ICAS-96-5.4.2

TEXTILE ROUTES TO DAMAGE TOLERANT COMPOSITE STRUCTURES FOR AEROSPACE APPLICATIONS

Backhouse, R.[#], Bibo, G. A.[*], Hogg, P. J.[*] and Mills, A.[#]

[#]Cranfield University of Technology, Cranfield, UK
[*]Department of Materials, Queen Mary and Westfield College,
Mile End Rd, London E1 4NS, UK

Abstract

An experimental programme has compared the mechanical properties of a conventional composite laminate based on an assembly of unidirection prepreg plies, and a laminate manufactured using a textile reinforcement. The textile was a triaxial non-crimp fabric produced from T300 carbon fibres. The experimental programme showed that the textile composite performed well in comparison to the unidirectional prepreg laminate particularly with respect to critical properties such as compression after impact strength. This coupled with manufacturing cost benefits suggests that the textile route is a promising approach to producing damage tolerant composite structures.

Introduction

As evidenced from the extensive use in the military sector, composites are viewed as essential material forms for the manufacturing of major structural items. Relatively speaking, the specification for designs that arise from a military interest are performance driven, while the civil/commercial area is more cost conscience. A kg of weight saving translates to increased revenue or reduced operating costs, however, if the expense incurred to achieve a weight saving can not be met by the manufacturer the aircraft unit cost may rapidly escalate. The customer (airline) must expect a higher return on the more expensive aircraft over its life cycle otherwise a heavier cheaper product that realises a profit is more attractive to the operator.

In order to offer a competitive composite structure, the high raw material costs must be offset by intelligent manufacturing techniques - tape laying and tow placement are already in commercial use whilst more fundamental approaches are being developed to address, directly, the high material costs. In particular the exploitation of textile technology to produce net shape preforms and rapid material deposition rates. In the conservative world of aerospace, the customer (apart from the regulatory bodies) must be convinced by reliability when new technology is introduced. These aspects have been demonstrated in the demanding military arena and are reflected in the confidence the major civil aircraft manufacturer's have by investing in design methodologies and tooling for composites. However, the most used form of monolithic structural composite, unidirectional prepreg tape, is susceptible to significant strength reductions associated with delaminations introduced by manufacturing defects and service impacts. Conservative design must take this into account when specifying material design allowables.

The use of textile technologies in the manufacture of aircraft structures may prove beneficial for two reasons.

Firstly, textile machinery can organise fibres rapidly and repeatedly creating complex shapes for preforms or flat sheet materials with pre-set fibre orientations and high areal weights. This may be expected to translate into lower unit manufacturing costs for a given part volume. Secondly, the creation of certain textile forms eliminates the weak interlaminar regions that characterise a laminate based on unidirectional plies. This in itself reduces the susceptibility to delamination in the material, raising the damage tolerance and off-setting possible negative factors resulting from non-optimal fibre arrangements in the textile compared to a UD ply stack.

A key textile form being developed for composite applications is the non-crimp fabric or warp knitted multiaxial fabric. This material combines multiple layers of well aligned non-woven fibres into a textile which is knitted together with a secondary stitching yarn. The product allows rapid lay-down of multiple plies in a single operation which may be consolidated into a final part using various resin infusion techniques.

The objectives of this paper are to show that the basic mechanical properties, and in particular, the compression after impact (CAI) strength of composites are not compromised as a result of using non-crimp fabrics. And that manufacturing advantages may be realised cost effectively in a real production environment.

Materials and Testing

The class of textile material form under investigation was a triaxial warp knit or non-crimp fabric (NCF) which distinguishes itself from two dimensional weaves and full three dimensional constructions by utilising a secondary yarn that binds tow 'bundles' of differing orientations together forming a 'blanket' with near zero crimp, figure 1.(1)

A laminate was constructed from the non-crimp fabric, (45 {220 g/m^2},-45 {220 g/m^2}, 0 {376 g/m^2}), such that it had four blankets with the following lay up, $[(45,-45,0),(0,-45,45)]_S$.

An equivalent construction was fabricated from unidirectional prepreg tape, $[45_2,-45_2,0_6,-45_2,45_2]_S$, to reflect the lay-up and mass distribution of the fibres in the non-crimp fabric.

The Ciba (Hexel) 914 resin was used for both material systems, which were processed using autoclave curing. Fibre volume fraction details are given in table 1.

Basic mechanical testing was carried out to the appropriate ASTM test standards in order to compare the performance of the non-crimp fabric in tension and compression with its equivalent unidirectional prepreg tape counterpart. Specimens were strain gauged on a single surface to facilitate stiffness (tension and compression) and, using cross gauges, Poisson's ratio (tension) measurements. These measured engineering values were also compared against theoretically derived terms from the composite membrane stiffness matrix.

Impact and compression after impact was conducted on both material systems in accordance with the Boeing test specification, using a Rosand impact machine over a range of impact energies that induced damage initiation to extensive contact and back face fracture.

Cost Benefits

The following consists of an estimation for the cost of a triaxial carbon fibre composite laminate (the system investigated in this study) using unidirectional prepreg tape and non-crimp fabric.

i) Unidirectional Prepreg Tape

The current commercial cost per square meter for a typical T300 fibre based prepreg is £14.20 (for over 1000 square meters). Manufacturing a laminate 300 mm by 600 mm in the triaxial construction used here, assuming no waste would require 5.04 m^2. The material cost is £71.57.

ii) Non-crimp Fabric

The non-crimp fabric used in this investigation also consisted of a T300 carbon fibre knitted to produce a fabric weighing 816 g/m^2 at a cost of £44 per kg. The non-crimp fabric laminates utilised 4 blankets, hence the fabric portion of the overall cost of a 300 mm by 600 mm plate is £25.85. To achieve a fibre volume fraction of 54% (that used in the study) about 0.36 kg of epoxy resin was used (i.e. 300 mm by 600 mm plate). The cost of a typical high performance RTM epoxy resin is £39 per kg, giving a resin contribution to the overall cost of the laminate of £14.04. The total laminate cost for the non-crimp fabric is £39.89.

A practical application is likely to realise significant extra cost benefits by virtue of reduced scrap content and lay-down time.

Results

Tension and Compression

Representative stress-strain curves for the non-crimp fabric and unidirectional prepreg tape, in tension and compression, are shown in figures 2a and 2b respectively. The tensile strength and stiffness of the unidirectional prepreg tape was clearly superior to that of the non-crimp fabric, figure 3a and 3b. A similar trend was observed in compression, figure 4a and 4b. The superiority of the unidirectional prepreg tape in terms of strength and stiffness may partly be attributed to differences in fibre volume fraction, table 1.

Figure's 3b and 4b show a comparison of 'engineering' modulus for the non-crimp fabric and unidirectional prepreg tape with predicted modulus using classical laminate theory, table 2. The measured modulus for the unidirectional prepreg tape and non-crimp fabric compare well with their respective predicted modulus from classical lamination theory. The measured Poisson's ratio for the unidirectional prepreg tape and non-crimp fabric compare very well with their predicted data, figure 5.

Photographs of the fracture state of representative non-crimp fabric and unidirectional prepreg tape tensile and compression specimens are depicted in figure 6. Damage at fracture, in the non-crimp fabric, was relatively localised compared with the unidirectional prepreg tape. Tensile tests resulted in almost complete delamination of the unidirectional prepreg tape specimen, figure 6a, while the non-crimp fabric remained intact other than at the fracture site, figure 6b.

Compression tests resulted in significant debris with delamination occurring between sublaminate groups (i.e. 0° and ±45°) for both the unidirectional prepreg tape and non-crimp fabric, figure 6c and 6d respectively. The initial fracture occurring in the unidirectional prepreg tape was observed to be delamination of the outer ply (45°) group.

Compression after Impact

The individual test points for each material system with a buckling estimate for the Boeing size coupon is shown plotted on the compression after impact curve, figure 7. The results are presented in the form of residual compression strength versus the delamination damage extent (perpendicular to load application) to emphasise the resistance of propagation of the damage created during impact and to separate any effects due to a greater susceptibility to damage during impact itself.(4) The trend and absolute values for the compression after impact data reveals little difference between the non-crimp fabric and unidirectional prepreg tape system.

The buckling estimate for the unidirectional prepreg tape is an upper bound as it is derived from classical laminate theory and does not incorporate a finite shear stiffness reduction factor.(5) This coupled with possible eccentric load introduction implies that at the lower bound of delamination damage there may be competing mechanisms for failure.

Discussion

Cost Benefits

Although the figures used to estimate the cost of manufacturing equivalent laminates using two different processes does not include issues such as labour time and additional equipment e.g. lay-up for the unidirectional prepreg tape, consumables for the bagging etc. and capital investment costs for equipment such as an autoclave, it would be expected on this basis that the non-crimp fabric is still likely to out perform the unidirectional prepreg tape i.e. significantly reduced labour time for preparation of laminate lay-up. The cost to an end user for the non-crimp fabric may increase if an intermediate party becomes involved, e.g. prepregger.

Other issues that have not come into the costing equation, some of which are relatively subtle, also favour the non-crimp fabric. These include requirements for refrigeration of the unidirectional prepreg tape compared with the necessity of only providing refrigeration for the resin in the case of the non-crimp fabric. The additional storage space required for the non-crimp fabric is compensated for by the reduced space for the resin. The non-crimp fabric does not have a shelf life and is more flexible in that it offers options on the route of manufacture e.g. prepregging and resin film infusion semi-processing with an autoclave cure and resin transfer moulding. Most importantly the non-crimp fabric has a built in potential for further reducing costs by allowing a more rapid ply deposition rate by virtue of the high fabric weights. Moreover, the non-crimp fabric is better suited to the production of complicated parts and better placed to exploit near net shape manufacturing, leading to less waste.

Tension and Compression

The ability to predict the macro-mechanical behaviour of the composite is very dependent upon the starting information (unit ply or lamina data). Here good agreement was found between the measured macro-behaviour ('engineering' modulus and Poisson's ratio) and that derived from the membrane or [A] matrix using classical laminate theory for both the non-crimp fabric and unidirectional prepreg tape in tension.(6)

The over estimates of composite stiffness in compression for both the non-crimp fabric and unidirectional prepreg tape may be partially attributed to the use of lamina tensile stiffness data in the analysis (equivalent starting compression data was not available for its fibre resin combination). Two schools of thought suggest this may be attributed to either strain softening or fibre misalignment.(7,8)

The carbon non-crimp fabric laminate's 'engineering' property data was estimated well by the classical laminate theory approach using lamina data to represent a 'ply', despite the heterogeneous mesostructure arising from the textile derived reinforcement architecture. The carbon non-crimp fabric also has a high local fibre volume fraction arising within the tows. The manufacturing technique for the resin impregnated non-crimp fabric has been extensively investigated and been shown to result in tows with excellent wetting. This achieves a high property translation efficiency within the geometrical constraints of local fibre waviness and bundle constriction.

The non-crimp fabric in tension and compression does not achieve the same level of global strain at failure as the unidirectional prepreg tape does, figure 2a and 2b, although the fibres themselves may. The stitching may locally induce a stress concentration resulting in minor premature fibre failure at relatively low global stresses. The fractured fibre(s) will further cause a local perturbation in the strain field with adjacent fibres directly affected.(9) Due to the inability to determine whether there is a strain magnification within the blanket, a more sophisticated approach to modelling (Finite Element Analyses) or measuring (Raman Spectroscopy) the effect stitching has on the overall properties of the composite may be required.

While the issue of strength may be some what clouded by differences in fibre volume fraction, it is clear that small levels of tow crimp may cause a reduction in strength.(10,11)

Compression after Impact

Despite the reduction in the 'as received' strength of the non-crimp fabric compared with its unidirectional prepreg tape equivalent, its performance in the aerospace industry's current design limiter, the compression after impact test, reflects a high level of strength retention.

The ability of the non-crimp fabric to maintain a high proportion of its undamaged strength may be linked to the mechanism associated with propagating the delamination fracture surfaces. The orthotropic nature of the material either side of the crack face would assist in setting up high interlaminar stress resulting from the desire of each crack surface to deform out of plane through. The lay up was constructed such that all delamination prone planes were within blankets and hence had through thickness stitching, figure 8. The possible mixed mode of crack propagation under the externally applied compression may be inhibited by the bridging effect of the stitch for mode I purposes.(12)

A high percentage strength retention after impact is required to allow these material forms to be competitive with the industry accepted metals. As this branch of the textile process improves in terms of producing composite fabrics, as does knowledge on how to mechanically enhance fracture toughness, these fabrics may exhibit superior damage tolerance to their unidirectional prepreg tape counterparts. Increases in fibre volume fraction may directly affect the undamaged strength and increase the stiffness, while with novel processing technology the industry may be better placed to take advantage of further innovations and exploit the potential to reduce manufacturing costs.

Conclusion

The experimental programme has shown that the basic mechanical properties of laminates based on non-crimp fabrics are somewhat inferior to those of laminates produced from unidirectional prepreg tape. However, these reductions are not excessive. The downstream property of compression after impact, which is used as a measure of the damage tolerance of the composite, is comparable in both material forms suggesting that for practical applications there is little penalty to be suffered by the airframe manufacturers by specifying a manufacturing approach based on fabric composites.

Acknowledgements

Mr. G A Bibo was funded by the DRA, Farnborough, Hampshire, UK.

References

(1) **Bibo, G. A. and Hogg, P. J.** Review: The role of reinforcement architecture on impact damage mechanisms and post-impact compression behaviour *Journal of Materials Science 31 (1996), pp 1115-1137.*

(2) **Ciba (Hexcel) Data Sheet.**

(3) **Personal Communication** Dr. J. Hodgkinson, Imperial College London.

(4) **Bibo, G. A., Hogg, P. J. and Kemp, M.** Damage tolerance of UD prepreg tape and textile reinforced glass epoxy *3rd International Conference on Deformation and Fracture of Composites, Surrey, UK, March 1995, pp 374-383.*

(5) **ESDU Data Sheet 80023.**

(6) **Agarwal, B. D. and Broutman, L. J.** Analysis and performance of fibre composites *John Wiley & Sons, New York, 1980.*

(7) **Stecenko, T. B. and Stevanovic, M. M.** Variation of Elastic Moduli with strain in carbon/epoxy laminates *Journal of Composite Materials, Vol 24, Nov. 1990, pp 1152-1158.*

(8) **Mrse, A. and Piggott, M. R.** Relation between fibre divagation and compressve properties of fibre composites *35th international SAMPE Symposium, April, 1990.*

(9) **Galiotis, C. and Chohan, V.** Fracture characteristics and interfacial strength of full composites using remote laser raman microscopy *3rd International Conference on Deformation and Fracture of Composites, Surrey, UK, March 1995, pp 115-125.*

(10) **Farley, G. L., Smith, B. T. and Maiden, J.** Compression response of thin layer composite laminates with through-the-thickness reinforcement *Journal of Reinforced Plastics and Composites, Vol 11, July 1992, pp 787-810.*

(11) **Farley, G. L. and Dickinson, L. C.** Mechanical response of composite materials with through-the-thickness reinforcement *NASA Conference Publication 3176 Fibre-tex 1991, The Fifth Conference on Advanced Engineering Fibres and Textile Structures for Composites, pp 123-143.*

(12) **Shu, D. and Mai, Y.** Delamination buckling with bridging *Composites Science and Technology 47, 1993, pp 25-33.*

Table 1

Fibre Volume Fraction Data for the Forms of Systems Used

Material	Thickness (mm)	Fibre Volume Fraction (%)
UDPT(C)	3.63	58
NCF(C)	3.62	54

Table 2

Lamina Property Data for NCF(C) and UDPT(C)(2,3)

NCF	UDPT
$E_{11} = 125.8$ GPa	$E_{11} = 140.0$ GPa
$E_{22} = 8.0$ GPa	$E_{22} = 8.5$ GPa
$G_{12} = 4.0$ GPa	$G_{12} = 4.5$ GPa
$\nu_{12} = 0.285$	$\nu_{12} = 0.280$
$t_{\pm 45^\circ} = 0.257$ mm†	$t_{\pm 45^\circ} = 0.130$ mm†
$t_{0^\circ/90^\circ} = 0.391$ mm†	$t_{0^\circ/90^\circ} = 0.130$ mm†

†Based on measured 'ply' thicknesses of cured samples.

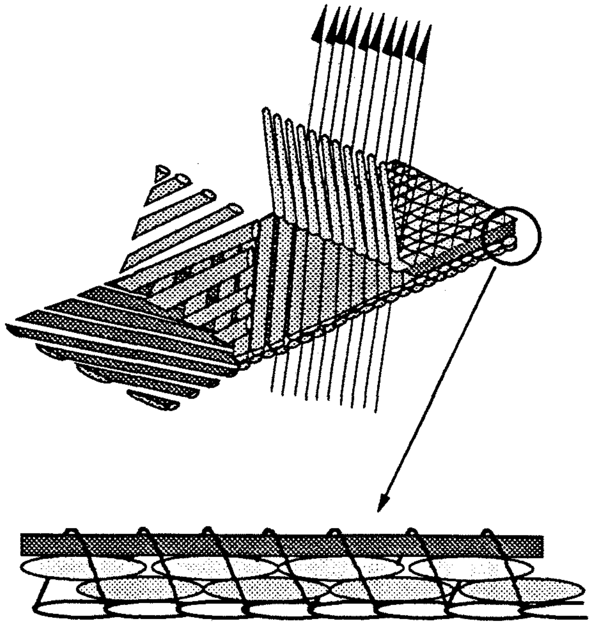
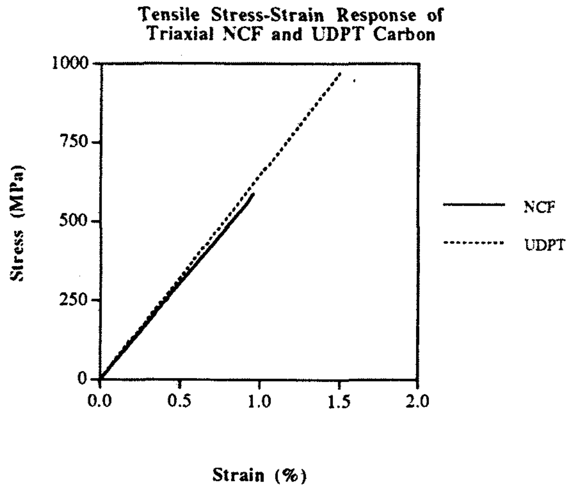
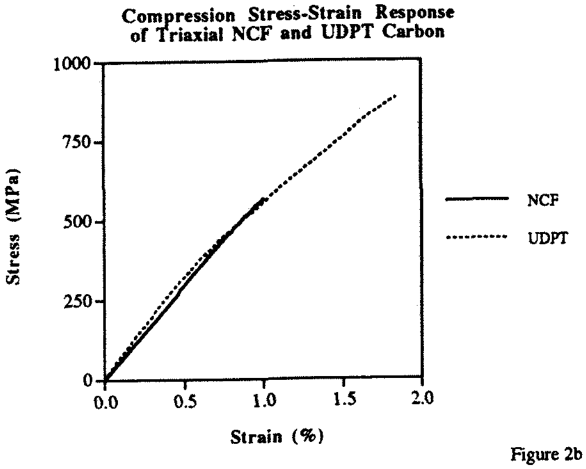


Figure 1 Idealisation of a multiaxial (non-crimp) fabric.



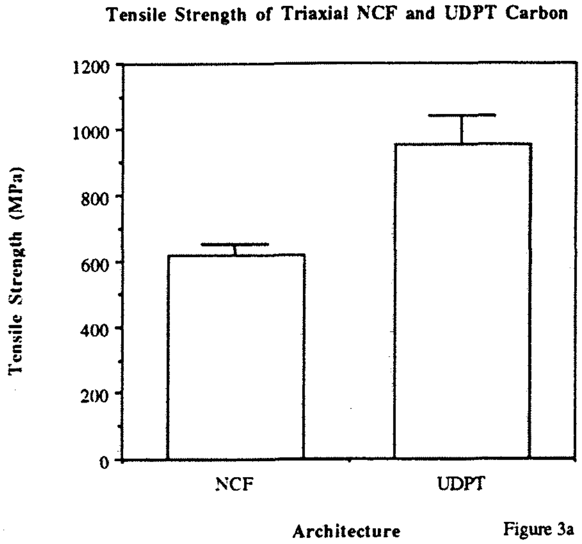
Tensile Stress-Strain Response of Triaxial NCF and UDPT Carbon

Figure 2a



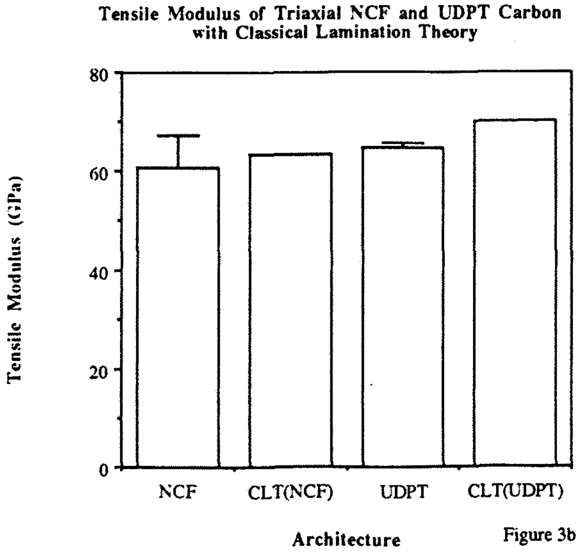
Compression Stress-Strain Response of Triaxial NCF and UDPT Carbon

Figure 2b



Tensile Strength of Triaxial NCF and UDPT Carbon

Figure 3a



Tensile Modulus of Triaxial NCF and UDPT Carbon with Classical Lamination Theory

Figure 3b

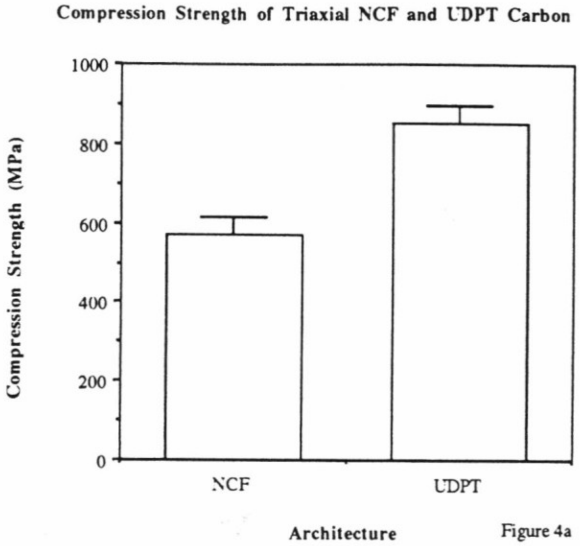


Figure 4a

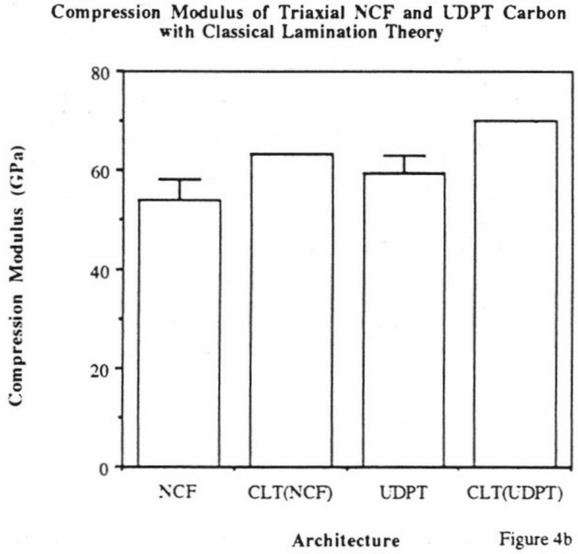


Figure 4b

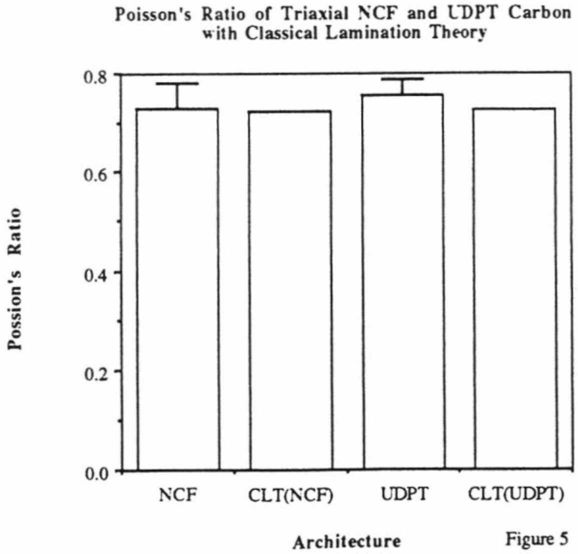


Figure 5

Figure 6a Top and side views of UDPT tensile specimen.

Figure 6b Top and side views of NCF tensile specimen.

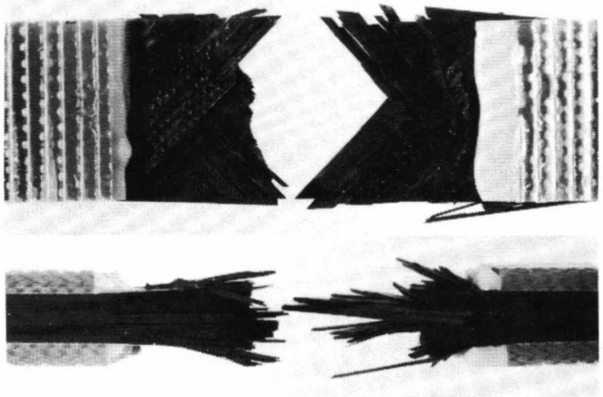


Figure 6c Top and side views of UDPT compression specimen.

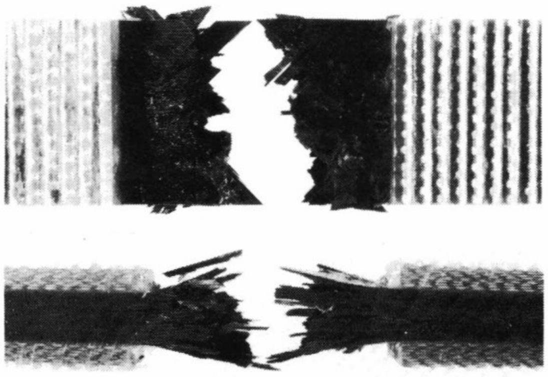


Figure 6d Top and side views of NCF compression specimen.

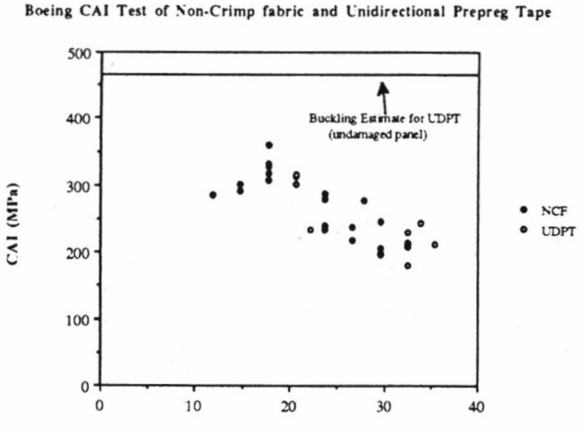


Figure 7

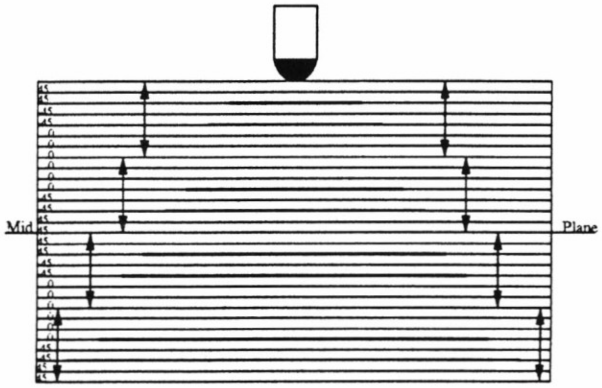


Figure 8 Shematic of the non-crimp fabric lay-up showing the stitch and potential planes for delamination.

——— Represents most likely planes of delamination.

↕ Represents the plies that are stitched together forming a blanket.

Note that all dissimilar interfaces (delamination prone areas) are within blankets.