Delamination behaviour of Z - pinned laminates

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SUMMARY: The paper presents the new technique of Z - fibre pinning as an approach to improving the through-thickness properties of continuous carbon fibre reinforced thermoset resin laminates. It describes the preparation of double cantilever beam delamination test specimens made from IMS/924 pre-pregs, pinned with carbon fibre/BMI pins. Delamination crack propagation resistance in Mode I loading conditions is found to increase from 200 J/m^2 in the control sample to nearly 5kJ/m^2 in specimens pinned with a high areal density of the Z-pins. Under Mode II loading conditions, the Z-pinned ENF specimens are found not to exhibit the expected catastrophic failure mode; the crack propagation delamination resistance reaches 7kJ/m^2 in the strongest specimens. The delamination behaviour of the Z-pinned specimens subjected to varying mixtures of Mode I and Mode II loading evolves in the expected manner. The fracture results are discussed in relation to the mesostructure of the samples.

KEYWORDS: Z direction reinforcement, Z-pins, delamination, Mode I, Mode II, MMB, mesostructure

Z - FIBRE PINNING OF COMPOSITES

Z-fibre pinning offers a completely new approach to solving the problems associated with the interlaminar weakness inherent in thermoset polymer matrix reinforced composites [1]. The Z-fibres^{TM} are inserted orthogonally to the plane of the composite plies during the manufacturing process, before the resin matrix is cured, effectively pinning the individual layers together. The pins are driven through the uncured laminate in a two stage process, which involves the use of a specialised ultrasonic insertion gun and a sequential removal of the collapsible foam in which the Z-fibres are held (the 'preform') (see Fig.1).

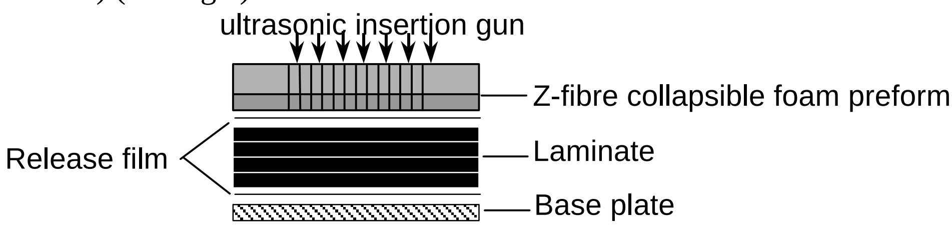

Figure 1: *Schematic of the ultrasonic gun insertion method of incorporating Z-pins into an uncured laminate.*

The foam supports the fibres during insertion, preventing them from buckling. The fibres can be made of steel, titanium, glass or carbon, having diameters between 0.15 and 1mm and with a range of surface treatments. The 'preforms' are therefore characterised by the type of fibre, type of support foam, and the areal density of the Z-fibres. This approach offers an alternative to other forms of through-thickness-reinforcement, notably to stitching.

MATERIALS AND METHODS

Z-pins having diameter of 0.28 mm, made from carbon fibre/BMI pultruded rods, were used in the present investigation. The advantage of carbon pins is primarily the ease of sample manufacture as the pins are driven into the required depth of the laminate and any excess length is removed easily by shear cutting. These pins are chamfered at one end to aid insertion, they also offer excellent adhesion to thermoset matrix resins.

Plates measuring 600 x 500 mm of 24-ply UD laminates of IMS/924 prepreg were laid up with a 12.5 μm polyimide crack starter film in the central plane, extending 60 mm from two opposite edges of the plate. The uncured laid up laminates were de-bulked and then pinned through the entire thickness, creating a band of pinned material 25 mm wide, orthogonal to the fibre direction. Two different areal densities of pinning were used: - a square array with 3.5 mm pin spacing (equivalent to 1% areal density i.e. "*low density*") and a square array with 1.8 mm pin spacing (equivalent to 2% areal density i.e. "*high density*"). The bands of pins were positioned so that the first row of pins was **5 mm beyond** the end of the crack starter film. The laminates were cured in an autoclave, according to manufacturer's instructions, C-scanned, cut to 20 mm wide beams parallel to fibre axis and tested to the current ESIS fracture protocols [2]. Modified beam theory and experimental compliance calibration data reduction methods were used as appropriate and onset of non-linearity in the load - displacement trace was taken as the critical load.

The delaminations were initiated under Mode I loading conditions directly from the starter film; samples were pre-cracked in Mode I for tests under Mode II (ENF) loading conditions and for all mixed mode (Mode I/ Mode II) tests (MMB) in order to arrive at a self-consistent set of fracture data for both initiation and propagation [3]. Acoustic emissions were monitored during the testing, using MISTRAS from Physical Acoustics Corporation. At the end of testing samples were broken open by peeling them apart.

A digital camera Fujifilm MX700 was used to obtain pictures during the tests as well as of the post-mortem fracture surfaces.

DELAMINATION BEHAVIOUR

Load - displacement traces of Mode I tests on pinned samples, compared to an unpinned control sample indicate that the crack initiation load is unaffected by the presence of the pins (5 mm ahead), whilst when the propagating crack finally encounters the discrete rows of Z-pins the fracture load increases significantly in comparison with the control sample. The stick-slip delamination propagation reflects the mesostructure of the sample. Acoustic emission signals identify the positions of crack arrest with the positions of the lines of Z-pins. The pins gradually pull out of the composite as the crack opening displacement increases.

Figure 2 shows that the most striking effect of the Z-pinning is the change of the R-curve : from a flat shape in the unpinned control samples (indicative of minimal fibre bridging) to a shallowly rising R-curve in the 'low density' pinned samples and a steeply rising R-curve in the 'high density' pinned samples. It is apparent that once the crack has passed through the pinned region the delamination propagation resistance reverts to that corresponding to the control sample. These results and those from mixed mode tests are summarised in Table 1; the propagation resistance values quoted here are the mean maximum G_p values corresponding to crack length of 50 mm for MMB tests and 100 mm for the Mode I loading tests.

Table 1: *Crack initiation and propagation resistance for Mode I , Mixed Mode M_I/M_{II}=4/1 and Mixed Mode M_I/M_{II}=1/1 loadings.*

	G_C J/m²	Initiation	R-Curve trend	Propagation
Mode I	Control	265 (±20)		290 (±40)
	Low Density	200 (±15)		1300 (±100)
	High Density	225 (±25)		5000 (±400)
Mixed Mode	Control	255 (±20)		350 (±15)
M_I/M_{II}=4/1	Low Density	280 (±40)		2700 (±500)
	High Density	320 (1 sample)		10000
Mixed Mode	Control	260 (±10)		410 (±10)
M_I/M_{II}=1/1	Low Density	336 (±10)		2600 (±155)
	High Density	360 (1 sample)		7500

As Mode II loading becomes dominant (ModeI DCB/ModeII ENF ≤ 1/4) the expected catastrophic failure is observed in the control samples (see Tables 2 and 3). In contrast, a **rising Mode II R-curve** is observed in the 'high density' pinned samples. All intermediate types of behaviour can be observed in the 'low density' pinned samples. A low magnification fracture surface (Fig.3) shows the initial starter film position, the Mode I pre-crack front, sheared off pins in the first two rows and the pins pulled out as the specimen was broken open at the end of the test.

Table 2: *Crack initiation and propagation resistance for Mixed Mode M_I/M_{II}=1/4 loading.*

G_C (J/m²) Mixed Mode M_I/M_{II}=1/4	Initiation	R-Curve trend	Propagation
Control	560 (±40)		0
Low Density	470 (±30)		1600 (±180)
High Density	600 (±40)		5600 (±300)

Table 3: *Crack initiation and propagation resistance for Mode II loading.*

G_{IIC} J/m² Mode II	Initiation	R-Curve trend	Propagation
Control	700 (±50)		0
	1200 (±300)		0
Low Density	800 (±100)		1000 (±100)
(2 samples in each case)	700 (±50)		2100 (±100)
High Density	820 (±100)		7500 (±600)

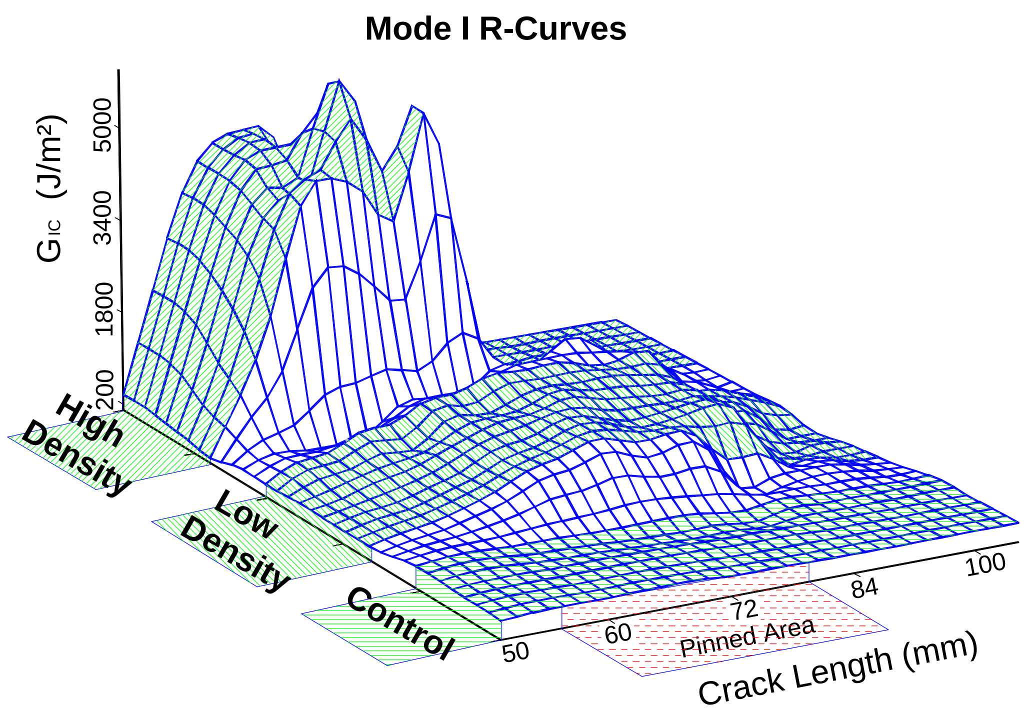

Figure 2: *Effect of Z-pinning on Mode I R-curves.*

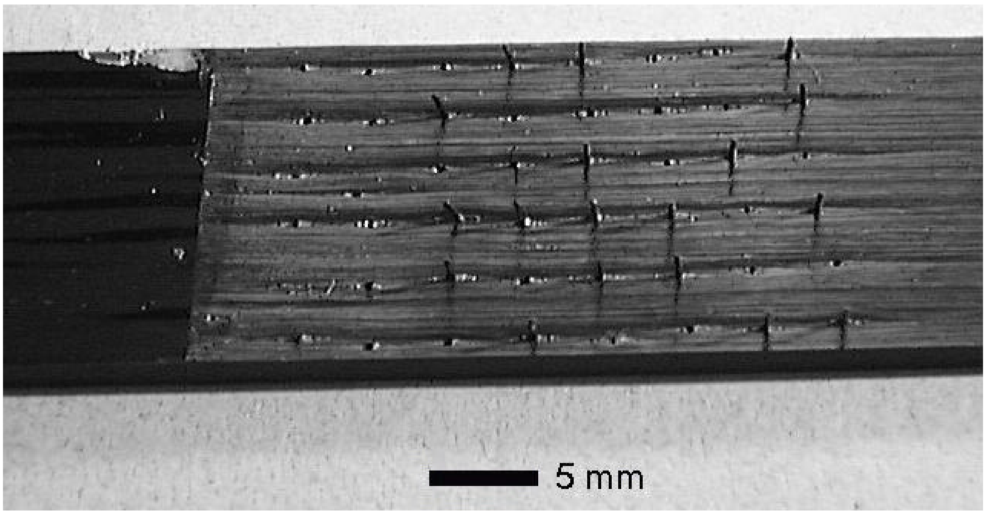

Figure 3: *Post-mortem fracture surface of a 'low density' pinned sample broken by Mode II loading.*

DISCUSSION

The behaviour of the pinned materials under Mode II (forward shear) loading is deserving of particular attention. It is generally agreed that this mode of loading represents a significant proportion of loading under realistic in-use conditions of composites - for example, the delaminations incurred upon impact of a laminated plate will initiate and propagate largely under the influence of Mode II loading. Thus the apparent ability of the Z-pins to stabilise this fracture process offers a potential for the control of delamination damage under impact or fatigue loadings. This may have profound effects on design of components for critical engineering applications such as load-bearing aircraft structures.

Figure 4 shows the dramatic increase in the crack propagation resistance in the 'high density' pinned beams under Mode II loading. This form of a 'surface' plot was chosen here (as in Fig.2) to give a graphical indication of the reproducibility / variability of the fracture behaviour - the batch sizes are 4 samples for both control and 'high density' pinned samples and 6 samples for the 'low density' pinned samples. On these plots the position of the first row of pins corresponds approximately with crack length a = 27 mm, depending on the exact pre-crack achieved in a given sample.

The role played by the Z-fibres in the overall energy absorption associated with the creation of the fracture surface in these samples appears to be dependent on the extent of the shear displacement reached. Pins may either break in shear as the (shear) crack passes through, as in the first two rows shown Fig.3, or they absorb energy by deforming and eventually pulling out under a mixed loading mode. The observation of unbroken pulled-out Z-fibres on the fracture surfaces of some of the Mode II ENF samples suggests the presence of an element of crack opening in the deformation mechanism. A similar suggestion has been made in the context of delamination behaviour of stitched composite laminates [4].

The potential advantages of the Z-fibre pinning in increasing the delamination resistance of continuous fibre laminates are clear. These must nevertheless be considered in the context of the whole balance of properties, with the most likely detrimental effect being seen in the compression behaviour of such laminates [5].

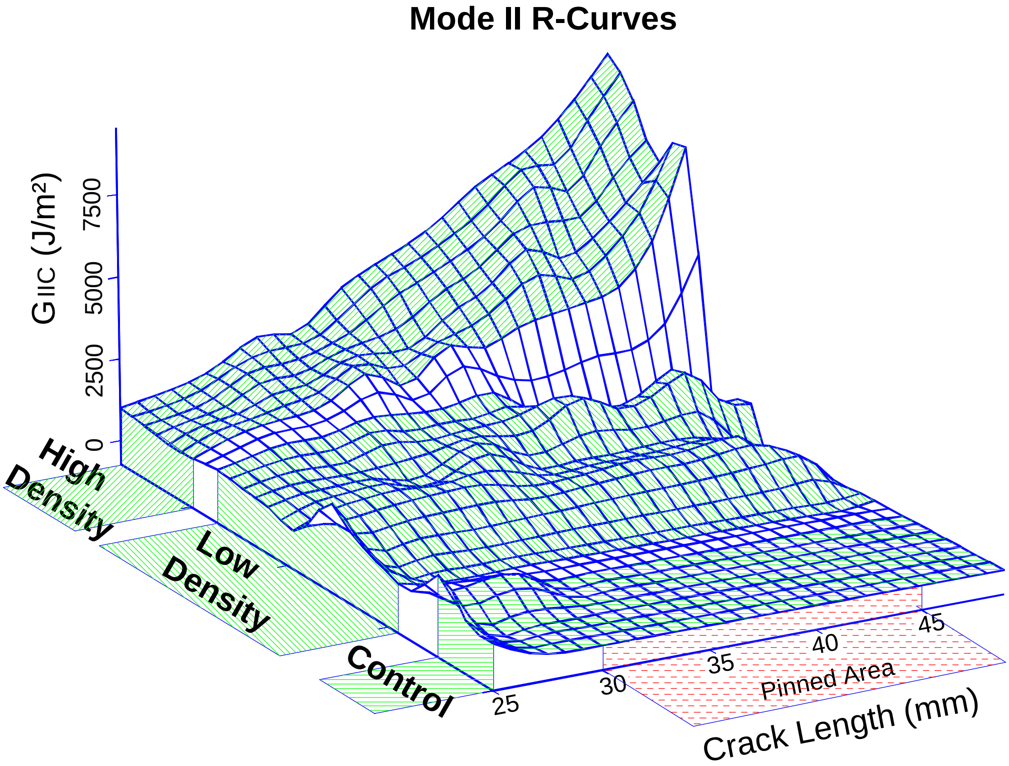

Figure 4: *Effect of Z-pinning on Mode II R-curves.*

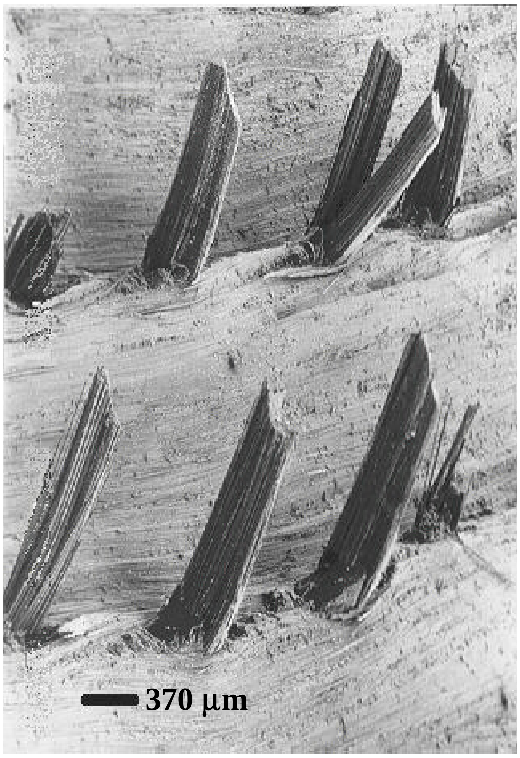

Figure 5: *SEM fracture surface of delamination in a 'high density' pinned sample broken by Mode II loading.*

ACKNOWLEDGEMENTS

The authors wish to thank Hexcel Composites (UK) and Aztex Inc (USA) for the supply of pre-preg material and of the Z-fibre pre-forms respectively. Helpful discussions with Mr. Tony Bonnington (Aztex Inc) and Dr. Brian Cox (Rockwell Science Center, USA) are gratefully acknowledged.

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