data were obtained with a standard dimensioned specimen. All observed failures were characterised by local wrinkling. Values of ultimate compressive strain are, for this reason, to be considered as a lower bound to the real material ultimate compressive values [6].

2. TEST METHODOLOGY, STRAIN GAUGES AND SPECIMEN TYPES

Tests were performed on 0/90 cross ply, +/-45 angle ply and on a 45/0/45 lay-up. Laminates were manufactured with Kevlar 49, 1270 denier, Cycom 985 epoxy resin, 5H satin weave. The ply nominal fibres volumetric fraction is 42÷48%.
Compressive tests were performed using the ASTM standard D5467-97 as a guideline. The specimen geometry suggested by the standard was adopted.
Hexcel 1/8-5056-0.02 aluminium honeycomb with 129.75 kg/m^3 density was used as core material. A 0/90 two grid strain gauge was applied in the middle of the specimen. Two additional strain gauges were applied in the load direction on the skin axis to check the uniformity of the specimen strain state and to provide data at different locations along the specimen axis. Tests were performed on an MTS Alliance RF/200 static test system adopting displacement control with a 1.55 mm/min head speed. Load was applied by four 20 mm diameter steel cylinders. Pads were interposed between cylinders and skins to avoid local failure in the load application area.
Stress-strain curves were evaluated from the total applied load and strain gauges time histories by applying the equations suggested in the standard.
Compressive tests were prosecuted up to the maximum load carrying capability of the specimen. Subsequently, the specimen was capsized and introduced in the same fixture to perform a tensile test on the previously compressed skin. An extensometer was applied across the skin failed region to record the material tensile behaviour in the most damaged zone, while the strain gauges not debonded during the compressive failure process provided data for the surrounding regions.
As local wrinkling occurred in the failed zone, the strain data collected by the extensometers showed an initial behaviour characterised by very low tangent stiffness.

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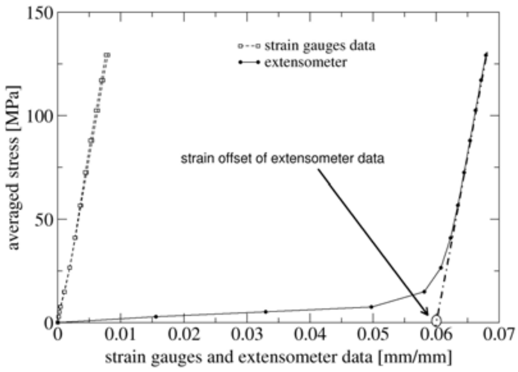

Fig. 1 –Tensile tests strain data reduction procedure.

During this phase the existing folds were removed. The end of the fold removal process and the consequent beginning of a true tensile test could be clearly identified from a sudden increase in the tangent stiffness.
To compare the strain data referred to the tensile behaviour of the skin in the wrinkled zone with the strain data collected by strain gauges in the remaining portions of the specimen, the first have been shifted of a strain offset as indicated in Fig. 1.

3. FIBRE YIELDING IN CROSS PLY LAMINATES

The cross ply laminate specimens set consisted of four sandwich specimens with $[0]_4$ lay-up upper skins. The skin overall average thickness was 0.95 mm.
For each test, recorded data from three strain gauges and the load time history allow to obtain three stress-strain curves, each one representing the single specimen behaviour at different locations along the specimen axis. A least square spline fitting curve has been computed for the complete data points set (Fig. 2).

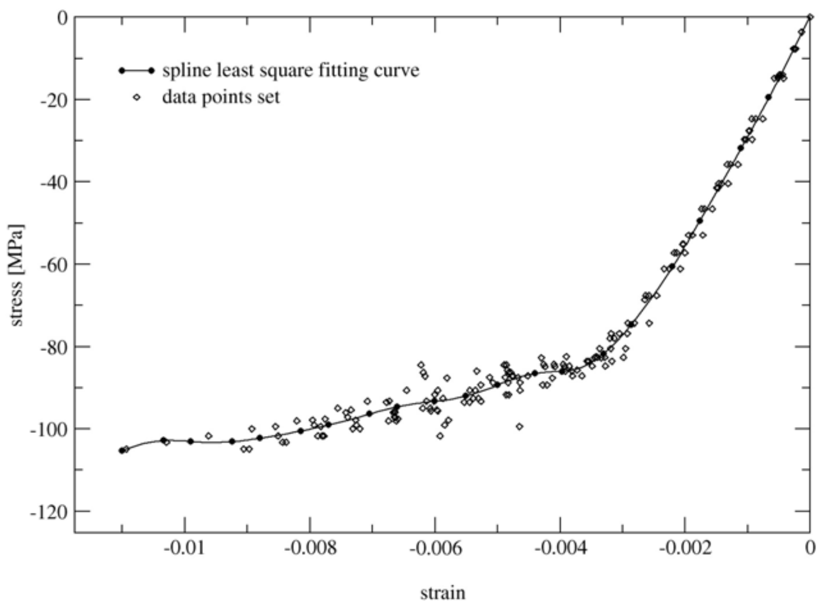

Fig. 2 –Spline least square fitting curve and data points sets for compressive tests on cross ply laminates

The non-linear behaviour of the laminate is evident from the results. Linear regressions have been carried out in both strain ranges (Tab. 1).
The transition between the linear elastic and non-linear regions can be precisely identified [7]. The linear regressions in both ranges intersect at ε=0.00296 and σ=82.2 MPa.

	Tangent Modulus [MPa]	Standard Error [MPa]
Linear Elastic Range	30452	277
Non Linear Range	3748	150

Tab. 1 – Linear regression coefficients for bilinear cross ply laminate response

The curves derived from a single specimen at different locations appear to indicate that the transition point can be reached at different strain levels inside the same specimen (Fig. 3).
The strain distribution is non-uniform in the specimen as non-linear mode is activated. All data indicate the occurrence of residual permanent strain at null stress level after specimen failure.

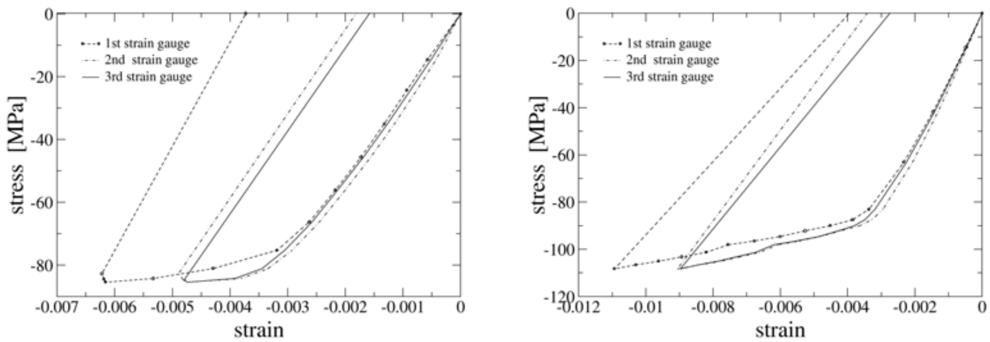

Fig. 3 – Stress-strain curves at different location of two specimens

The non-linear response of the laminate is to be interpreted as a consequence of an intrinsic fibre microbuckling process. To show this a comparison can be carried out with the fibre compressive response reported in [1]. The reported data are collected from tests carried out on a single Kevlar 49 fibre placed on a PMMA beam. The kink bands formation process in the fibre microstructure is described in detail and a stress-strain non-linear curve is derived from Raman spectroscopy data. The compressive response of the single fibre reported in [1] can be reduced to an averaged stress-strain curve referred to the fibre reinforcement volumetric content declared for the fabric plies tested (23% mean value in the load direction). This reduced curve is compared with the averaged response obtained in the tests (Fig. 4).
The comparison shows that though the reinforcement is misaligned due to the fabric style and is embedded in the matrix phase the fibre intrinsic microbuckling process strongly influences the response of this thin laminate. The differences between the ply and the fibre reinforcement response can be attributed to fibres weaviness and to matrix and transverse reinforcement behaviours.
The final failure occurred with the development of local wrinkling (Fig. 5). Experimental evidence shows the absence of fibre breakage after the failure. No in-plane kink band of the fibre yarns is detectable. Due to the weave pattern and to the considerable fibres weaviness at warp/filling interlacing locations, both a true compressive failure mode of the fabric as well as the instability of the locally debonded laminate can be hypothesised as failure modes. The ultimate stress-strain level and the measured toughness can however be interpreted as lower bounds with respect to the compressive properties of the laminates.

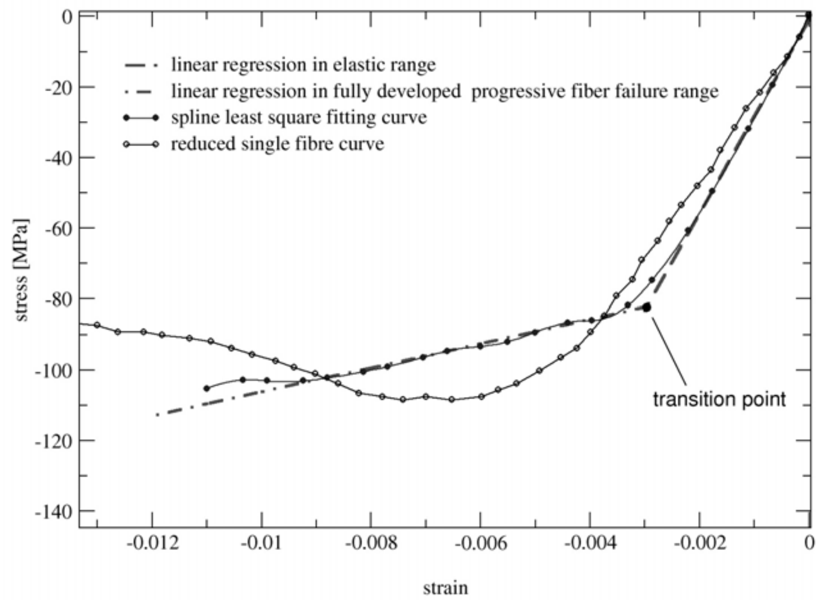

Fig. 4 – Averaged ply curves and fibre reinforcement reduced response

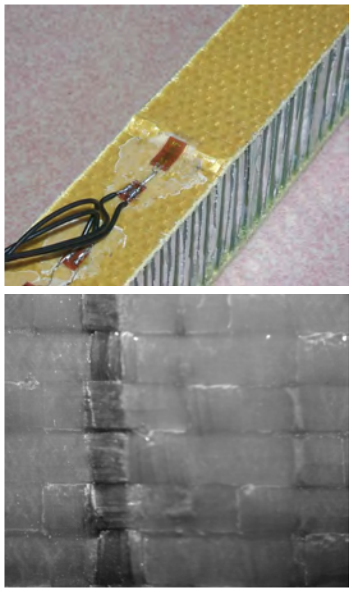

Fig. 5 – Final failure in the compressive cross ply tests

4. RESIDUAL TENSILE STRENGTH AND BEHAVIOUR OF CROSS PLY LAMINATES

The overall results of the tensile tests performed on three of the cross ply specimens previously failed in compression are reported in Figs. 6-7. For each test it was possible to measure the strain from the extensometer in the failed zone and from two undamaged strain gauges Data presented in Fig. 6-7 are referred to the complete data points set in the three tests.

Fig. 6 indicates that the residual tensile stiffness in the failed zone and in the remaining portion of the laminate are the same. As the tensile behaviour in the fibre direction is dominated by the fibre properties, this mean that the local failure and wrinkling did not affect the fibre stiffness more than the pure compressive stress-strain state reached in whole laminate. A single residual tensile stress-strain curve can describe the behaviour of the skin.

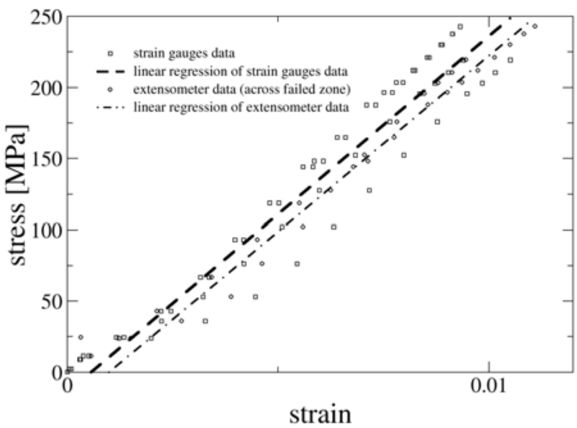

Fig. 6 – Strain data reduction for tensile test on tensile cross ply specimen

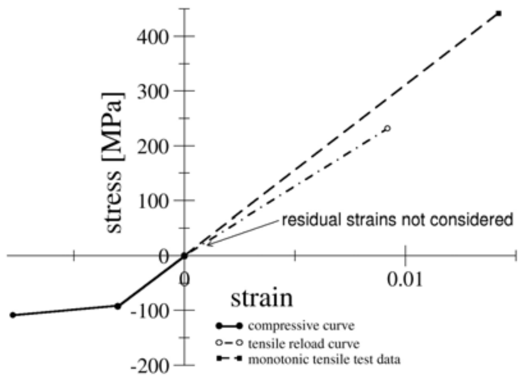

Fig. 7 – Compressive, tensile original and tensile after compressive failure curves

In Fig. 7 the compressive response and the averaged residual tensile behaviour are shown and compared with a monotonic tensile test curve taken from [8]. The final failure in the tensile test occurred along the same transverse failure line developed in compression (Fig. 5). A 20% reduction of tensile modulus and a 48% reduction of tensile strength have been recorded in the tests with respect to monotonic tensile tests data. The results indicate that the laminate retained a significant tensile stiffness after compressive tests prosecuted up to 10000 $\mu\varepsilon$, well beyond the occurrence of fibre yielding.
The evaluated tensile residual strength shows that the kinked yarns in the wrinkled zone retained almost half of their initial tensile load carrying capability.

5. ANGLE PLY AND 45/0/45 LAMINATES BEHAVIOUR

The test procedure and data reduction methodology described for the cross ply laminates have been applied to a set of three specimens with $[+/-45]_4$ lay-up upper skins (0.95 mm average thickness). The complete compressive tests data points set has been fitted by a fourth order polynomial least square curve, showed in Fig. 8.
A non-linear behaviour is evidenced in the recorded response. Mohr's formula shows that the normal compressive stress and the shear stress acting in material axes coordinates are 0.5 times the stress in load direction. Comparison between the 82.0 MPa level attributed in par. 3 to the transition point, corresponding to the fibre yielding onset in the cross ply tests, seems to indicate that fibres yielding is not activated in the +/-45 compressive tests.
Assuming that the reinforcement response is linear, the non-linearity in Fig. 8 can be correlated to the typical non-linear shear stress-strain response of long fibre reinforced composites. This non-linear behaviour can be attributed to several mechanisms activated in the composite material, such as plasticity and crazing of the polymer matrix as well as damaging of the matrix-resin interface [9].
Fig. 9 shows the shear response derived from a uniaxial tensile test on a +/-45 laminate, reproduced from the data reported in [8] for the same material. The specimen typology and manufacturing technologies adopted in [8] were different with respect to the sandwich specimens used in this experimental campaign.
Assuming the curve reported in Fig. 9 as the shear-stress response of the material, a prediction can be carried out with regard to the microbuckling of the fibre embedded in the matrix.
The compressive stress related to this failure mode, typical of long fibre-reinforced composite and specifically of carbon reinforced plies, can be predicted through the theoretical formulation developed in [10, 11] and extended to stress states including shear in [4].
According to this formulation fibre microbuckling can be predicted by knowing the shear-stress response of the composite and the value of the maximum misalignment angle of the fibre with respect to the nominal reinforcement direction.
Applying the graphic methodology described in [4], the misalignment parameter corresponding to the experimental averaged ultimate stress of 78 MPa turns out to be equal to 5.5 deg. By varying this misalignment angle the maximum compressive sustainable stress of a +/-45 ply compressed in uniaxial test can be evaluated (Fig. 10). The 46% declared averaged fibres volumetric content of the plies was used in the computation. A 5.5 deg misalignment can be considered high for unidirectional tapes, where the estimations carried out in [4,14] gave fibres misalignment maximum values of 3.5÷4 deg. The predicted maximum compressive stress for the fabric ply at hand, with a 4 deg fibres misalignment in the laminate plane, turns out to be 85 MPa.

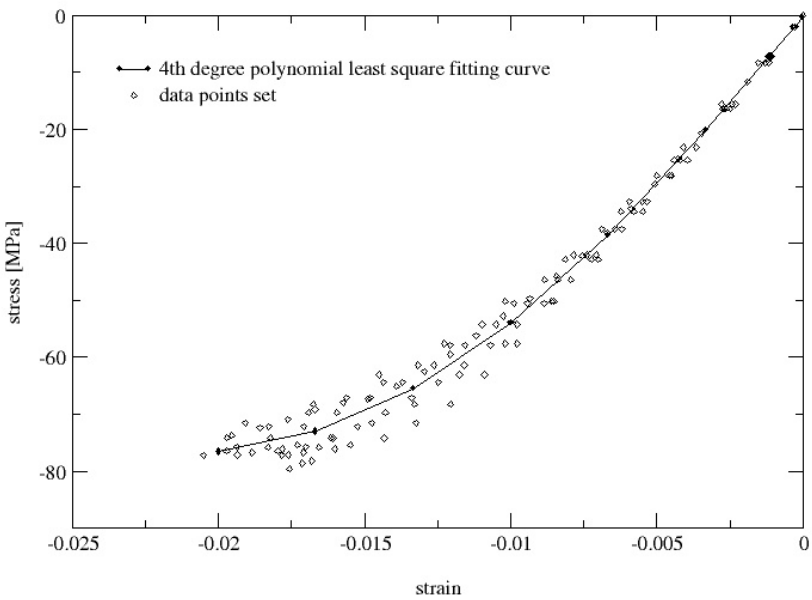

Fig. 8 - Least square fitting curve and data points sets for compressive tests on +/-45 angle ply laminates

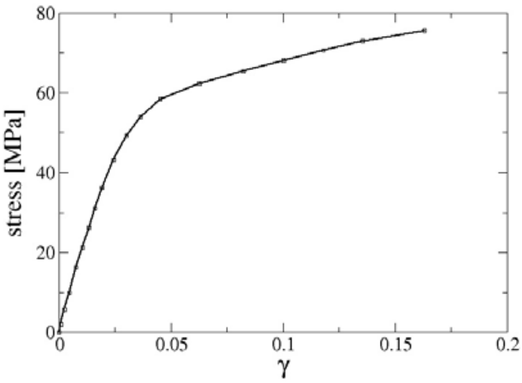

Fig. 9 – Shear stress response in a uniaxial +/-45 tensile test [8]

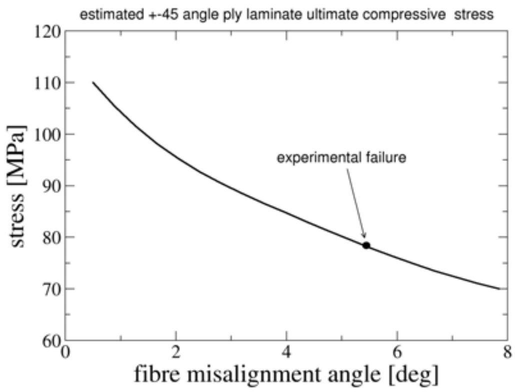

Fig. 10 – Estimated ultimate stress of a +/-45 uniaxially compressed ply at different fibre misalignment angles

The results of this evaluation suggest that Kevlar reinforced composite can undergo stress states where the microbuckling of the fibre-matrix system occurs before the fibre yielding in compression. The observed failure modes were characterised by wrinkling developed along lines with +/-45 orientation with respect to the specimen axis.

The residual strength tensile tests results are reported in Fig. 11. Stress-strain experimental data are fitted by 2nd order polynomial curves. Tests were performed on three specimens. Fig. 11 reports, also, the compressive response and the results, reported in [8], of the monotonic tensile tests on +/-45 specimens.

A significant difference has been detected in the behaviour of the failed zones with respect to the surrounding regions. The tensile stress-strain curves collected by the strain gauges did not exhibit a significant degradation of the mechanical properties with respect to the compressive curves. The curve derived from extensometer data, shifted of the amount of strain related to the fold removal, indicates, on the contrary, significantly degraded mechanical properties in the failed zone.

This could be predicted by observing the condition of the laminate in the failed zone, where matrix appeared to be severely damaged and fibres exhibit local kinking (Fig. 12).

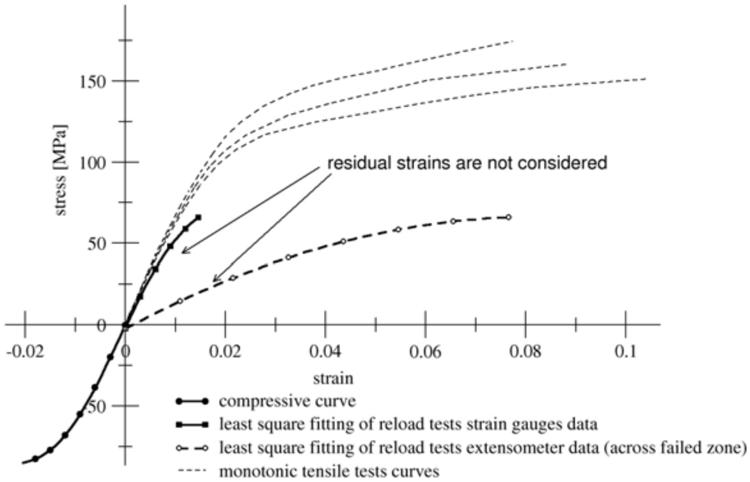

Fig. 11 – Compressive, tensile original and tensile after failure

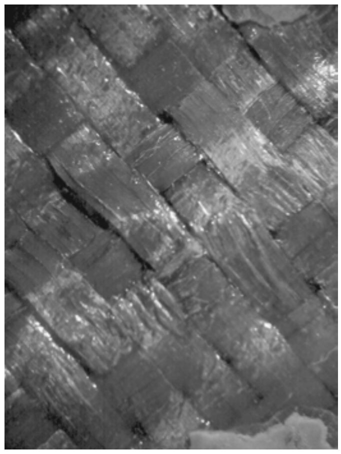

Fig. 12 -Final failure in compressive angle ply

Damage localisation produced strain localisation and a tensile failure in the extensometer region at a stress level of about 0.5 times the values recorded in [8] for the monotonically loaded material. The toughness of the skin was severely reduced with respect to the monotonic tensile performance. Data indicate that a local compressive failure of uniaxially compressed +/-45 specimens affects significantly the subsequent tensile response of the material in the load direction.

The compressive tests on the 45/0/45 laminates were performed on two specimens. The averaged thickness of the laminates was 0.715 mm. Fig. 13 shows the averaged compressive force per unit width vs. strain curve evaluated with a 3^{rd} order polynomial least square fitting of the complete data points set.

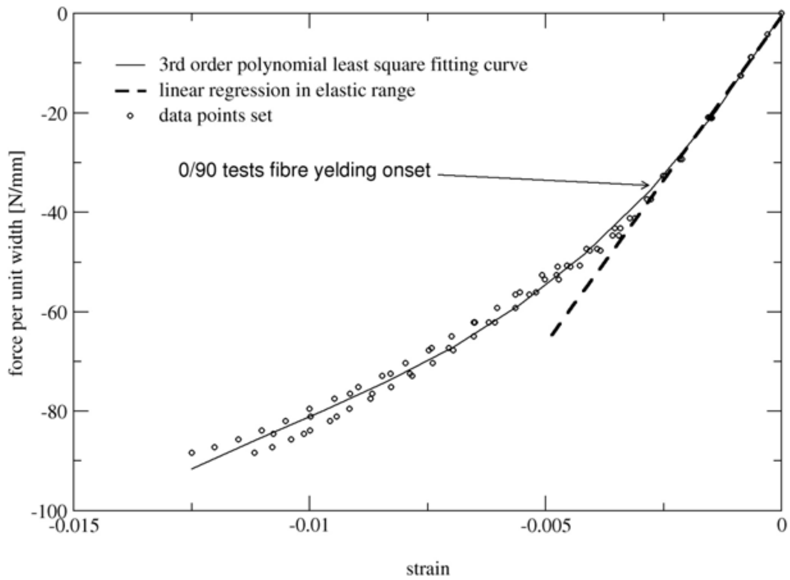

Fig. 13 - Least square fitting curve and data points sets for compressive tests on 45/0/45 laminates

The deviation from linear behaviour evidenced in Fig. 13 has occurred approximately at the strain level evaluated for the transition point in the compressive tests on the cross ply laminates. Non-

linear behaviour could thus be attributed to the intrinsic failure mechanism of the fibre in the 0/90 ply.
By evaluating the elastic stiffness matrix of the orthotropic ply this can be confirmed even by a simplified laminate model. The model is based on the classical lamination theory where the +/-45 plies are assumed to remain in the linear elastic range, while the response of the 0/90 ply is represented by the curve derived from compressive tests (Fig. 2). Fig. 14 compares the predicted and experimental response. Fig. 15 shows the final compressive failure mode.

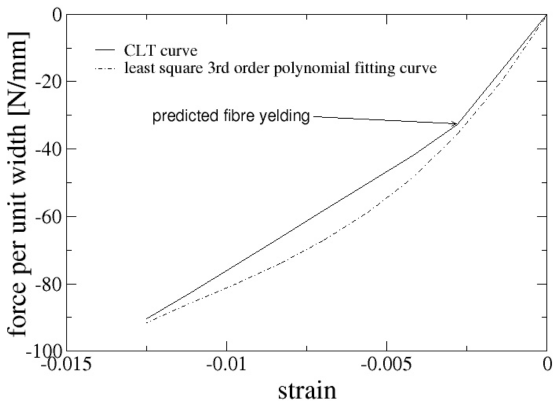

Fig. 14 – Numerical simplified laminate response

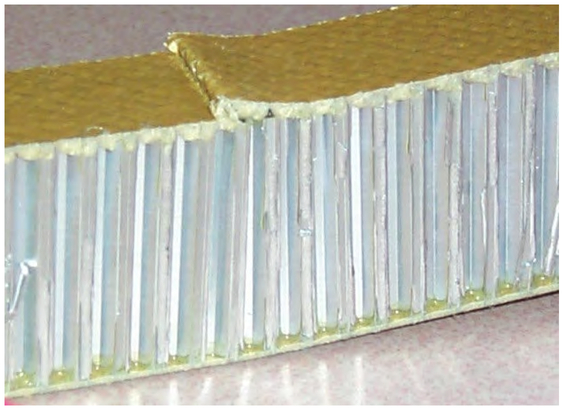

Fig. 15 – Final failure in the compressive tests on a 45/0/45 laminate

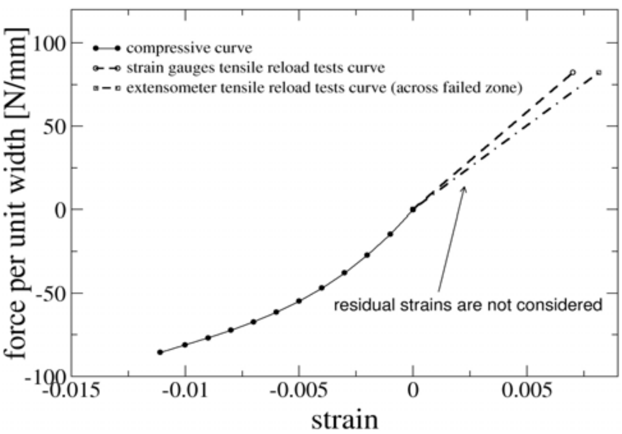

Fig. 16 – Compressive and tensile after compressive failure curves of 45/0/45

The failure of the laminates in the compressive tests occurred at approximately the strain level corresponding to the failure of cross ply laminates (see Figs. 13 and 2). Failure mode is similar.
The response observed during tensile tests on the failed laminates was linear. Tests showed a slightly different stiffness between the wrinkled region and the remaining portions of the laminate.
The laminate appears to retain a significant stiffness but fails at a strain level lower with respect to the tensile test on 0/90 cross ply laminates (Fig. 16).

6. CONCLUSIONS

The overall compressive response of 0/90 and 45/0/45 Kevlar fabric laminates has been found to be strongly influenced by the aramid fibres compressive yielding, a well-known mechanism studied on single fibres and on unidirectional tapes. Woven fabric 0/90 plies exhibit, as expected, low compressive strength level, but fail at considerably high strain levels, thus leading to high toughness values. The cross plies lay-ups retain a very high residual tensile stiffness and a remarkable residual tensile strength after compression, even if kinking of the fibres and folding of the laminates have occurred.

Compressed 45/0/45 laminates have showed a valuable load carrying capability which can not be explained without taking into consideration the non-linear behaviour of the 0/90 ply.
Shear induced non-linearity and in-plane fibres microbuckling characterise, on the contrary, the compressive response of +/-45 angle ply laminates. The toughness of these laminates in compression is comparable with the cross ply lay-ups, but failure modes can be characterised by a local degradation of the shear carrying capability. This leads to poor toughness properties and to a premature failure if tensile loads are subsequently applied.
As far as energy absorption capabilities, ultimate stress levels and residual strength of laminates are concerned the present research shows that aramid fibre yielding, non linear shear response and fibre microbuckling have to be taken into account in the design process to correctly predict Kevlar laminates behaviour.

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