

Cranfield University

School of Industrial and Manufacturing Science

Advanced Materials Department

PhD Thesis

Academic years 1996-2000



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Effect of Z-Fibres™ on the Delamination Behaviour of Carbon Fibre / Epoxy Laminates

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December 2000

Abstract

The study presented in this thesis investigates the relationship between the experimentally determined behaviour of Z-pinned laminates under various delamination fracture loading conditions and their mesostructure. Mode I, mode II and mixed mode I/II delamination fracture testing was carried out on Z-Fibre™ reinforced unidirectional beams of IMS/924 laminates. For the Double Cantilever Beam specimens (DCB) under mode I loading, the crack propagation resistance of the beam is enhanced with increased pinning density. For the range of pin diameters and pinning densities used for this study, the load carrying capability has been improved by up to 5 times and the apparent toughness has been improved by up to 20 times. The most noteworthy example of the effectiveness of Z-Fibre™ pinning is the stabilisation of delamination crack propagation under mode II loading conditions in the intrinsically unstable 3pt-ENF configuration.

Although the current data analyses, based on LEFM, included in the test protocols for the calculation of delamination toughness values are invalidated by the presence of the through-the-thickness reinforcement, they are used here as the best currently available means of normalising the fracture results. However, these data reduction methods do not allow direct quantification of effects of the different pinning parameters on the crack bridging capability of the through-the-thickness reinforcement.

In order to relate the micromechanics at the pin level with the Mesomechanics of the delamination fracture specimens, the determination of the traction laws of a single Z-Fibre™, bridging a crack and deforming under various loading conditions, have been determined successfully by single pin experiments. A finite element approach, utilising these experimentally determined single pin bridging laws, is presented as a tool to carry out parametric studies of the effects of pin length, diameter and location on the behaviour of delaminating beams. The good agreement between the simulated and experimental R-curves demonstrates that the mode I delamination behaviour of DCB specimens is related to the single pin pullout traction laws.

Finally, preliminary studies of the compression after impact behaviour of Z-Fibre™ reinforced laminates indicate the existence of a complex relationship between the dramatic enhancement of the delamination crack propagation resistance of a material and the much lower (up to 50%) ultimate improvement in its compression after impact performance.

Acknowledgements

It is difficult to express how grateful I am to Ivana Partridge for her continuous support, patience, energy and more particularly for giving me the opportunities to meet and work with leading people in our field, such as the whole ESIS TC4 committee, Professor Norman Fleck, Dr Brian Cox and Professor Yiu-Wing Mai. Professor Phil Irving must not be forgotten for his valuable help at the beginning of this project.

I am very thankful to Tony Bonnington, President of Aztex Inc., for bringing such an exciting field to us. I am also indebted to Professor Denys Gamby (ENSMA, Poitiers) for giving me the initial opportunity to come to Cranfield.

I would like to thank Jim Hurley for his friendship and his ability to solve all kinds of technical crises, Peter Logan for his support, Andrew Dyer and Colin Matthews for their patience towards us when using their precious microscopes (This must be a scary experience for them!), Dr Mike Lock for the use of the C-scan, Tony Scott and all the technical staff who are there when we need them.

Life in England would not have been so pleasant without my friends who introduced me to some very interesting (but not that dangerous) leisure activities. John, Tim, Jason, Gwen, Henrik, Matt, Kevin, Lynn, Mark, Anu, Pascal, Ges and many others to whom I express my gratitude and my apologies for not being able to write their name here. A special kiss to Sandhya, Marina and Rossella.

Thanks to the original team for their support: Rosi, Alex, Kevin, George, David and David, Neil, without forgetting the youngsters: Mauro, Manos and Mihalis.

Last but not least, this thesis is dedicated to my family for their support always present when needed and their understanding about my too rare visits.

This thesis is dedicated to my parents

Contents

Abstract.....	ii
Acknowledgements	iii
Contents	iv
List of Figures.....	ix
List of Tables	xv
Nomenclature.....	xvi
Chapter 1 General Introduction	1
1.1 Thesis topic.....	2
1.2 Applications of Z-fibre pinning.....	6
1.3 Objectives of the study and thesis structure	9
Chapter 2 Literature Review on Delamination Testing.....	11
2.1 General introduction	12
2.2 Delamination testing.....	12
2.2.1 Mode I	16
2.2.2 Mode II	19
2.2.3 Mixed mode I/II.....	27
2.2.4 Crack initiation and pre-cracking	32
2.3 Delamination with through-the-thickness reinforcement.....	35
2.3.1 Experimental observations	35
2.3.2 Jain & Mai models.....	38
2.3.3 Massabò & Cox models.....	40
2.3.4 Cox ‘single ligament’ model	45
2.4 Conclusions	46
Chapter 3 Manufacturing with Z-Fibres™.....	47

3.1 Z-Fibre™ and Z-Fibre™ preform	48
3.2 Specific preparation for Z-Fibre™ reinforcement.....	50
3.3 Autoclave insertion.....	51
3.4 UAZ™ (Ultrasonically Assisted Z-Fibre™) insertion	52
3.4.1 The UAZ™ device	52
3.4.2 Insertion using UAZ™	55
3.5 Operator experience.....	57
Chapter 4 Materials and Test Methods.....	61
4.1 Materials	62
4.1.1 IMS/924.....	62
4.1.2 Z-Fibres™	63
4.2 Delamination testing of Z-pinned laminates	65
4.2.1 Specimen preparation	65
4.2.2 Pre-cracking.....	66
4.2.3 Stick-slip behaviour.....	66
4.2.4 Test conditions.....	67
4.3 Acoustic emission.....	70
4.4 Crack propagation imaging	71
4.5 Experimental programme	71
Chapter 5 Delamination and Compression After Impact Test Results.....	73
5.1 Introduction	74
5.2 Mode I	75
5.2.1 Initiation / propagation	75
5.2.2 Mesomechanics	76
5.2.3 0.5% - 0.28mm - pin-to-pin 3.5mm.....	77
5.2.4 2% - 0.28mm - pin-to-pin 1.75mm.....	79
5.2.5 2% - 0.51mm - pin-to-pin 3.1mm.....	80
5.2.6 Pin depth or pin length	82
5.2.7 Interleaving.....	84
5.3 Mode II	85
5.3.1 Behaviour	85

5.3.2 Mesomechanics	86
5.3.3 Resistance curves.....	88
5.3.4 Inconsistency with 0.5% - 0.28mm	89
5.3.5 Acoustic emission.....	90
5.3.6 Pin length.....	92
5.3.7 Interleaving.....	92
5.4 MMB	93
5.4.1 MMB 20% - $M_I/M_{II}=4/1$	93
5.4.2 MMB 50% - $M_I/M_{II}=1/1$	97
5.4.3 MMB 80% - $M_I/M_{II}=1/4$	98
5.5 Summary of the delamination behaviour.....	98
5.6 Compression after impact results	104
Chapter 6 Single Pin Testing.....	110
6.1 Introduction	111
6.2 Materials	111
6.3 Pull-out testing.....	112
6.3.1 Theory on pull out testing.....	112
6.3.2 Design problem	114
6.3.3 Results	115
6.4 Shear testing	117
6.4.1 Test design.....	117
6.4.2 Results	120
6.5 Conclusions	132
Chapter 7 : Finite Element Modelling.....	134
7.1 Objectives	135
7.2 F.E. Package used.....	135
7.3 Model.....	136
7.3.1 Model of the beam.....	137
7.3.2 Model of the Z-Fibre™	139
7.3.3 Crack growth criterion.....	141
7.3.4 Algorithm	142

7.4 Validation of the beam model	143
7.5 Results	144
7.5.1 Mode I	144
7.5.2 Mode II	147
7.6 Limitations of the model	148
Chapter 8 Discussion.....	149
8.1 Manufacturing	150
8.1.1 Pre-cure laminate thickness	150
8.1.2 Surface finish requirement	152
8.2 Validity of the LEFM analysis methods.....	153
8.3 Energy absorption mechanisms.....	154
8.4 Pinning quality.....	157
8.4.1 Effects of the pinning quality	157
8.4.2 Assessment of the pinning quality.....	160
8.5 Compression after impact.....	161
8.6 Need for pinning quality metrics.....	163
Chapter 9 Conclusions and Suggestions for Further Work	165
9.1 Conclusions	166
9.2 Suggestions for further work.....	167
References	170
Appendix A: C-scans.....	182
Appendix B: Delamination Test Data	186
Specimen GE6: Mode I, Control	187
Specimen GRE3: Mode I, 0.5%-0.28mm.....	191
Specimen GTE1: Mode I, 2%-0.51mm	195
Specimen GSE7: Mode I, 2%-0.28mm	199
Specimen GE11: Mode II Control.....	203
Specimen GRE8: Mode II, 0.5%-0.28mm	204
Specimen GTE2: Mode II, 2%-0.51mm.....	205

Specimen GSE3: Mode II, 2%-0.28mm.....	206
Crack Propagation Imaging of MMB $M_I/M_{II}=4/1$	207
Appendix C: Single Pin Testing Imaging.....	212
Appendix C_1: Composite Z-Fibre™ in composite laminate.....	213
Appendix C_2: Titanium Z-Fibre™ in composite laminate	215
Appendix C_3: Titanium Z-Fibre™ in polycarbonate	217
Appendix C_4: Composite Z-Fibre™ in polycarbonate	219
Appendix C_5: Composite Z-Fibre™ in polycarbonate	221
Appendix C_6: Composite Z-Fibre™ in polycarbonate	223
Appendix D: Code of F.E. Procedures	225
Procedure DCBCAL.DGIBI.....	226
Procedure DELARCU8.DGIBI.....	229

List of Figures

Figure 1-1: Boeing CAI test performance in a range of carbon fibre reinforced laminates (After Cartié and Irving 2001).....	3
Figure 1-2: Various types of stitching and tufting from (Mouritz and Cox, 2000) and (Backhouse, 1998).....	4
Figure 1-3: Schematic of the Z-Fibre™ insertion process: insertion with the ultrasonic horn and sequential removal of the collapsed preform.....	5
Figure 1-4: A flying application of Z-Fibres™: The F18 E/F.....	6
Figure 1-5: Example of the use of Z-Fibres™ as reinforcement of a stiffener to skin joint.....	6
Figure 1-6: Applications for the automotive industry: crack arresters and higher energy absorption for crash structures.....	7
Figure 1-7: Large composite I beam tested under 3pt-bend configuration	8
Figure 1-8: Effects of Z-Fibres™ on co-cured and co-bonded joints	8
Figure 2-1: Basic modes of loading (Desoyer, 1996).....	13
Figure 2-2: Delamination testing of a cross ply laminate.....	14
Figure 2-3: Solid characteristics (After Williams, 1989a)	15
Figure 2-4: Mode I DCB test configuration and nomenclature.....	17
Figure 2-5: 3 pt-ENF test configuration	19
Figure 2-6: SENF control mode	22
Figure 2-7: ELS configuration.....	23
Figure 2-8: 4pt ENF configuration	25
Figure 2-9: Various mixed mode I/II test configurations (after Reeder, 1990 and Ducept, 1996).....	27
Figure 2-10: Superposition principle applied to a MMB specimen	28
Figure 2-11: MMB configuration.....	29
Figure 2-12: Schematic of the load/displacement curve of a delamination fracture test with initiation points NL, VIS, 5%, MAX and the propagation values (PROP) (From ISO 15024)	34
Figure 2-13: Effects of Z-Fibre™ reinforcement on Mode I fracture toughness	36

Figure 2-14: Schematic representation of mode I crack propagation through a stitched composite specimen (from Dransfield et al, 1995).....	37
Figure 2-15: R-curves comparing unstitched and stitched materials (from Dransfield et al 1995).....	37
Figure 2-16: The ENF problem (after Cox et al, 1997).....	41
Figure 2-17: Crack sliding displacement profiles (from Massabò et al, 1998).....	43
Figure 2-18: Load/Deflection curves (from Massabò et al, 1998)	43
Figure 2-19: Crack profiles in the mode I problem with $M_I=0$ (Dugdale-type bridging law) (from Massabò and Cox, 1999c)	44
Figure 2-20: Bridging tractions and crack displacements (from Cox, 1999a)	45
Figure 2-21: Mode II predicted tractions law compared with a direct experimental measurement (from Cox, 1999c).....	45
Figure 3-1: Z-Fibre™ Preform and a close-up of one pin.....	49
Figure 3-2: Preparation of the laminate stack.....	51
Figure 3-3: Heat and Pressure Insertion Process (from Aztex Inc.).....	52
Figure 3-4 : Hand held UAZ™ Unit	53
Figure 3-5: New gantry currently in use at Cranfield.....	54
Figure 3-6: Z-Fibre™ insertion	55
Figure 3-7: Cutting of the excess pin length and foam removal	56
Figure 3-8: Schematic of metal Z-Fibre™ insertion	57
Figure 3-9: Fully automated Z-Fibre™ insertion machine (Picture Aztex Inc.).....	58
Figure 3-10 : Damage to the laminate due to too much heat generated during pin insertion	60
Figure 4-1: Effect of the chamfer on the Z-pin effective length	64
Figure 4-2: Delamination test beam, film and pin position.....	65
Figure 4-3: Load/Displacement trace of an unstable DCB specimen test.....	67
Figure 4-4: Extract of the lab book records for the same test.....	67
Figure 4-5: Schematic representation of Mode I DCB specimens	68
Figure 4-6: Schematic of Mode II 3pt ENF specimen and loading conditions	69
Figure 4-7: Schematic of mixed mode I/II MMB specimen and loading conditions	70
Figure 5-1: Typical force vs. displacement traces of mode I DCB tests	75
Figure 5-2: In situ SEM photo of a mini-DCB test in progress.....	76

Figure 5-3: Pins pulling out of the arms of DCB samples (2% - 0.28mm).....	77
Figure 5-4: Mode I R-curve and fracture surface of a 0.5%-0.28mm DCB specimen....	78
Figure 5-5: Mode I R-curve of a 2% - 0.28mm DCB specimen	79
Figure 5-6: Mode I R-curve and fracture surface of a 2%-0.51mm DCB specimen (Specimen ref. GTE1).....	80
Figure 5-7: Optical micrograph of the fracture surface of a 2%-0.51mm DCB specimen	81
Figure 5-8: R-curve and fracture surface of a 2%-0.51mm DCB specimen (Specimen ref. GTE9).....	82
Figure 5-9: Effect of Pin Length on Mode I R-Curves.....	83
Figure 5-10: Effects of Interleaving on Mode I R-Curves	84
Figure 5-11: Effect of interleaving on pinned specimens (0.5% - 0.28mm).....	85
Figure 5-12: Mode II load vs. displacement traces	86
Figure 5-13: In situ SEM photo of a mini-ENF test in progress	87
Figure 5-14: Fracture surface of an 3pt-ENF specimen (0.5% - 0.28mm).....	87
Figure 5-15: Schematic of the different failure modes of the pins subjected to shear displacement.....	88
Figure 5-16: Typical mode II R-curves for stable samples	89
Figure 5-17: Inconsistency on the stability of the 3pt-ENF specimens pinned with 0.28mm density 0.5%.....	90
Figure 5-18: Behaviour of a control specimen under mode II loading conditions.....	91
Figure 5-19: Typical mode II load vs. displacement trace 2%-0.28mm	91
Figure 5-20: Effect of interleaving on Mode II load traces.....	93
Figure 5-21: Force vs. displacement curve of a control MMB specimen, $M_I/M_{II}=4/1$ and its acoustic emission trace	94
Figure 5-22: Force vs. displacement curve of a pinned 0.5% - 0.28mm MMB specimen, $M_I/M_{II}=4/1$ and its acoustic emission trace	94
Figure 5-23: Force vs. displacement curve of a pinned 2% - 0.28mm MMB specimen, $M_I/M_{II}=4/1$ and its acoustic emission trace	95
Figure 5-24: Arm failure of specimen under mixed mode loading conditions ($M_I/M_{II}=4/1$) Pin Density 2% Pin Diameter 0.28mm.....	95

Figure 5-25: 3D plot of the force vs. displacement traces of the MMB specimens for $M_I/M_{II}=4/1$	96
Figure 5-26: 3D plot of the force vs. displacement traces of the MMB specimens for $M_I/M_{II}=1/1$	97
Figure 5-27: 3D plot of the force vs. displacement traces of the MMB specimens for $M_I/M_{II}=1/4$	98
Figure 5-28: Effects of Pin Density on Mode I R-Curves	99
Figure 5-29: Effects of Pin Diameter on Mode I R-Curves (Density 2%)	100
Figure 5-30: Effects of Pin Density on Mode II R-Curves (Pin Diameter 0.28mm)	103
Figure 5-31: Effects of Pin Diameter on Mode II R-Curves (Density 2%)	104
Figure 5-32: Mode I R-curves (T300/914)	105
Figure 5-33: Mode II R-curves (T300/914)	106
Figure 5-34: Pinning configuration in CAI specimens	107
Figure 5-35: Impact performance of pinned laminates	107
Figure 5-36: Force history of a 15J impact on T300/914	108
Figure 5-37: Compression after impact strength of pinned laminates	109
Figure 6-1: Schematic of a Z-Fibre™ pulling out of a laminate	113
Figure 6-2: Typical pull-out curve	113
Figure 6-3: Typical pull-out curve of a T300/BMI Z-Fibre™ from a UD laminate	115
Figure 6-4: Typical pull-out curve of a titanium Z-Fibre™ from a UD laminate	116
Figure 6-5: Z-Fibre™ deforming in shear loading conditions	117
Figure 6-6: Exploded view of the shear pin test rig components	118
Figure 6-7: Shear test configuration with opening displacement allowed	119
Figure 6-8: Shear test configuration with opening displacement constrained	119
Figure 6-9: Coordinate system of the angle of the Z-Fibre™	119
Figure 6-10: Force vs. displacement traces of shear tests of titanium Z-Fibre™ inserted in polycarbonate	120
Figure 6-11 a and b: Post-mortem pictures of polycarbonate reinforced with a single titanium Z-Fibre™	121
Figure 6-12: Force vs. displacement traces of shear tests of T300/BMI Z-Fibre™ in polycarbonate	122
Figure 6-13: Shear test of a T300/BMI Z-Fibre™	123

Figure 6-14: Post mortem SEM of a T300/BMI Z-Fibre™ in polycarbonate.....	124
Figure 6-15: As above, higher magnification.....	124
Figure 6-16: Post-mortem photograph of a polycarbonate specimen pinned by a single T300/BMI Z-pin.....	125
Figure 6-17: Force vs. displacement traces of shear tests of titanium Z-Fibre™ in IMS/924 laminate.....	126
Figure 6-18: Post-mortem photo of a titanium Z-Fibre™ in shear, $\phi > 0^\circ$: pullout.....	126
Figure 6-19: Post-mortem photo of a titanium Z-Fibre™ in shear, $\phi < 0^\circ$: tensile failure	126
Figure 6-20: Force-displacement traces of titanium Z-Fibres™ reinforcing IMS/924 laminates (Pins in the nap)	127
Figure 6-21: Titanium Z-Fibre in shear in the nap (No opening displacement).....	128
Figure 6-22: Titanium Z-Fibre™ is shear, pull out from both side of the cracked laminate	128
Figure 6-23: Force-displacement traces of titanium Z-Fibres™ reinforcing IMS/924 laminates (Pins against the nap)	128
Figure 6-24: Titanium Z-Fibre™ against the nap (No opening displacement).....	129
Figure 6-25: Force vs. displacement trace of shear tests of T300/BMI Z-pins in IMS/924 UD laminate.....	130
Figure 6-26: Carbon Z-Fibre™ pulled out after a shear test ($\phi > 0$)	130
Figure 6-27: Post-mortem photo of a IMS/924 laminate reinforced with T300/BMI Z- pin ($\phi = -8^\circ.7$)	130
Figure 6-28: Force-displacement traces of T300/BMI Z-Fibres™ reinforcing IMS/924 laminates.....	131
Figure 6-29: Post-mortem photo of an IMS/924 laminate reinforced with a T300/BMI Z-Fibre tested in shear without opening displacement.....	132
Figure 6-30: As Figure 6-29, higher magnification.....	132
Figure 7-1: Coordinate system of the beam model.....	137
Figure 7-2: Mesh of the crack tip	137
Figure 7-3: Deformed mesh of the double cantilever beam	138
Figure 7-4: Force/Displacement trace of a pull out test	140
Figure 7-5: Bridging law of 0.28mm diameter pins at a density of 0.5%	140

Figure 7-6: Pullout test of a Z-Fibre™ Laminate: G986/M21	141
Figure 7-7: Bridging law modelling an angled pin pulling out of G986/M21	141
Figure 7-8: Structure of the calculations	142
Figure 7-9: Comparison of FE output vs. Experimental load-displacement traces.....	145
Figure 7-10: R-curves of IMS/924 DCB reinforced with 0.5%-0.28mm diameter Z-Fibres™ and the FE calculations for a similar beam.....	145
Figure 7-11: Test case with manufacturing imperfection, Z-Fibre™ density 2%, diameter 0.51mm.....	146
Figure 7-12: Resistance curves for the above case.....	146
Figure 7-13: Effects of Z-Fibre diameter on the apparent toughness.....	147
Figure 8-1: Effect of compaction before insertion on final pin angle	151
Figure 8-2: Surface finish of a pinned specimen cured with a polymeric release film on the surface.....	152
Figure 8-3: Surface finish of a pinned specimen cured with a fabric peel ply on the surface of the tools.....	152
Figure 8-4: Steady-state crack propagation of Z-Fibre™ reinforced laminates.....	155
Figure 8-5: Effective insertion depth differences between 2%-0.28mm Z-Fibres™ (top) and 2%-0.51mm Z-Fibres™ (bottom) in IMS/924	158
Figure 8-6: Insertion depth of 2%-0.51mm Z-Fibres™ (top) and 2%-0.28mm Z-Fibres™ (bottom) in T300/914 (Bitsianis, 1999).....	159
Figure 8-7: Top and bottom surface of a 2%-0.51mm Z-Fibre™ reinforced T300/914 DCB specimen (Sample by courtesy of Bitsianis, 1999)	159
Figure 8-8: Top and bottom surface of a 2%-0.28mm Z-Fibre™ reinforced T300/914 DCB specimen (Sample by courtesy of Bitsianis, 1999)	159
Figure 8-9: High resolution C-scan of the pinned area (After Cartié et al, 2000).....	160
Figure 8-10: Polished cross-section of a pinned QI laminate (After Cartié et al, 2000)	161
Figure 8-11: Top and bottom surface of a 2%-0.28mm pinned CAI specimens (Sample by courtesy of Bitsianis, 1999).....	161
Figure 8-12: Top and bottom surface of a 2%-0.51mm pinned CAI specimens (Sample by courtesy of Bitsianis, 1999).....	162
Figure 8-13: Damage of CAI samples impacted at 20J.....	162

List of Tables

Table 4-1: Tenax IMS fibre properties (from Hexcel Composites Ltd.).....	62
Table 4-2: 924 neat resin properties (from Hexcel Composites Ltd.).....	63
Table 4-3: Loading saddle position	69
Table 4-4 : Specimens tested for manufacturing and testing feasibility	72
Table 4-5 : Number of specimens tested for the second series	72
Table 4-6 : Specimens tested for interleaving trials	72
Table 5-1: Initiation toughness of 0.5%-0.28mm pinned 3pt-ENF specimens, with samples separated by fracture behaviour type.....	90
Table 5-2: Effect of interleaving on mode II delamination toughness (initiation).....	92
Table 5-3: Correction factors Δ and n (case of mode I DCB tests).....	101
Table 5-4:Crack initiation and propagation resistance for mode I, Mixed Mode $M_I/M_{II}=4/1$ and Mixed Mode $M_I/M_{II}=1/1$ loading conditions	101
Table 5-5: Crack initiation and propagation resistance for Mixed Mode $M_I/M_{II}=1/4$ loading conditions	102
Table 5-6: Crack initiation and propagation resistance for Mode II loading conditions	102
Table 5-7: Critical threshold force for impact damage initiation for pinned and control CAI samples	108
Table 6-1: Pull-out results	117
Table 7-1: Material properties used in the FE models.....	143
Table 7-2: Comparison of experimental DCB and FE model	144

Nomenclature

$'G_{IC}'$	Apparent mode I delamination toughness (J/m^2)
$'G_{IIC}'$	Apparent mode II delamination toughness (J/m^2)
a	Crack length (mm)
b	Unit width of fracture area or specimen width (mm)
C	Compliance of the specimen (m/N)
c	Saddle position (mm) (MMB)
C_I	Change in compliance (N^{-1}) (4-pt ENF)
c_{lever}	Distance from the centre of gravity of the lever to the centre of the loading roller (mm) (MMB)
C_o	Compliance at $a=0$ (m/N)
C_S	Compliance function of the shear displacement (m/N) (SENF)
D	Dissipative energy related with the fracture (J)
D	EI/b (4-pt ENF)
E	Longitudinal Young modulus (GPa)
E_{If}	Corrected Young modulus of the MMB specimen (GPa)
F	Large displacement correction factor (DCB and 3-pt ENF)
F_a	Maximum pullout force (N)
G	Energy release rate calculated at the crack tip (FEA) (J/m^2)
G_C	Total critical energy release rate (J/m^2)
G_I	Mode I strain energy release rate (J/m^2)
G_I	Mode I strain energy release rate (J/m^2)
G_{IC}	Mode I critical energy release rate (J/m^2)
G_{II}	Mode II strain energy release rate (J/m^2)
G_{IIC}	Mode II critical energy release rate (J/m^2)
h	Specimen half thickness (mm)
L	Half span length (mm) or debonded length (mm) (single pin pullout)
l_1	Distance from the centre of the loading pin to the midplane of the specimen beam (mm)
l_2	Distance from the loading pin centre to the edge of the load block (mm)
m	Slope of the curve C vs a^3 (Mode II) ($N^{-1}m^{-2}$)

N	Load block correction factor (DCB and 3-pt ENF)
n	Slope of the curve $\ln C$ vs $\ln a$ (Mode I)
nb_{pin}	Number of pins per row
P	Applied load (N)
P_I	Load accounting for mode I loading (N) (MMB)
P_{II}	Load accounting for mode II loading (N) (MMB)
P_{lever}	Weight of the lever (N)
r	Z-Fibre™ radius (mm)
S	Transverse shear correction factor
T	Kinetic energy (J)
U	Elastic strain energy (J)
W	External work (J)
Y	Pullout length (mm)
Δ	Crack length increase (DCB) (mm)
χh	Crack length correction factor (mm) (MMB)
δ	Load point displacement (mm)
δ_s	Shear displacement of the crack face (mm) (SENF)
ϕ	Pin angle to the normal of the laminate (°)
θ_1	Large displacement correction factor (ELS)
θ_2	Loading block correction factor (ELS)
τ_a	Adhesion shear stress (MPa)
τ_f	Friction stress (MPa)
τ_i	Maximum shear stress (MPa)
τ_w	Average shear stress (MPa)

Chapter 1 General Introduction

1.1 Thesis topic

Interlaminar weakness of laminated composite materials is generally recognised as being a major limitation to the application of these materials in damage critical structures. Different attempts at overcoming the problem have included toughening of the resin matrix (Bucknall and Partridge, 1983), (Evans and Masters, 1987a), (Bucknall and Gilbert, 1989), (Kim et al, 1993), control of the fibre-resin interface, resin interleaving (Bradley, 1989), (Ozdil and Carlsson, 1992), (Aksoy and Carlsson, 1992), (Singh and Partridge, 1995a) and, more recently, through-the-thickness reinforcement.

The through-the-thickness reinforcement, such as textile stitches or fibre ‘tufts’ or rods, bridges the delaminations and shields their tips from the applied load, so reducing the crack driving force. Depending on the structure geometry and on the applied loading mode, delamination crack growth can be rendered stable. For example, the use of through-the-thickness stitches in a 3-point-bend Edge Notch Flexure (ENF) specimen, which is an intrinsically unstable configuration in classical laminates, stabilises the delamination fracture when the load is applied under displacement controlled conditions. This consideration of stabilisation of the failure process is critical to design of damage tolerant composite structures. The ultimate strength is increased and the notch and impact sensitivities reduced (Massabò and Cox, 1999a).

Delaminations in composite parts on aircraft are commonly caused by low energy impacts, such as a dropped tool on the wing skins, debris projected from the runway during take off and landing or vehicle impact on loading bay doors. It is therefore reasonable to assess the damage tolerance of the composite material by the so-called ‘Compression After Impact’ (CAI) test with impact level selected to be a realistic representation of in-service events. Material selection and certification currently relies heavily on the outcome of such tests, the most commonly used test being the Boeing CAI test (Keith, 1999) (Cabanac, 2000). Figure 1-1 illustrates the influences of changing the constituent of a composite on its CAI performance.

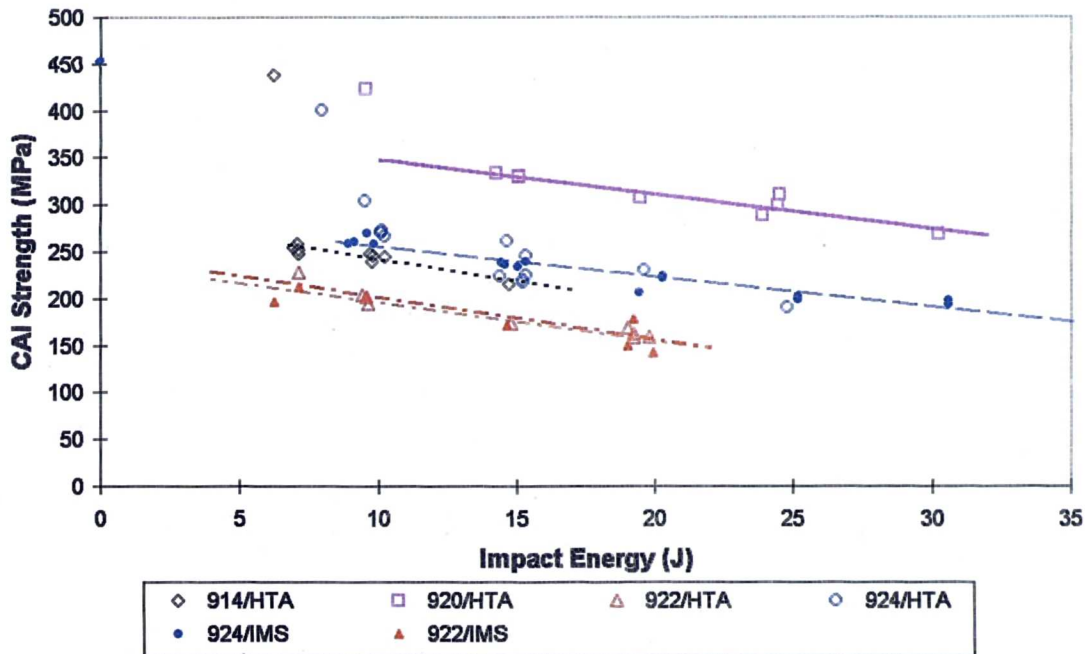


Figure 1-1: Boeing CAI test performance in a range of carbon fibre reinforced laminates (After Cartié and Irving 2001)

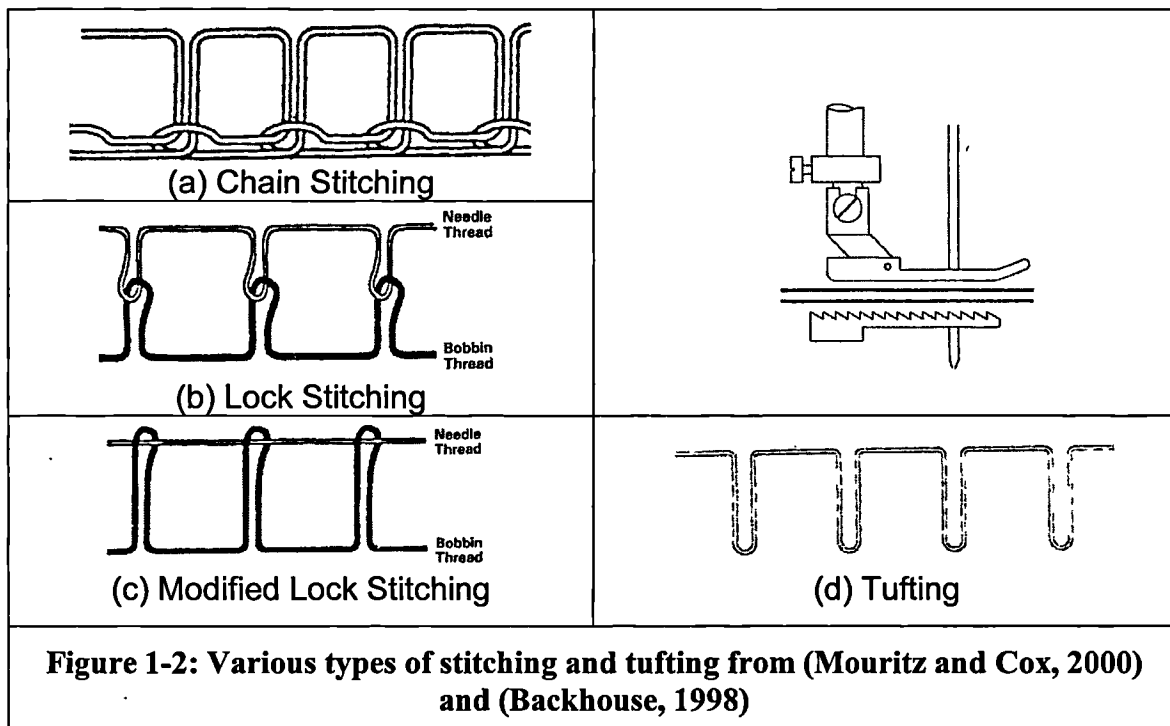
In this series of materials the range of unreinforced resin toughness is from 50 J/m² (922) to 510 J/m² (920) and the range of the fibre tensile strength is from 3.4 GPa (HTA) to 5.4 GPa (IMS). As can be seen, considerable differences between resins and between fibres result in relatively minor differences in the CAI performance of the resulting laminates.

The CAI performance is believed to be linked strongly to the delamination resistance of the composite, both in mode I (crack opening) and in mode II (shear) (Masters, 1987b) (Davies et al, 1994). It may therefore be expected that a truly effective enhancement of the delamination resistance of the composite by through-the-thickness reinforcement will result in a better compression after impact performance.

Through-the-thickness reinforcements, such as stitching or tufting, involves the insertion of a dry carbon, aramid or glass yarn into the laminate using a relatively large (2.3mm diameter) sewing needle. During the **stitching process**, the yarn is pushed by

the needle through the laminate and interacts with another mechanical component to form a loop (Figure 1-2-a) or to interlock with another thread (Figure 1-2-b & c). This process requires access from both sides of the laminate and heavy machinery for the manufacture of sizable parts. **Tufting** is based on the same machinery as stitching (Figure 1-2-d). A needle pushes the yarn through the laminate and through a specialised form tool described as an ‘elastic foam’. Instead of forming a lock or a loop, a fine balance of frictions between the yarn, the needle and foam encourages the yarn to remain in-situ whilst the needle withdraws. It is therefore a one-side access process, but requires special tooling.

Stitching is the most widely studied form of through-the-thickness reinforcement, to date. It has been shown to improve the delamination propagation resistance (Jain and Mai, 1997) (Cox et al, 1997) and CAI performance of the composites (Mouritz et al, 1999) (Keith, 1999). However, both stitching and tufting need heavy machinery and are very difficult to implement when processing materials which already contain a resin matrix, such as pre-pregs.



Z-Fibre™ pinning, which is the topic of this thesis, represents an entirely new form of through-the-thickness reinforcement. Rigid rods called Z-Fibres™ 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 (Figure 1-3), 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 originally. The Z-pins are made from a wide range of materials and diameters. However, T300/BMI pultruded rods of diameters of 0.28mm and 0.51mm are the most commonly used materials for the manufacture of the Z-Fibre™. The pins, contained in a double layer foam are known commercially as 'the preform'. This is characterised by the length, diameter and areal density of the Z-Fibres™ it contains. The main role of the preform foam layers is to prevent the Z-Pins from distorting during the insertion stage, which is facilitated by the fact that the pins are chamfered. After insertion, any excess pin length is cut off cleanly by a shearing action, resulting in good surface quality of the finished product. This process requires access to one side of the laminate and can be carried out on the lay-up tool.

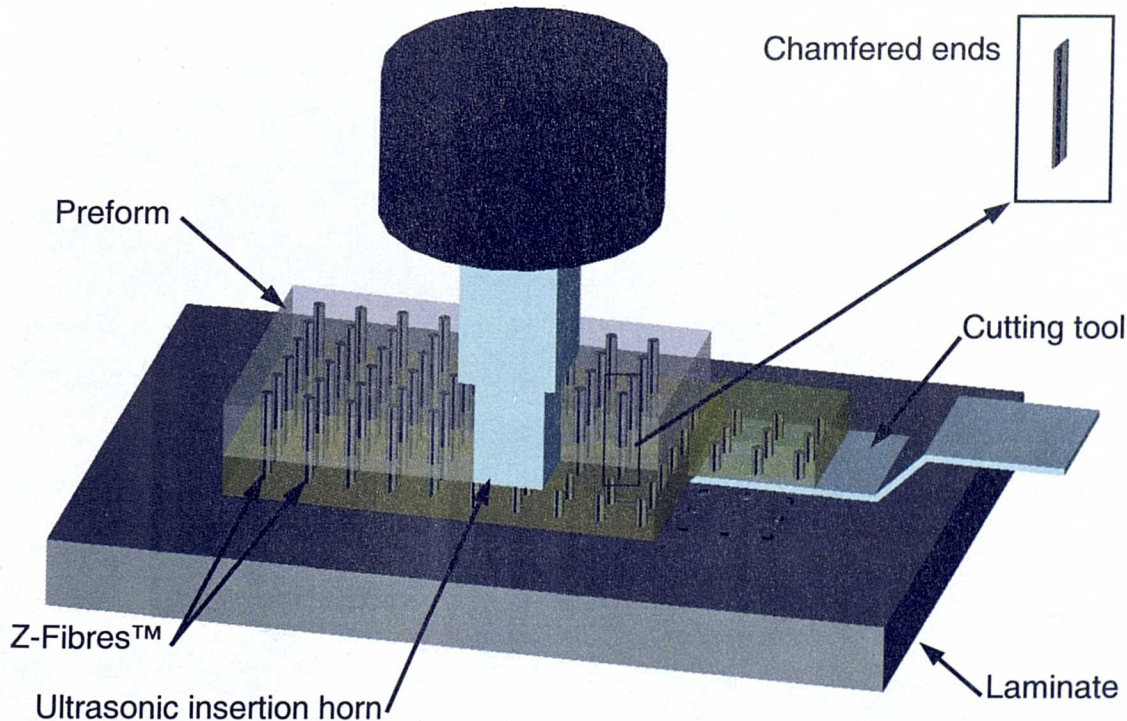


Figure 1-3: Schematic of the Z-Fibre™ insertion process: insertion with the ultrasonic horn and sequential removal of the collapsed preform

1.2 Applications of Z-fibre pinning

To date, the principal market for Z-Fibre™ pinning is in the aeronautical industry, with an increasing interest from the automotive industry. Z-Fibres™ are used for attachment of subcomponents and are certified in the USA in the F18 E/F fighters (Figure 1-4).



Figure 1-4: A flying application of Z-Fibres™: The F18 E/F

Another typical aeronautical example is the reinforcement of stiffener to skin joints, where the principal mode of failure is delamination between the skin and the stiffener foot (Figure 1-5).

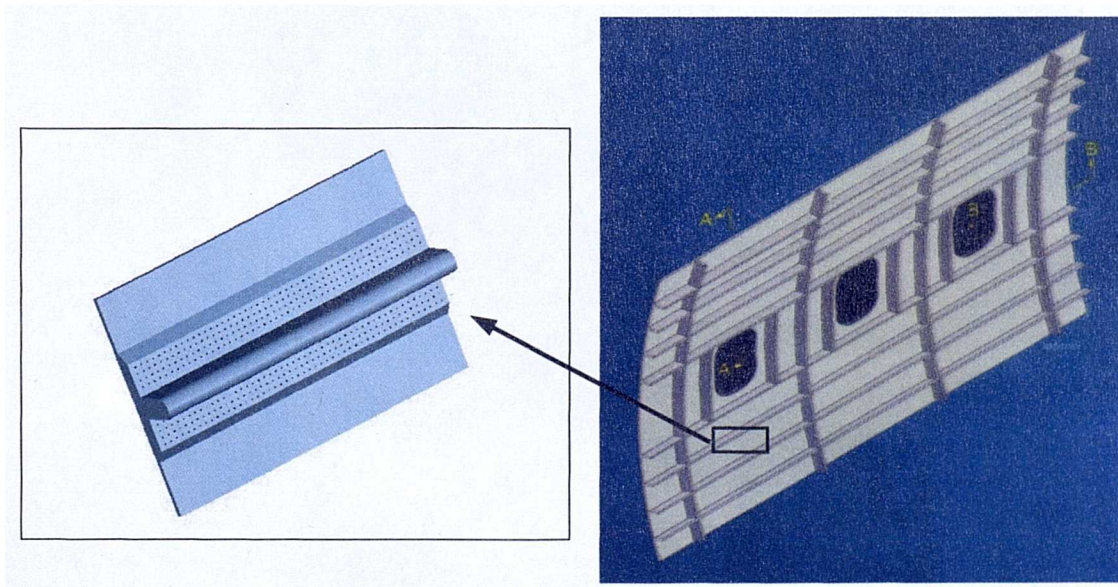


Figure 1-5: Example of the use of Z-Fibres™ as reinforcement of a stiffener to skin joint

However, Z-Fibre™ pinning can be applied to any composite structures susceptible to fail by delamination cracking. Its efficiency in the stabilisation and eventual arrest of cracks makes the technology attractive to the automotive industry and to civil engineering.



Figure 1-6: Applications for the automotive industry: crack arresters and higher energy absorption for crash structures

The potential of Z-Fibres™ as crack arresters makes the technology very attractive to the automotive industry. Z-pinning can improve the resistance to damage of safety structure, allowing savings in costs and weight to be made.

The civil engineering industry is beginning to use increasing amount of composite materials in order to either repair existing structures or to build new lightweight edifices. Figure 1-7 is a photograph of a large structural composite I/H beam representative of structures used in the civil engineering. This structure has been manufactured using a co-bonding technique. Subcomponent (skins and flanges) were manufactured and cured separately and the structure was bonded together using a tough adhesive. The beam was tested under 3pt-bending configuration until failure. The main mode of failure is delamination within the top skin, but not at the bond interfaces between the different substructures. The use of Z-Fibres™ in these skins improves the delamination resistance of the material used, by better stress transfer through the thickness of the skins. It therefore increases the strength to failure of the structures, as shown by a comparative study of pinned co-cured and pinned co-bonded joints (Figure 1-8).

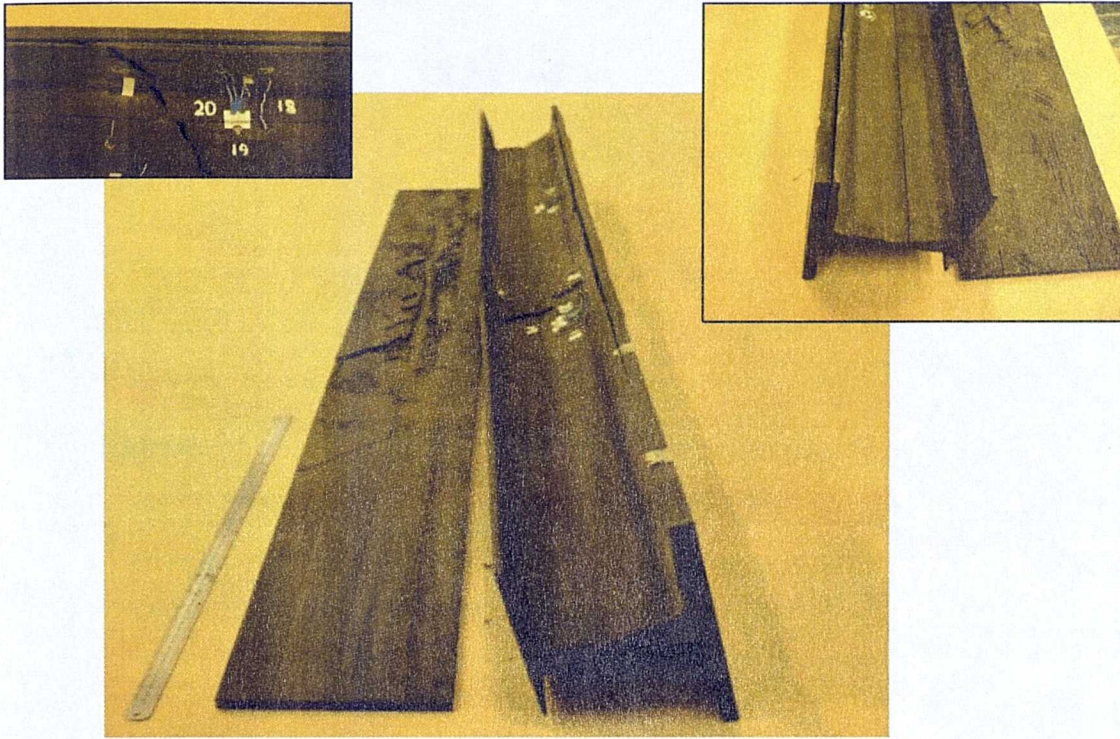


Figure 1-7: Large composite I beam tested under 3pt-bend configuration

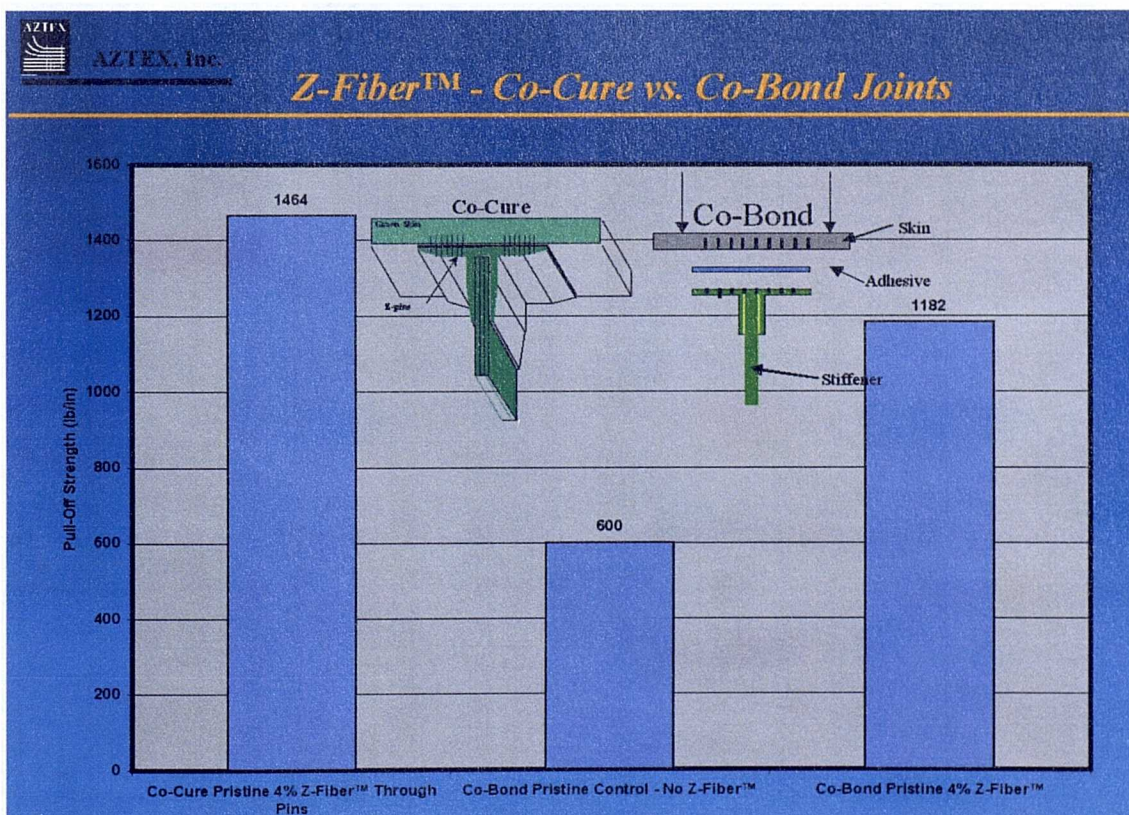


Figure 1-8: Effects of Z-Fibres™ on co-cured and co-bonded joints
(Courtesy of Aztex Inc.)

Z-Fibre™ pinning is also used as a means to control through-the-thickness thermal conductivity of composites. An optimised material choice for the pin allows better heat transfer in the Z-direction of the laminate.

1.3 Objectives of the study and thesis structure

In view of the fact that Z-Fibre™ pinning is already used in several commercial applications, the effectiveness of Z-pins as a through-the-thickness reinforcement for composites is taken as the initial hypothesis. However, while the manufacturer's existing data on Z-Fibre™ pinning confirms this hypothesis (Childress and Freitas, 1992) (Freitas et al, 1994), no extensive scientific study of the modes of failure of such laminates had been carried out at the time of start of the study reported in this thesis. The objectives of this thesis are therefore to **report, illustrate and quantify the effects of Z-pinning on the delamination behaviour of composite materials**. In attaining these objectives the identification of key structural parameters and their effects on the failure by delamination of Z-pinned laminates was found to be necessary. Alongside the primary objective, the work reported here set out to establish manufacturing feasibility and reproducibility, to develop new test procedures applicable to this type of 3D material and to identify the different energy absorption mechanisms involved in the fracture of Z-pinned composites.

The test program consists primarily of interlaminar fracture testing of unidirectional laminates, supplemented by relevant impact and compression after impact measurements. The experimental results are rationalised by the use of a parametric numerical tool, developed specifically for this study.

A review of the current delamination test procedures for unpinned laminates is carried out in Chapter 2, alongside a survey of the effects of through-the-thickness reinforcements on the delamination behaviour of CFRP laminates. The specific uses of Z-Fibres™ and their installation in the composite are described in Chapter 3, followed by detailed descriptions of the delamination test methods and the materials used in the

present work in Chapter 4. Chapter 5 presents the experimental results of all the delamination tests performed in this study. It also includes early experimental data on compression after impact tests of Z-pinned composites, generated in two parallel MSc projects in which the author was directly involved.

Chapter 6 is kept self-contained and focussed on single-pin testing, where the actions of individual Z-Fibres™ bridging an already existing crack are investigated. The results of single pin testing are used directly in Chapter 7, describing the creation of a relatively simple finite element tool designed for use in parametric studies of the delamination behaviour of Z-pinned laminates.

Chapters 5 -7 include individual discussion sections, appropriate to the topic being covered. The final chapter (Chapter 8) then discusses general aspects of use of Z-Fibres™, in particular the influence of manufacturing parameters on 'Z-pinning quality' and, in turn, the effects of that pinning quality on the performance of the Z-pinned laminates. The current status of understanding of the micromechanisms of failure in Z-pinned composites is also reviewed. Following a 'Conclusions and Suggestions for Further Work' section, the appendices regroup some examples of raw data, pictures taken from videos and photographs of the experiments and a listing of codes of the finite element procedures developed.

Chapter 2 Literature Review on Delamination Testing

2.1 General introduction

Development of international standards for delamination testing is a long and ongoing process. In this chapter classical test configurations for delamination testing of unidirectional 2D laminates will be described and the corresponding data analysis methods reviewed. The problem of analysing such data from novel 3D composites can be studied by using a 'black box' approach, i.e. applying standard test methods and their analysis on specimens containing through-the-thickness reinforcement. Although the validity of such an approach is questionable, it is a method to carry out comparative study of the effects of through-the-thickness reinforcement on delamination testing. Such studies found in the literature will be reviewed in the case of Z-Fibre™ pinning and stitching. Finally, models dealing with the analysis of through-the-thickness reinforcement will be reviewed.

2.2 Delamination testing

Linear elastic fracture mechanics (LEFM) has been developed originally to describe fracture in isotropic materials (Griffith, 1920). Later on, its use has been extended successfully to delamination fracture of orthotropic materials such as composites.

LEFM quantifies the capability of a composite material to resist the propagation of a delamination crack by its critical energy release rate, G_C , the energy necessary to propagate a delamination per unit of surface. G_C , also called delamination toughness, is considered to be a material property, independent of the specimen geometry, which includes the effects of the matrix toughness, the fibre properties, the fibre to matrix adhesion as well as the interface strength between plies. However, G_C is dependent on the mode of failure. It is therefore necessary to define carefully the conditions under which the crack is initiated and propagated. Figure 2-1 shows the different modes of failure. It is generally agreed that any crack propagates under some combination of these three different loading conditions: -mode I opening, mode II shear and mode III tear.

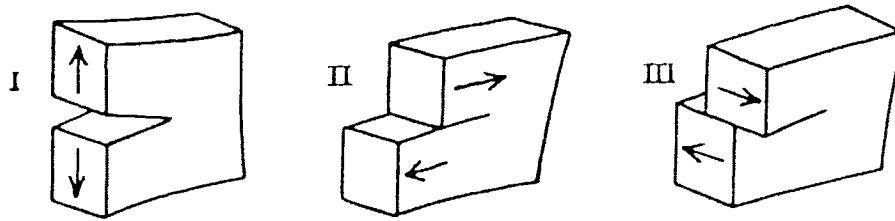


Figure 2-1: Basic modes of loading (Desoyer, 1996)

G_C is used as a failure criterion during design of composite structures or during finite element analysis of fracture behaviour (Hinton and Soden, 1998). There is thus a clear need for accurate and meaningful values of this parameter. First studies on delamination of composite materials are about 20 years old, mainly regarding mode I loading conditions. They are reviewed in the following references (Tanaka et al, 1994) and (O'Brien and Martin, 1992).

In general terms, development work of delamination tests is carried out by standardisation organisations such as the American Society of Testing and Materials (ASTM), the Japanese Industrial Standards group (JIS) and by the European Structural and Integrity Society (ESIS). These organisations identify the key parameters for optimisation of the test itself. A draft protocol of the test is proposed alongside with one or several data analysis methods. The protocol is improved, usually under the format of round-robin testing. When the protocol has reached a sufficient degree of maturity, the protocol is proposed as a new work item into ISO or ASTM. Further cycles of checks and improvements are needed before the test protocol is accepted as a finalised test standard.

In the case of delamination testing under mode I, mode II and mixed mode I/II loading conditions, the specimen width and thickness have been optimised in order to reduce edge effects and to limit large deformation, thus avoiding non-linear behaviour. Definitions of the initiation value are given with a systematic way to deduce them from

the test data (load/displacement traces for example). The initial conditions are also well defined in order to obtain reproducible values. For example, it is advised to insert a thin non-adhering starter film at the mid-plane of the laminate during lay-up. This artificial crack avoids the need for difficult notching of the specimens and will insure that the crack initiates at the mid-plane of the laminate.

At present, all the developed delamination test protocols deal with unidirectional laminates. Not only does the ply orientation affect the toughness values, but it also changes the behaviour of the specimens. Figure 2-2 is a photograph of a cross-ply specimen tested at Cranfield for a round robin exercise of the ESIS Technical Committee 4 (TC4) group. It is apparent that the behaviour of the crack is affected by the presence of a 0/90 interface at the mid-plane of the laminate. The crack front does not stay in the centre plane of the laminate, but oscillates around it in a regular manner.

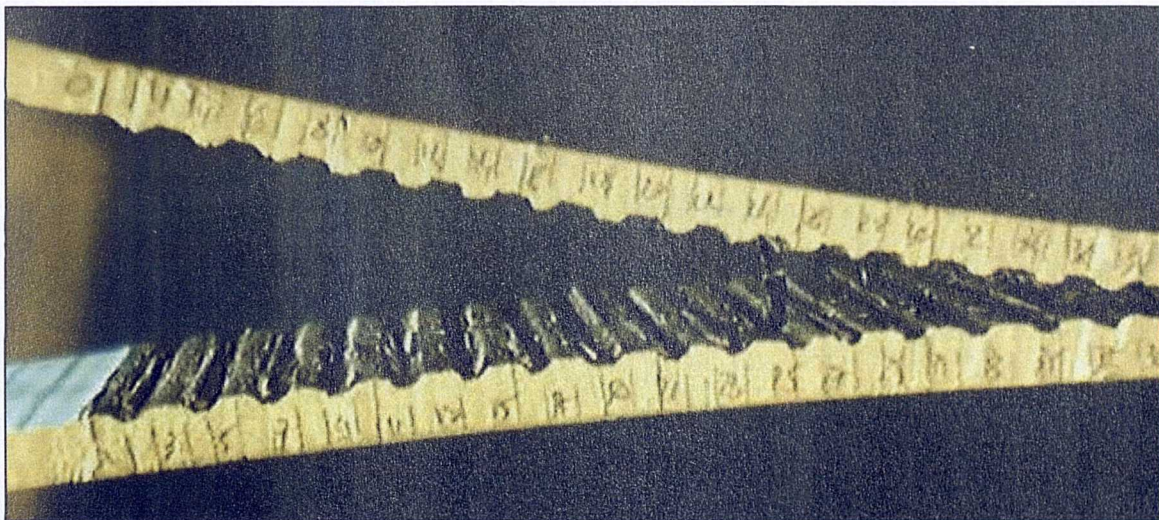


Figure 2-2: Delamination testing of a cross ply laminate

Each protocol usually suggests several data analysis methods for each kind of loading condition. The basics of LEFM in its application to delamination testing are described below.

Consider a composite beam containing a crack of a length a , having the characteristics as shown in Figure 2-3.

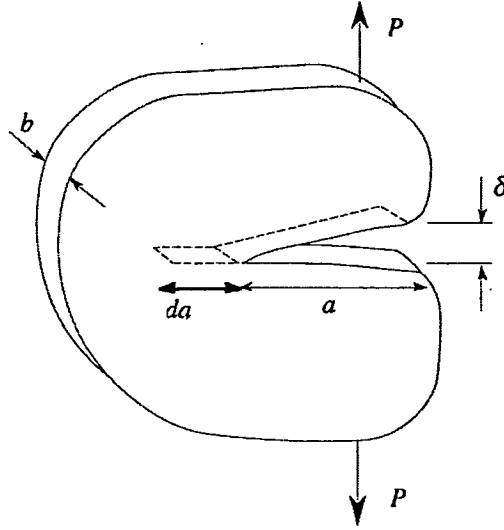


Figure 2-3: Solid characteristics (After Williams, 1989a)

The total energy balance can be written :

$$W=U+T+D \quad \text{Equation 2-1}$$

where W is the external work, U the elastic strain energy, T the kinetic energy and D the dissipative energy related with the fracture. By definition, in the configuration shown in Figure 2-3 and neglecting the kinetic energy, the energy release rate is :

$$G_c = \frac{1}{b} \frac{dD}{da} \quad \text{Equation 2-2}$$

Equation 2-2 gives (Griffith, 1920) (Williams, 1989a) :

$$G_c = \frac{1}{b} \left(\frac{dW}{da} - \frac{dU}{da} \right) \quad \text{Equation 2-3}$$

Introducing the deflection δ of the solid and the applied load P :

$$\frac{dW}{da} = P \frac{d\delta}{da} \quad \text{Equation 2-4}$$

$$\text{and} \quad U = \frac{1}{2} P \delta \quad \text{Equation 2-5}$$

Combining Equation 2-3 with Equation 2-4 and Equation 2-5, we obtain :

$$G_c = \frac{1}{2b} \left[P \frac{d\delta}{da} - \delta \frac{dP}{da} \right] \quad \text{Equation 2-6}$$

The compliance of the beam is defined by :

$$C = \frac{\delta}{P} \quad \text{Equation 2-7}$$

Finally, the energy release rate is given by :

$$G_c = \frac{P^2}{2b} \frac{dC}{da} \quad \text{Equation 2-8}$$

Equation 2-8 is valid for any beam of a width b , containing a crack of a length a , growing of an area bda with a crack front perpendicular to the edge of the specimen, with no fibre bridging, whatever the loading conditions. All data reduction methods of mode I, mode II and mixed mode I/II delamination tests are based on Equation 2-8. The problem consists of finding correct expressions of Equation 2-8 from the data obtained during testing for each test configuration.

2.2.1 Mode I

Delamination testing under mode I loading conditions is carried out following the double cantilever beam (DCB) configuration. The test conditions have been agreed by the main standardisation organisations and the protocol proposed by the ESIS TC4 group, in consultation with the ASTM, was accepted as ISO standard ISO 15024 in September 2000. Figure 2-4 shows the main characteristics of the DCB test configurations.

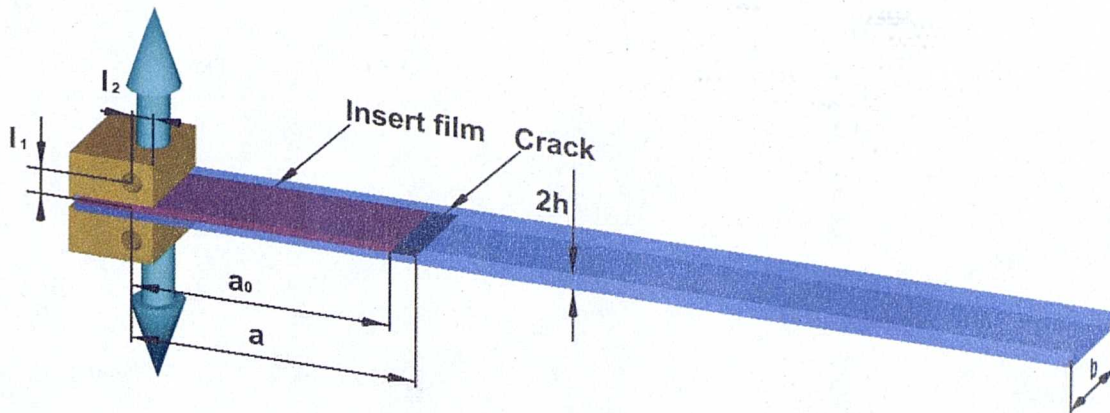


Figure 2-4: Mode I DCB test configuration and nomenclature

The nomenclature is shown in Figure 2-4. P is the load applied and δ is the opening displacement of the beam at the loading points. The compliance can be expressed as a function of the crack length using the beam theory :

$$C = \frac{8a^3}{bh^3E} \quad \text{Equation 2-9}$$

where E is the longitudinal Young's modulus.

After deriving C as a function of the crack length, G_I can be written as :

$$G_I = \frac{3P\delta}{2ba} \quad \text{Equation 2-10}$$

This expression underestimates the compliance of the beam. A first correction factor is applied, treating the beam as having a slightly longer crack length, $(a + |\Delta|)$, where $|\Delta|$ is defined as the intercept of the plot of $C^{1/3}$ vs. crack length with the x-axis.

Two other correction factors N and F are used to correct the effects of the stiffening of the arm by the loading blocks and the displacement of the loading points because of the tilting of the end blocks (Williams, 1987).

$$N = 1 - \left(\frac{l_2}{a}\right)^3 - \frac{9}{8} \left[1 - \left(\frac{l_2}{a}\right)^2 \right] \left[\left(\frac{\delta_1}{a}\right) - \frac{9}{35} \left(\frac{\delta}{a}\right)^2 \right] \quad \text{Equation 2-11}$$

$$F = 1 - \frac{3}{10} \left(\frac{\delta}{a} \right)^2 - \frac{3}{2} \left(\frac{\delta l_1}{a} \right) \quad \text{Equation 2-12}$$

The corrected beam theory data reduction method for the DCB test is finally expressed by :

$$G_{IC} = \frac{3P\delta}{2b(a+|\Delta|)} \frac{F}{N} \quad \text{Equation 2-13}$$

When some fibre bridging is created in the wake of the crack, the apparent stiffness of the specimen is increased by the bridging actions, therefore the correction factor on the crack length Δ is increased.

Alternatively, a method based on experimental determination of the compliance of the beam is also proposed. The compliance, C , can be expressed by :

$$C = ka^n \quad \text{Equation 2-14}$$

n and k are determined experimentally by plotting $\ln C$ as a function of $\ln a$.

Therefore, deriving C as a function of a gives :

$$\frac{dC}{da} = nka^{n-1} = \frac{nC}{a} \quad \text{Equation 2-15}$$

And finally,

$$G_{IC} = \frac{nP\delta}{2ba} \quad \text{Equation 2-16}$$

The above correction factors F and N are applicable and the experimental compliance method for data reduction of the DCB tests is :

$$G_{IC} = \frac{nP\delta}{2ba} \frac{F}{N} \quad \text{Equation 2-17}$$

As discussed above, the presence of small scale fibre bridging will reduce the compliance of the specimen and the parameter n will decrease.

Further information on the analysis can be found in the standard (Moore, 2000).

2.2.2 Mode II

Unlike the case of mode I loading, delamination testing standardisation under mode II loading conditions is not yet finalised. Several test configurations are still under investigation and discussions on the effects of the friction at the crack wake on the behaviour of the crack growth are still ongoing. However, the basic specimen parameters (width, thickness, insert film) are very similar to mode I testing (Williams, 1987).

2.2.2.1 3 pt-ENF configuration

The 3 pt-ENF or end notched flexure test configuration is shown in Figure 2-5. Shear loading at the crack tip is applied by a 3-point bending configuration of a beam containing a defect.

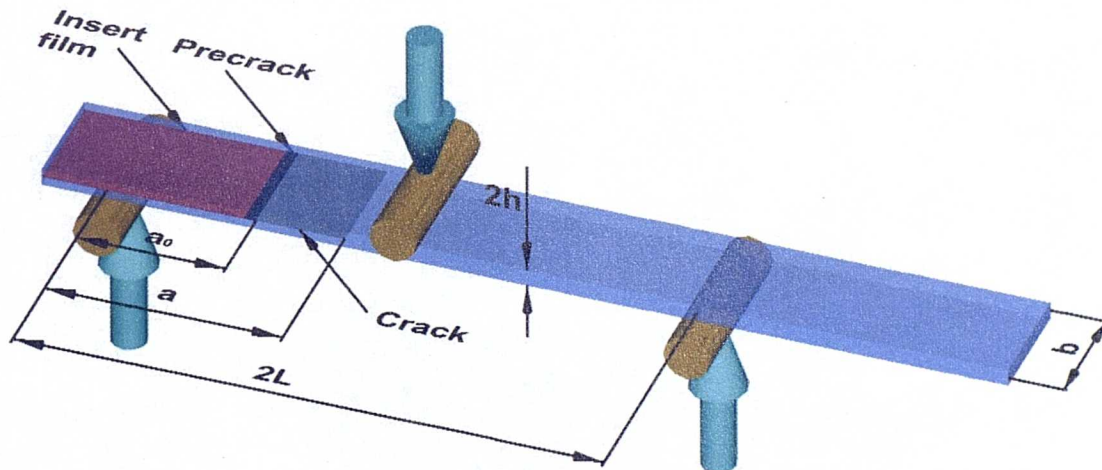


Figure 2-5: 3 pt-ENF test configuration

In this configuration, using standard beam theory, the deflection at mid-span is given by (Carlsson et al 1986) :

$$\delta = \frac{P(2L^3 + 3a^3)}{8bh^3E} = CP$$

Equation 2-18

Deriving Equation 2-18 and substituting in Equation 2-8 gives :

$$G_{IIC} = \frac{9a^2 \delta P}{2b(2L^3 + 2a^3)} = \frac{9a^2 P^2}{2b(8bh^3 E)} \quad \text{Equation 2-19}$$

E (flexural Young's modulus) can be determined experimentally by a simple 3-point bend test with a crack length $a=0$. Then :

$$E = \frac{L^3}{4bh^3 C_0} \quad \text{Where } C_0 = \frac{\delta_0}{P_0} \quad \text{Equation 2-20}$$

Similarly to mode I testing, correction factors F , N , and S , are used to compensate for the effects of large displacement and transverse shear (Williams, 1987).

$$F = 1 - \frac{3 \left\{ 15 \left[1 - \left(\frac{a}{L} \right)^3 \right]^2 - 40 \left(\frac{a}{L} \right)^2 \left[1 - \left(\frac{a}{L} \right)^3 \right] + 48 \left(\frac{a}{L} \right)^4 \right\}}{5 \left[2 + 3 \left(\frac{a}{L} \right)^3 \right]^2} \cdot \left(\frac{\delta}{L} \right)^2 \quad \text{Equation 2-21}$$

$$N = 1 + \frac{3}{35} \frac{\left[37 + 147 \left(\frac{a}{L} \right)^3 + 210 \left(\frac{a}{L} \right)^6 + 105 \left(\frac{a}{L} \right)^9 \right]}{\left[2 + 3 \left(\frac{a}{L} \right)^3 \right]^3} \quad \text{Equation 2-22}$$

$$S = 0.2 \frac{Eh^2}{G_{I3} a^2} \quad \text{Equation 2-23}$$

Another method consists of determining experimentally the compliance of the beam as a function of the crack length, doing a series of flexural tests prior to and/or after testing with different crack lengths. The compliance is then expressed :

$$C = C_0 + ma^3 \quad \text{Equation 2-24}$$

Finally, the experimental data can be analysed using three different methods:

Direct beam theory :-

$$G_{IIC} = \frac{9a^2 P \delta}{2b(2L^3 + 3a^3)} \frac{F}{N} (1 + S) \quad \text{Equation 2-25}$$

Corrected beam theory :-

$$G_{nc} = \frac{9a^2 P^2}{8b^2 h^3 E} \frac{F}{N} (1 + S) \quad \text{Equation 2-26}$$

Experimental compliance calibration :-

$$G_{nc} = \frac{3ma^2 P^2}{2b} \frac{F}{N} (1 + S) \quad \text{Equation 2-27}$$

Condition of stability:

In order to investigate the stability of the test, we need to differentiate G with respect to the crack length when expressed as a function of the controlling parameter of the test, δ , in the case of displacement controlled testing (Gamby, 1996). Differentiating Equation 2-19 :

$$\frac{\partial G(a, \delta)}{\partial a} = \frac{9a\delta^2}{2b} \left(\frac{L^3 - 3a^3}{(2L^3 + 3a^3)^3} \right) \quad \text{Equation 2-28}$$

Which means that, in displacement controlled conditions, the test is stable if :

$$L^3 - 3a^3 \leq 0 \Leftrightarrow \frac{a}{L} \geq \frac{1}{\sqrt[3]{3}} \approx 0.7 \quad \text{Equation 2-29}$$

Typically, $L=50\text{mm}$ and the initial crack length $a_0=25\text{mm}$. In theory, the crack growth becomes stable for $a=35\text{mm}$, however, the kinetic energy due to the initial instability leads the cracks to propagate further than the loading point at $a=50\text{mm}$, invalidating any propagation values. Most often, when using the 3pt-ENF configuration, only initiation values are useable.

The 3-pt ENF test is still often used because of its simple configuration. Most laboratories possess a 3-point bend test rig. However, a lot of work has been carried out in order to develop alternative methods.

2.2.2.2 SENF configuration

The Japanese Industrial Standards group proposed a solution to stabilise the ENF test configuration (JIS, 1993). The principle involves using the 3-point bend configuration, but introducing the load by applying a constant shear displacement speed, $\dot{\delta}_s$, at the split end of the specimen, as opposed to applying constant crosshead speed $\dot{\delta}$. A computer connected to a clip gauge measuring δ_s controls the testing machine.

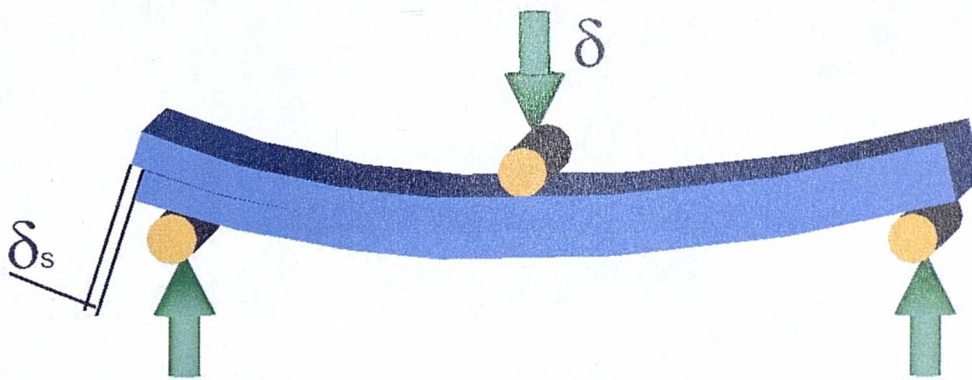


Figure 2-6: SENF control mode

Two different data analyses are proposed. The first is based on the beam theory :

$$G_{IIC} = \frac{3P\delta_s}{4b(2h)} \quad \text{Equation 2-30}$$

The second is based on experimental compliance determination :

$$G_{IIC} = \frac{9a^2P^2C_s}{2b(2L^3 + 3a^3)} \quad \text{with} \quad C_s = \frac{\delta_s}{P} \quad \text{Equation 2-31}$$

Due to the complexity of the test configuration and the specialised equipment needed to control the testing machine, the SENF is not frequently used. More research has been done in order to design simple test configurations offering a greater range of stable crack growth.

2.2.2.3 ELS configuration

ELS or end loaded split test configuration is an alternative to the ENF and SENF. The mode II loading of the crack tip is introduced by flexure of a split cantilever beam. It is to be noted that a pencil lead is introduced in the crack under the loading point in order to reduce the friction between the crack lips (Figure 2-7) (ESIS, 1995).

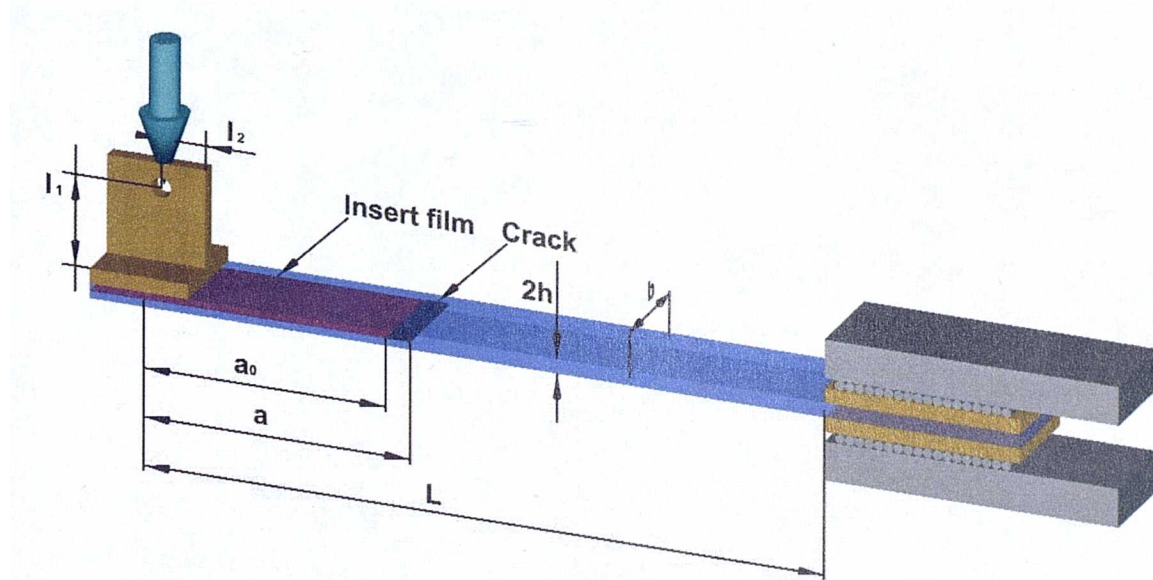


Figure 2-7: ELS configuration

The approach for the data reduction analysis is very similar to that used in the previously described tests. Using beam theory, the compliance of the split beam is :

$$C = \frac{3a^3 + L^3}{3EI} \quad \text{Equation 2-32}$$

And after deriving Equation 2-32, the energy release rate can be written :

$$G_{IIc} = \frac{3P^2 a^2}{2bEI} \quad \text{Equation 2-33}$$

where E is the flexural Young's modulus and I the moment of area of the beam.

A simple flexural test on the uncracked part of the specimen would give EI .

$$EI = \frac{PL^3}{3\delta} \quad \text{Equation 2-34}$$

Alternatively, if E is known

$$G_{IIC} = \frac{9P^2 a^2}{4b^2 E h^3} \quad \text{Equation 2-35}$$

As in mode I, a correction to the compliance has to be applied. In order to do that, the crack length a is replaced by $(a + \Delta_{II})$ where $\Delta_{II} = 0.42\Delta_I$ and Δ_I is the correction determined during a mode I DCB test accordingly to paragraph 2.2.1 . The value 0.42 has been determined using finite element analysis (Wang and Williams, 1992).

Finally

$$G_{IIC} = \frac{3P^2 (a + \Delta_{II})^2}{2bEI} = \frac{9P^2 (a + \Delta_{II})^2}{4b^2 E h^3} \quad \text{Equation 2-36}$$

Using a similar determination of the compliance as in the ENF test, the experimental compliance method is defined by

$$G_{IIC} = \frac{3ma^2 P^2}{2b} \quad \text{Equation 2-37}$$

Correction factors have been developed in order to take into account the effects of large displacement (θ_1) and the stiffening of the beam by the loading blocks (θ_2) (Wang and Williams, 1992).

$$\theta_1 = \frac{3}{20} \frac{\left[15 + 50 \left(\frac{a}{L} \right)^2 + 63 \left(\frac{a}{L} \right)^4 \right]}{\left[1 + 3 \left(\frac{a}{L} \right)^3 \right]^2} \quad \text{Equation 2-38}$$

$$\theta_2 = -3 \left(\frac{L}{a} \right) \frac{\left[1 + 3 \left(\frac{a}{L} \right)^2 \right]}{\left[1 + 3 \left(\frac{a}{L} \right)^3 \right]} \quad \text{Equation 2-39}$$

These correction factors are valid for both beam theory and experimental compliance methods. They have to be applied as follows:

$$G_{IIC(\text{corrected})} = G_{IIC} \left[1 - \theta_1 \left(\frac{\delta}{L} \right)^2 - \theta_2 \left(\frac{\delta l_1}{L^2} \right) \right] \quad \text{Equation 2-40}$$

Condition of stability

Simple stability analysis similar to Equation 2-28 gives :

$$\frac{dG_{IIC}}{da} = \frac{27a\delta^2 EI}{b} \left[\frac{L^3 - 6a^3}{(3a^3 + L^3)^3} \right] \quad \text{Equation 2-41}$$

This means that the crack propagation is stable if

$$L^3 - 6a^3 \leq 0 \Leftrightarrow \frac{a}{L} \geq \sqrt[3]{6} \approx 0.55 \quad \text{Equation 2-42}$$

Typically, in ELS tests, $L=80\text{mm}$, which allows the crack propagation to be studied over a length of more than 35mm.

2.2.2.4 4-pt ENF configuration

Most recently, the 4-point ENF test configuration has become the subject of comparative studies with the ELS configuration within ESIS TC4. The 4-pt ENF has been designed to reduce the friction effects between the crack faces and to propagate the crack in a stable manner by introducing the shear load at the crack tip through applying moments at both ends of the beam as opposed to a shear stress in the case of 3-pt ENF (Martin and Davidson, 1997).

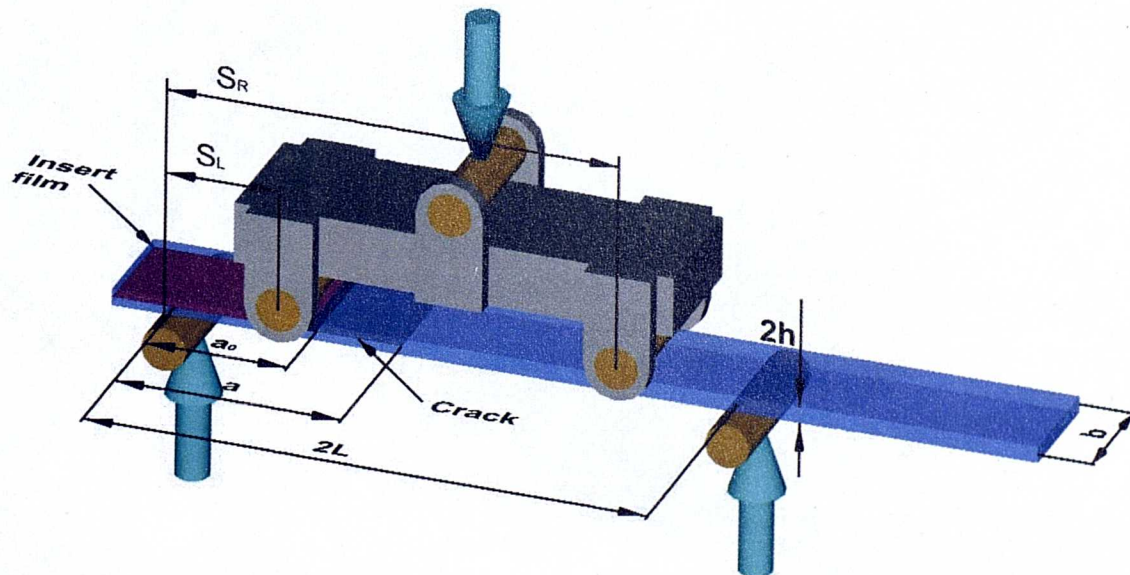


Figure 2-8: 4pt ENF configuration

Similarly to the previous tests, for the configuration shown in Figure 2-8, beam theory analysis leads to :-

$$G_{II} = \frac{P^2(R-2)}{16b^2D} \left[S_L + a \left(1 - \frac{S_L}{2L} - \frac{S_R}{2L} \right) \right]^2 \quad \text{Equation 2-43}$$

(for homogeneous materials in plane stress, $D=EI/b$ and $R=8$.)

Introducing the compliance defined as in Equation 2-7,

$$G_{II} = \frac{P^2 S_L^2 (R-2)}{16b^2 D} = \frac{\delta^2 S_L^2 (R-2)}{16b^2 D C^2} \quad \text{Equation 2-44}$$

Beam theory, as well as experiments, has shown that the change of the compliance with the crack length can be expressed by :

$$C = C_0 + C_1 a \quad \text{Equation 2-45}$$

The compliance calibration method is therefore obtained by substituting Equation 2-45 into Equation 2-8 :

$$G_{II} = \frac{P^2 C_1}{2b} \quad \text{Equation 2-46}$$

Condition of stability

Under displacement control, G_{II} could be derived by the following :-

$$\frac{\partial G_{II}}{\partial a} = - \frac{\delta^2 S_L^2 (R-2)}{8b^2 D} \frac{C_1}{(C_0 + C_1 a)} \quad \text{Equation 2-47}$$

This function is always negative, which means that the test is always stable, whatever the crack length (Martin and Davidson, 1997).

2.2.3 Mixed mode I/II

2.2.3.1 Introduction

In the case of a real structure, it is unlikely to encounter a delamination propagating under pure mode I or mode II loading conditions. There is no evidence that the delamination toughness of a laminate fracturing under mixed mode loading conditions can be deduced in a simple manner from the knowledge of mode I and mode II energy release rates. Investigation of the mixed mode I/II toughness envelope is therefore totally justified. Various test configurations are available to study delamination cracks under mixed mode loading conditions (Figure 2-9).

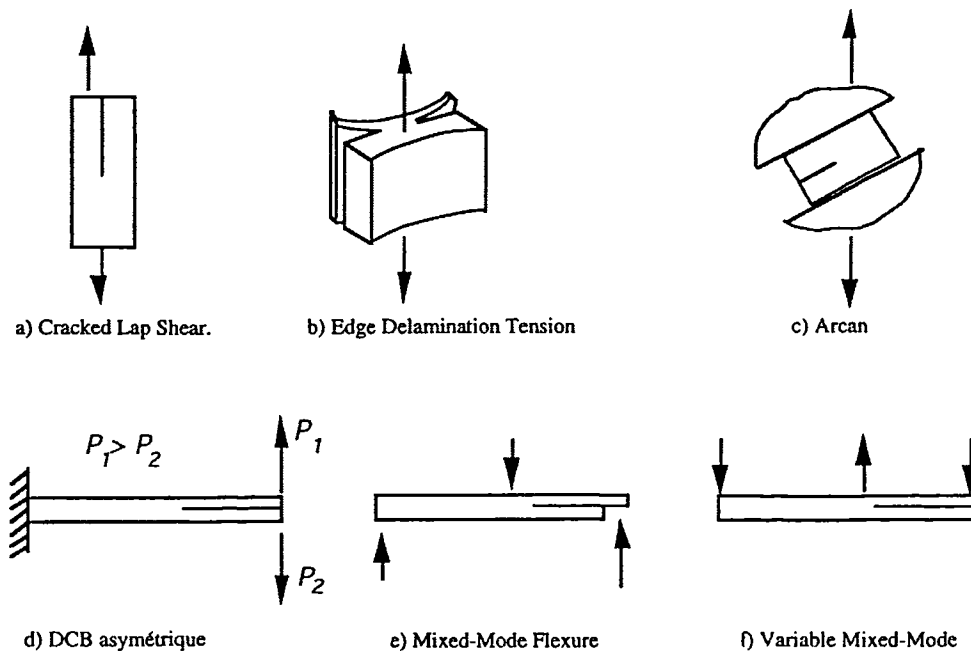


Figure 2-9: Various mixed mode I/II test configurations (after Reeder, 1990 and Ducept, 1996)

One of the configurations, the most frequently used, is the MMB test (mixed mode bending). It is literally the superposition of mode I DCB and mode II ENF (Figure 2-10). The ratio of mode I / mode II can be varied from almost pure mode I to pure mode II, by changing the position of the loading point. Close collaboration between the ASTM and ESIS TC4 allowed the test protocol and the analysis to be constantly

improved. A draft standard was proposed to ASTM for validation in 1998. Another round robin is about to begin (at the time of writing this thesis) between ASTM and ESIS TC4 in order to perform a final check on the protocol and obtain more bias statistics necessary for the standard to be accepted.

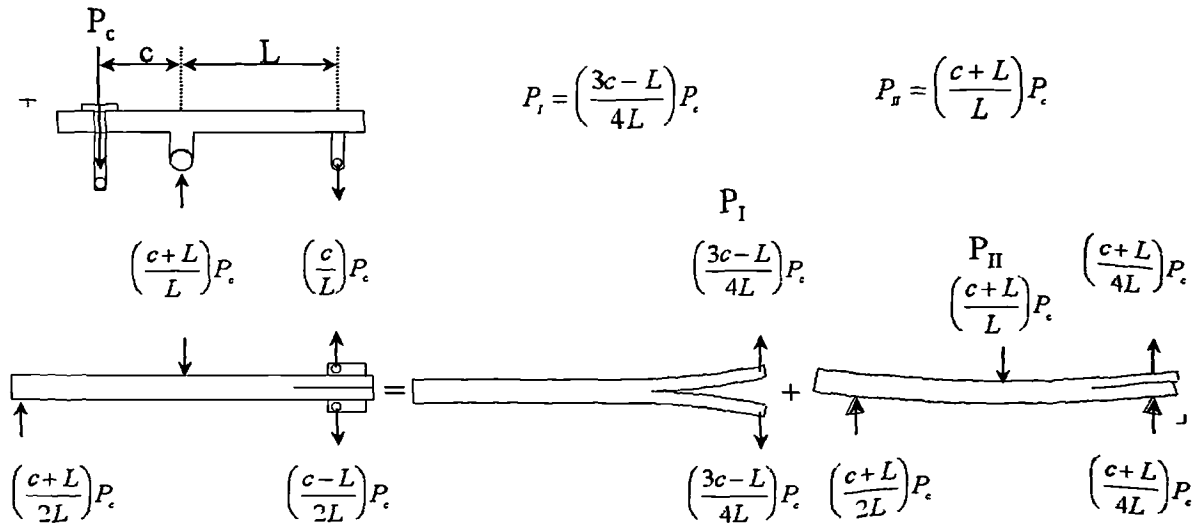


Figure 2-10: Superposition principle applied to a MMB specimen

(Reeder and Crews, 1990)

2.2.3.2 MMB test apparatus

The MMB test apparatus is shown in Figure 2-11. Loading forces are introduced via tabs, which are bonded near the split end of the specimen and through rollers, which bear against the specimen on the undelaminated region. The base of the apparatus holds the specimen in place while the load is introduced via a lever. The position of the lever, c , can be changed to vary the ratio of the pulling on the tab to the load bearing through the roller, thus changing the mode I/mode II loading condition ratio.

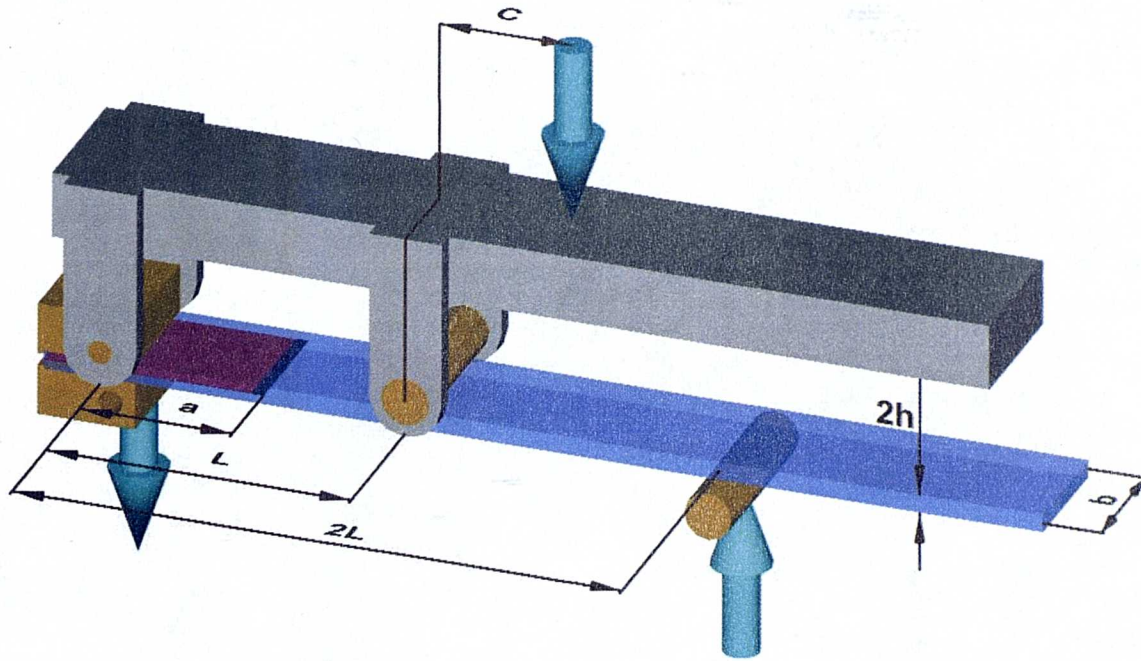


Figure 2-11: MMB configuration

Force equilibrium on the lever combined with the principle of superposition gives

$$P_I = \left(\frac{3c - L}{4L} \right) P \quad \text{Equation 2-48}$$

$$P_{II} = \left(\frac{c + L}{4L} \right) P \quad \text{Equation 2-49}$$

2.2.3.3 Beam theory data analysis

A first analysis of MMB test, based on the beam theory, was proposed by Crews and Reeder (1988). It has been validated using finite element analysis (Reeder and Crews, 1990). The different evolutions of the analysis are described here, leading to the current version actually suggested in the draft ASTM standard.

For a DCB test, the compliance can be expressed by :

$$C_I = \frac{8a^3}{bh^3E} \quad \text{Equation 2-50}$$

and the mode I energy release rate is :

$$G_{IC} = \frac{P_I^2}{2b} \frac{dC_I}{da} = \frac{12P_I^2 a^2}{b^2 h^3 E} \quad \text{Equation 2-51}$$

In the case of an ENF test, the compliance can be written as :

$$C_{II} = \frac{(2L^3 + 3a^3)}{8bh^3 E} \quad \text{Equation 2-52}$$

And therefore :

$$G_{IIC} = \frac{P_{II}^2}{2b} \frac{dC_{II}}{da} = \frac{9a^2 P_{II}^2}{16bh^3 E} \quad \text{Equation 2-53}$$

Using Equation 2-48 and Equation 2-49 we obtain :

$$G_{IC} = \frac{3a^2 P^2}{4b^2 h^3 L^2 E} (3c - L)^2 \quad \text{Equation 2-54}$$

$$G_{IIC} = \frac{9a^2 P^2}{16b^2 h^3 L^2 E} (c + l)^2 \quad \text{Equation 2-55}$$

The mode I to mode II ratio can be calculated from :

$$\frac{G_{IC}}{G_{IIC}} = \frac{4}{3} \left(\frac{3c - L}{c + L} \right)^2 \quad \text{Equation 2-56}$$

It is to be noted that the ratio G_{IC}/G_{IIC} is not dependent of the crack length a . It is a function of c/L only.

As before, correction factors have to be applied to correct the possible rotation of the crack tip, the transverse shear and compliance error (Williams, 1989b) (Wang and Williams, 1992). It leads to the determination of the correction factor χh applied to the crack length :-

$$E_{1f} = \frac{8(a_0 + \chi h)^3 (3c - L) + [6(a_0 + 0.43 \chi h)^3 + 4L^3] (c + L)^2}{16L^2 b h^3 \left(\frac{1}{m} + C_{sys} \right)} \quad \text{Equation 2-57}$$

with :

$$\chi = \sqrt{\frac{E_{11}}{11G_{13}} \left[3 - 2 \left(\frac{\Gamma}{1 + \Gamma} \right)^2 \right]} \quad \text{Equation 2-58}$$

$$\Gamma = 1.18 \frac{\sqrt{E_{11}E_{22}}}{G_{13}} \quad \text{Equation 2-59}$$

During a particular round-robin, testing of relatively thin (3mm) specimens showed up some significant discrepancies between the results of the different laboratories. It appears that depending on the choice of the material used to build the testing jig, the weight, P_{lever} , of the lever itself can introduce a non-negligible force on the specimen and modify the results. The weight of the lever therefore has to be taken into consideration. Equation 2-48 becomes :-

$$P_I = \left(\frac{3c - L}{4L} \right) P + \left(\frac{3c_{\text{lever}} - L}{4L} \right) P_{\text{lever}} \quad \text{Equation 2-60}$$

And Equation 2-49 becomes :-

$$P_{II} = \left(\frac{c + L}{4L} \right) P + \left(\frac{c_{\text{lever}} + L}{4L} \right) P_{\text{lever}} \quad \text{Equation 2-61}$$

where c_{lever} is the distance from the centre of gravity of the lever to loading point of the central roller.

Finally, the data reduction analysis proposed currently in the ASTM draft standard with all the corrections for the different problems is :-

$$G_I = \frac{4[P(3c - L) + P_{\text{lever}}(3c_{\text{lever}} - L)]^2}{64bL^2 E_{1f} I} (a + \chi h)^2 \quad \text{Equation 2-62}$$

$$G_{II} = \frac{3[P(c + L) + P_{\text{lever}}(c_{\text{lever}} + L)]^2}{64bL^2 E_{1f} I} (a + 0.42\chi h)^2 \quad \text{Equation 2-63}$$

In a recent publication, Chen et al proposed a slight modification of the test apparatus to avoid having to apply the lever weight corrections (Chen et al, 1999).

2.2.3.4 Experimental compliance method

Other authors have proposed data analyses based on experimental compliance methods (Thesken et al, 1994), (Martin and Hansen, 1996), (Benzeggagh and Kenane, 1996).

The compliances C_1 and C_2 are expressed in the same way as in Equation 2-14 and Equation 2-24. Decomposition of the displacement for the specimens in terms of δ_1 (opening) and δ_2 (displacement of the central loading point relative to the specimen as opposed to the jig) allows :

$$G_I = \frac{nP\delta_1}{2ba} \frac{F_I}{N_I} \quad \text{Equation 2-64}$$

And :

$$G_{II} = \frac{3ma^2P^2}{2b} \frac{F_{II}}{N_{II}} (1 + S) \quad \text{Equation 2-65}$$

Here F_I , N_I (resp. F_{II} , N_{II} and S) are the correction factors applied in the data analysis of pure mode I DCB (resp. pure mode II ENF) tests. Detailed expressions for δ_1 and δ_2 can be found in reference (Thesken et al, 1994).

The experimental compliance calibration method is not proposed in the ASTM draft standard.

The most up to date compilation of the test standards can be found in Moore (2000).

2.2.4 Crack initiation and pre-cracking

It is generally agreed by the testing community that to initiate a delamination crack in a composite material by inserting a starter film during lay-up is the most reproducible and simple. The film will avoid the need for the difficult notching and offers the advantage of knowing the initial conditions. Usually made from PTFE or polyimide, the effect of the thickness of this film has been considered, with regard to its influence on crack

initiation values; a thicker film would create a resin rich pocket at its end and artificially modify the initiation value (Turmel et al, 1995).

Two different approaches can be taken when considering pre-cracking. A first approach is to use initiation/pre-cracking methods, which yield the most conservative values. This approach is supported by the fact that the existing crack may have been created by an impact or any other event, and the way the structure is loaded during service may not be related to the loading conditions of the crack creation. The second approach says that the crack propagates most often during cycling loading and the delamination toughness value has to be obtained by pre-cracking under the same loading conditions as those of the test. The value may not be conservative. Supporting the second approach for pre-cracking, it does not require bonding of tabs and machine setting up time with a different configuration.

Turmel et al (1995) reviewed the different pre-cracking techniques and insert films, used as crack initiators and studied their effects on the initiation values of the interlaminar fracture resistance.

The main conclusions were:

- 1-Generally, the thinner the crack initiator used, the lower the fracture energy measured, both under mode I and mode II loading conditions.
- 2-Mode I specimens tested from insert with an insert film thinner than $15\mu\text{m}$ gives most conservative results.
- 3-Mode I pre-crack on mode II and mixed mode I/II specimens generally leads to the most conservative values.

During the test, the load/displacement signal is recorded. Figure 2-12 shows a typical load/displacement trace of a stable delamination fracture test. The data required for the analysis are the crack length, a , the corresponding load, P , and cross head displacement, δ . Several sets of values of a , P and δ are defined for further analysis:

NL is the point at which the load/displacement trace first deviates from linearity.

VIS corresponds to the point of visual observation of the delamination onset, i.e. the first point at which the delamination is observed to move.

5% is the point of the load/displacement trace at which the original compliance C_0 has increased by 5%.

MAX is the maximum load point of the force/displacement curve, used only if it occurs before the 5% offset value.

When using these initiation points, the crack length used during the data analysis is assumed to be the original crack length at the start of the test, often measured a posteriori by observation of the fully open specimen.

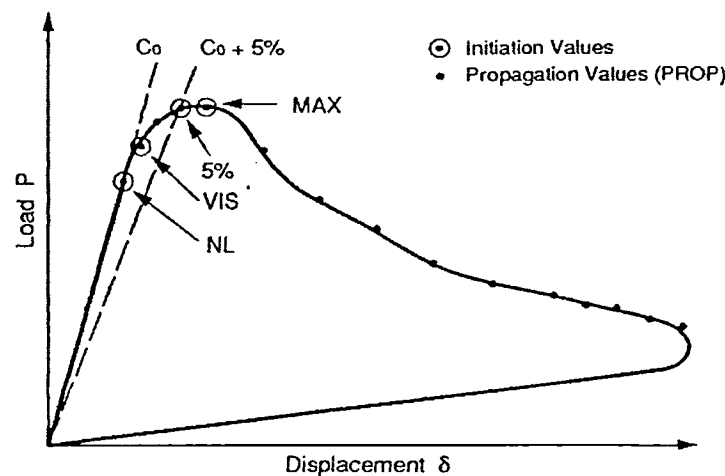


Figure 2-12: Schematic of the load/displacement curve of a delamination fracture test with initiation points NL, VIS, 5%, MAX and the propagation values (PROP) (From ISO 15024)

In the case of unstable crack growth, the initial shape of the curve is similar, therefore the definition of the initiation points are kept the same. As well as the initiation points, propagation values can be determined for each delamination length measured during crack propagation.

2.3 Delamination with through-the-thickness reinforcement

The number of references dealing with the specific problem of the effects of Z-Fibre™ reinforcement on delamination testing is very small (Childress and Freitas, 1992) (Freitas et al, 1994) (Barrett, 1996). Therefore, in this paragraph, the problem will be considered from a broader perspective: a variety of through-the-thickness reinforcements will be considered. Stitching is the closest 3D reinforcement to Z-pin reinforced laminates and is therefore reviewed in some detail. Several authors feel that the differences between stitching and Z-Fibre™ pinning are only a matter of boundary conditions and that the two problems can be treated in a similar way (Cox, 1999a) (Jain and Mai, 1994a).

2.3.1 Experimental observations

In this section, studies of the effects of through-the-thickness reinforcement on interlaminar toughness of composite laminates are reviewed. In all these publications, the data were analysed by LEFM, using the 'black box' approach. Although the appropriateness of the standard LEFM data reduction analysis is highly questionable, these methods allow qualitative observations to be made of the effects of through-the-thickness reinforcement on delamination cracks. Foster-Miller Inc., patent holder of the Z-Fibre™ process, first reported an improvement of the delamination toughness by using Z-Fibre™ pinning in a DCB test. The so-called toughness was increased by a factor of 50 by using Celion G30-400/Epoxy Z-Fibre™ with an areal density of 1.5% on AS4/3501-6 composite. They also stated that with a density of 2%, the crack could not propagate and the specimens failed in flexure (Figure 2-13) (Freitas et al, 1994). Although not explicitly stated in the paper, it might be assumed that the toughness values reported related to crack propagation.

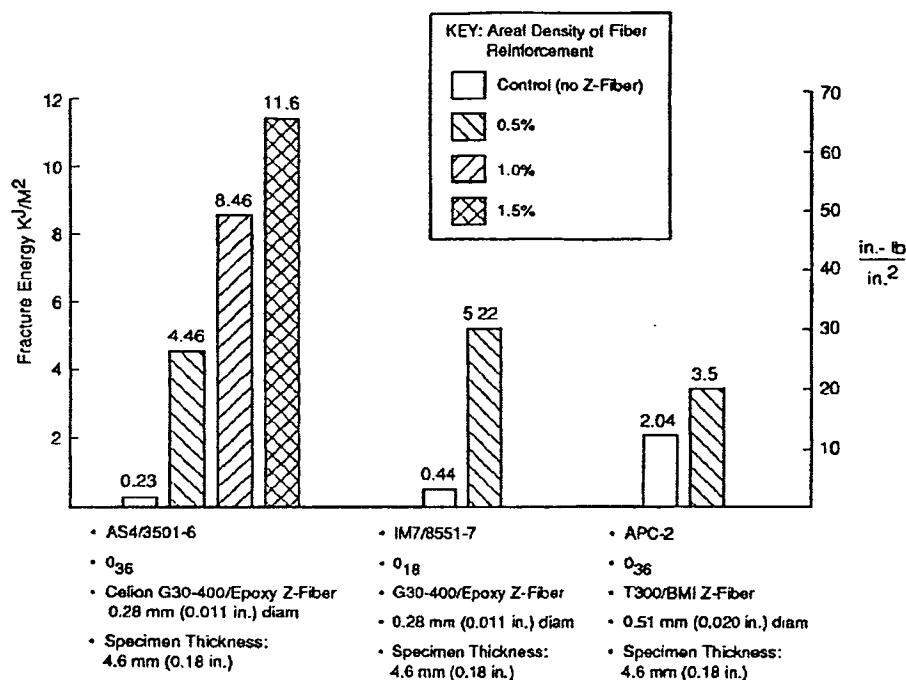


Figure 2-13: Effects of Z-Fibre™ reinforcement on Mode I fracture toughness

(from Freitas et al, 1994)

Considering the mode I loading conditions further, the spacing between each row of reinforcement affects the behaviour of the beam. If the spacing is sufficiently high, the crack propagation adopts a stick-slip behaviour: on a UD glass NCF laminate, with stitching at nominally 11mm intervals across the fabric, the crack growth process has been identified as a series of stick-slip events with the crack stopping just beyond a line of through-the-thickness reinforcement followed by a large crack jump when the stitches failed (Simmer and Hogg, 1993). If the stitches are concentrated in a narrow zone, the crack stops when it encounters the stitches. Depending on the stitch material, the crack can either propagate after failure of the stitches, inducing an increase of the toughness up to 15 fold in the case of Kevlar stitches, or the specimens fail in flexure in the case of carbon stitches (Ishai, 1998).

The size of the reinforcement zone is also important; in the configuration described in Figure 2-14 where the DCB specimen is stitched along the whole length, a steady state crack propagation with flat R-curves can be reached (Figure 2-15). As the crack propagates, the number of bridging ligaments stays constant (Dransfield et al, 1995).

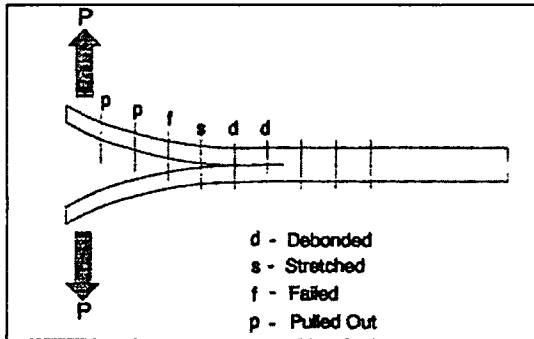


Figure 2-14: Schematic representation of mode I crack propagation through a stitched composite specimen (from Dransfield et al, 1995)

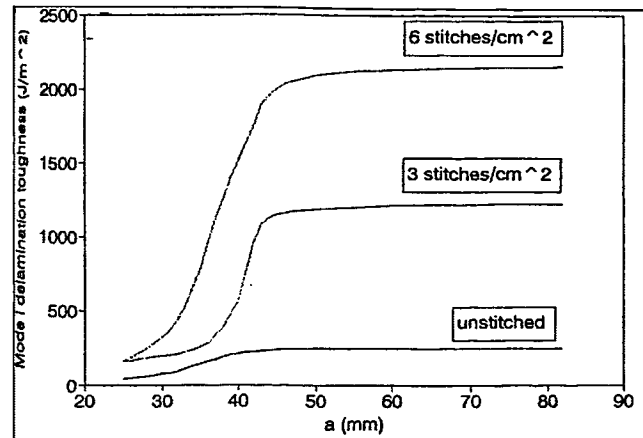


Figure 2-15: R-curves comparing unstitched and stitched materials (from Dransfield et al 1995)

Effects of stitching on delamination growth under mode II loading conditions have also been reported. The crack propagation in the 3-pt ENF configuration has been stabilised by introducing Kevlar or carbon stitches. The increase of the ' G_{IIC} ' for carbon stitches is above seven fold, the ultimate failure is a flexural fracture (Ishai, 1998)

It is also stated that the data reduction may not be valid because of the change of compliance due to the presence of the stitches, however interlaminar fracture toughness test may provide a sensitive tool for parametric evaluation of through-the-thickness reinforcement (Ishai, 1998). In a further development, a numerical simulation carried out by Barret (1996) has shown that the bridging action of perfectly bonded Z-Fibres™ prevents the crack tip from seeing high stresses. However, this finite element model does not give comparative predictions of the behaviour of a 3D laminates. Recently two major groups have been working actively on analytical models of stitched materials Mai and colleagues at the University of Sydney, Australia and Cox and colleagues at Rockwell Inc. USA.

2.3.2 Jain & Mai models

Jain and Mai have proposed models based on linear-elastic beam theory in order to calculate the interlaminar fracture toughness G_{IC} as well as the crack growth resistance G_{IR} curves of stitched laminates under mode I and mode II loading conditions (Jain and Mai, 1994a, 1994b, 1995) (Dransfield et al, 1998) (Jain et al, 1998) (Mouritz and Jain, 1997).

In the case of mode I loading conditions, Jain and Mai developed two models in order to calculate G_{IR} . The first one, called ‘discontinuous stitching model’, is based on the assumption that the stitches are independent of each other. The interlaminar toughening is due to the frictional resistance of the stitches pulling out under increasing opening displacement. The second model, called ‘continuous stitching model’, is based on the assumption that the stitches are interconnected and fail along the crack plane. The interlaminar toughening is due to the frictional slip and stretching of the stitches in the bridging zone before their rupture. Jain and Mai showed that the stitches tend to fail at the stitch loop and then pull out (Jain and Mai, 1997). The two models have to be combined to obtain a ‘modified model’, which better describes the experimental observations (Dransfield et al, 1998).

The mode I resistance is given in terms of the stress intensity factor by :-

$$K_{IR}(\Delta a) = K_{IC} + Y \int_{-0}^{\Delta a} p(t) \frac{1}{\sqrt{h}} f\left(\frac{t}{h}\right) dt \quad \text{Equation 2-66}$$

where Δa is the crack growth length, K_{IC} is the critical fracture toughness stress intensity factor of the unstitched laminate, h the half thickness of the composite, t the distance from the crack tip, $p(t)$ is the crack closure traction due to the stitches and Y is an orthotropic correction factor defined by :-

$$Y = \sqrt{\frac{E_0}{E_c}} \quad \text{Equation 2-67}$$

Here E_0 is the orthotropic modulus, defined by Equation 2-68 (Jain and Mai, 1994a) and E_c is the flexural modulus of the stitched composite.

$$\frac{1}{E_0} = \left(\frac{S_{11}S_{22}}{2} \right)^{1/2} \left[\left(\frac{S_{22}}{S_{11}} \right)^{1/2} + \left(\frac{2S_{12} + S_{66}}{2S_{11}} \right) \right]^{1/2} \quad \text{Equation 2-68}$$

where S_{ij} are the components of the compliance matrix when analysing the elastic behaviour of orthotropic materials.

Finally, $f(t/h)$ is a geometric correction factor defined by :

$$f\left(\frac{t}{h}\right) = \sqrt{12} \left(\frac{t}{h} + 0.673 \right) + \sqrt{\frac{2h}{\pi t}} - \left[0.815 \left(\frac{t}{h} \right)^{0.619} + 0.429 \right]^{-1} \quad \text{Equation 2-69}$$

The closure traction is calculated by iteratively solving the beam equations. The interlaminar fracture resistance $G_{IR}(\Delta a)$ may be obtained from K_{IR} using :

$$G_{IR}(\Delta a) = \frac{K_{IR}^2(\Delta a)}{E_0} \quad \text{Equation 2-70}$$

The models proposed to solve the problems of stitched laminates subjected to mode II loading conditions are based on shear deformation laminated plate theory and Griffith's theory for strain energy release rate fracture (Jain and Mai, 1994b) (Jain and Mai, 1995).

For the 3-pt ENF configuration, the models assume that the stitch failure process consists of elastic stretching of the threads due to relative slip of the top and bottom sections of the delaminated region followed by rupture in the crack plane. The actions of the stitches are modelled by introducing a linear shear stress, τ , between the crack faces in the delaminated region.

The strain energy release rate available for crack propagation is then calculated (Jain et al, 1998).

$$G_{II} = \frac{A^*}{\cosh^2(\lambda \Delta a)} \left\{ \tau \left(\frac{\sinh(\lambda \Delta a)}{\lambda} + a_0 + \alpha h \right) - \frac{\lambda}{A^*} \left(\frac{\alpha_1}{\alpha_2} \right) \sinh(\lambda \Delta a) \right\}^2 \quad \text{Equation 2-71}$$

where α is a correction factor for shear deformation, α_1 and α_2 are stitching parameters and A^* is a function of the different axial, bending and shear stiffnesses of the sub-

laminates. λ is related to material properties through A^* and α_1 . The expressions for τ , α , α_1 , α_2 , λ and A^* can be found in references (Jain and Mai, 1994b, 1995) and (Jain et al 1998).

The shear stress τ is then calculated using steady state crack propagation condition $G_{II} = G_{IIC}$ then the critical strain energy release rate for a stitched composite may be deduced from :

$$G_{IIR} = A^* \tau^2 (a + \alpha h)^2 \quad \text{Equation 2-72}$$

These models are capable of calculating the mode I and mode II interlaminar fracture toughness of stitched polymer composites. They have been validated recently against experiments in a review published by Mouritz and Jain (1999). They require detailed knowledge of physical and interlaminar fracture properties of the unstitched material, of the stitching conditions and of the mechanical properties of the stitch material. However, these models quantify the resistance to crack propagation introduced by given stitching conditions.

2.3.3 Massabò & Cox models

Another line of argument has been developed by Massabò and Cox. Their models use first order shear deformation theory for anisotropic laminated plates in cylindrical bending and small deformations. The analysis considers a thin anisotropic laminate plate loaded by shear tractions, τ , acting along the faces of the delamination length, a , (Figure 2-16). The shear traction, τ_b , represents the bridging mechanisms acting along the bridged portion of the delamination by the through-the-thickness reinforcement. τ_b is dependent on the sliding displacement w , $\tau_b(w)$.

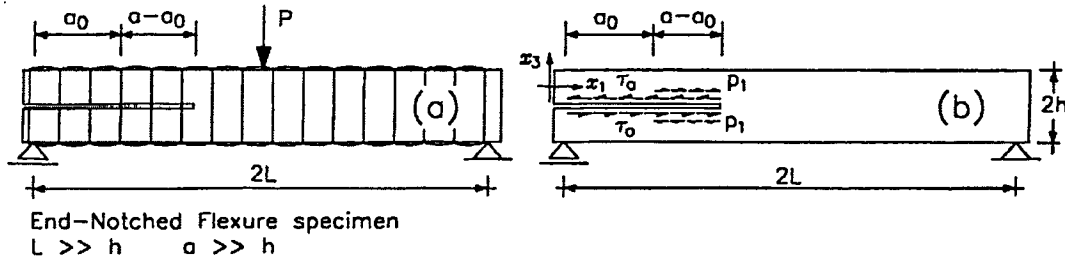


Figure 2-16: The ENF problem (after Cox et al, 1997)

It is assumed that the crack growth is controlled by two mechanisms. The first is the intrinsic toughness of the unreinforced laminate, G_{IIC} ; the second is the shielding effect at the crack tip due to the bridging tractions of the through-the-thickness reinforcement in the delaminated area. The case of ENF test will be presented here, however, solutions for the mode I DCB problem using similar analysis are presented in Appendix II of reference (Massabò and Cox, 1999a).

Two limiting configurations are defined to characterise the crack history of the problem posed in Figure 2-16. The first is called ACK limit in attribution to work of Aveston, Cooper and Kelly (1971) on mode I matrix crack in fibrous composites. The ACK limit is characteristic of a crack entirely bridged with intact ligaments (Massabò et al, 1998). It is assumed that the shear stress, τ , at the crack wake opposes the bridging traction, τ_b . During crack propagation, the critical shear stress, τ_{cr} , is a constant value τ_{ACK} , which is independent of the crack length or specimen dimension.

The other limiting configuration is called small scale bridging limit. It is characteristic of a situation where the unbridged segment will expand. In a long enough specimen, the size of the bridged zone will be a constant value, l_{SSB} . In this configuration, the composite fracture energy will be the sum of the intrinsic interlaminar fracture energy G_{IIC} and the energy supplied by the bridging G_b . The two characteristic lengths l_{ACK} and l_{SSB} are defined in detail in reference (Massabò et al, 1998).

The problem is solved in the case of large scale bridging, which is representative of the stitched laminates. Forward and inverse problems are defined. The forward problem

consist of solving the above problem knowing or assuming the traction law, $\tau_b(w)$, due to the through-the-thickness reinforcement. In the delaminated region ($0 \leq x \leq a$), the plate is represented as the assemblage of two disbonded sub-laminates, free to bend with the same curvature. The in-plane displacements are $u(z) = u^0 + \varphi z$, with u^0 the displacement at the mid-plane and φ the bending rotation. The out-of-plane displacements are v . The stress field is described by the stress resultants over a unit of width: the normal force N , the bending moment M , and the shear force Q . With partial differentiation denoted by a comma, the constitutive and equilibrium equations are :-

$$\begin{array}{ll} \text{if } 0 \leq x \leq a & \text{if } a \leq x \leq 2L \\ \begin{cases} N_d = A_d u_{d,x}^0 + B_d \varphi_{d,x} \\ M_d = B_d u_{d,x}^0 + D_d \varphi_{d,x} \\ Q_d = K_d (v_{d,x} + \varphi_d) \end{cases} & \begin{cases} N_i = A_i u_{i,x}^0 \\ M_i = D_i \varphi_{i,x} \\ Q_i = K_i (v_{i,x} + \varphi_i) \end{cases} \end{array} \quad \text{Equation 2-73}$$

$$\begin{array}{ll} \begin{cases} N_{d,x} = \tau - \tau_b(w) \chi \\ M_{d,x} = -0.5h(\tau - \tau_b(w) \chi) + Q_d \\ Q_{d,x} = 0 \end{cases} & \begin{cases} N_{i,x} = 0 \\ M_{i,x} = Q \\ Q_{i,x} = 0 \end{cases} \end{array} \quad \text{Equation 2-74}$$

w is half of the total sliding displacement, A_d , D_d , K_d , are respectively the axial, bending and shear stiffnesses of the upper laminate per unit of width and B_d is the bending-extensional coupling stiffness; A_i , D_i and K_i refer to the bonded region.

Boundary conditions are then applied in relation with the continuity of the two half problems and with the load applied. A numerical procedure based on J-integral methods used to solve the resulting set of equations is proposed in reference (Massabò and Cox, 1999). A critical shear stress $\tau_{cr}(a)$ corresponding to crack propagation is calculated (Massabò and Cox, 1999) :-

$$\tau_{cr} = \left[\frac{G_{IIC}}{2} - \int_0^{w_{notch}} \tau_b(w) dw \right] \frac{1}{w_{cmsd}} \quad \text{Equation 2-75}$$

Here w_{cmsd} and w_{notch} are the crack sliding displacements at $x=0$ and $x=a_0$.

Finally, the fracture toughness, G_{IIC} , can be determined experimentally by measuring the critical load P_{cr} for a particular crack length, $P_{cr} = 8/3 \tau_{cr} h d$. Figure 2-17 shows

calculated and measured sliding displacements for a linear bridging law for an ENF specimen.

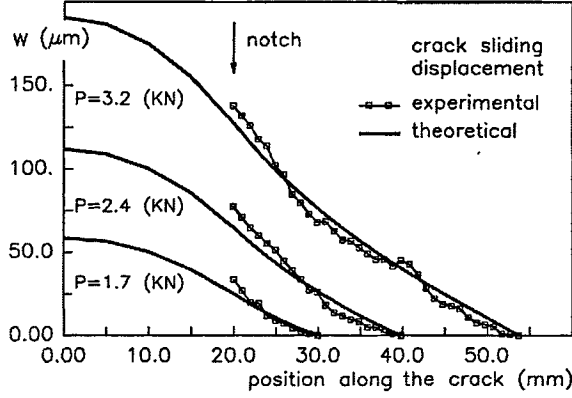


Figure 2-17: Crack sliding displacement profiles (from Massabò et al, 1998)

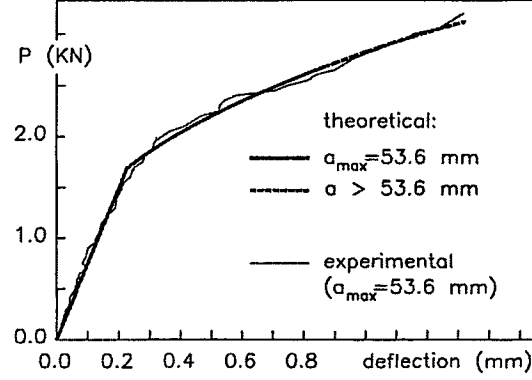


Figure 2-18: Load/Deflection curves (from Massabò et al, 1998)

The inverse problem consists of determining the bridging traction $\tau_b(w)$ from the sliding displacement measured during an ENF test, for a given load. Two methods are proposed to solve the problem, both of them use discretised expressions of the bridging stresses represented by a set of n basic functions (e.g. Legendre polynomials) :

$$\tau_b(w) = \sum_{k=1}^n \gamma_k g_k(w) \quad \text{Equation 2-76}$$

With the discretised problem, $\underline{\tau}_b = \{\tau_{b1}, \dots, \tau_{bm}\}$, at the m points $\tilde{x}$.

And the relation :

$$\underline{\tau}_b = G \underline{\gamma} \quad \text{Equation 2-77}$$

Where G is a $m \times n$ matrix, representative of the crack sliding displacement in $\tilde{x}$. Thus, the bridging actions are defined fully as a function of the displacements.

The bridging law, τ_b , can be used to determine the structural response in terms of load vs. displacement. Figure 2-18 shows the experimental and theoretical load vs. displacement curve of an ENF specimen. The theoretical one has been computed by using a non-linear bridging law. For further details, the reader is referred to Massabò and Cox (1999) and Massabò et al (1998).

The mixed mode delamination fracture in the presence of large scale bridging is studied using the principle of superposition and solving two idealised problems of DCB and ENF specimens (Massabò and Cox, 1999b) (Massabò and Cox, 1999c). It is assumed that for the MMB configuration, the through-the-thickness reinforcement imposes a bridging law that can be written as $p=(p_1(u_1), p_3(u_3))$, where p is representative of a bridging traction and u is representative of a displacement. The direction 1 is parallel to the delamination and the direction 3 follows the Z-direction.

Different formulations of the bridging law have been studied ($p_3=p_{30}$, $p_3=\beta_3 u_3$, $p_3=p_{30}+\beta_3 u_3$). In the case of DCB, the problem is posed and solved in a similar way as in Equation 2-73 and Equation 2-74. It is to be noticed that in the particular case of Dugdale type of bridging law ($p_3=p_{30}=cte$) with no bending moments, the limit configuration is shown for which the two delaminated beams come into contact at the crack tip and the energy release rate G_I vanishes (Figure 2-19)

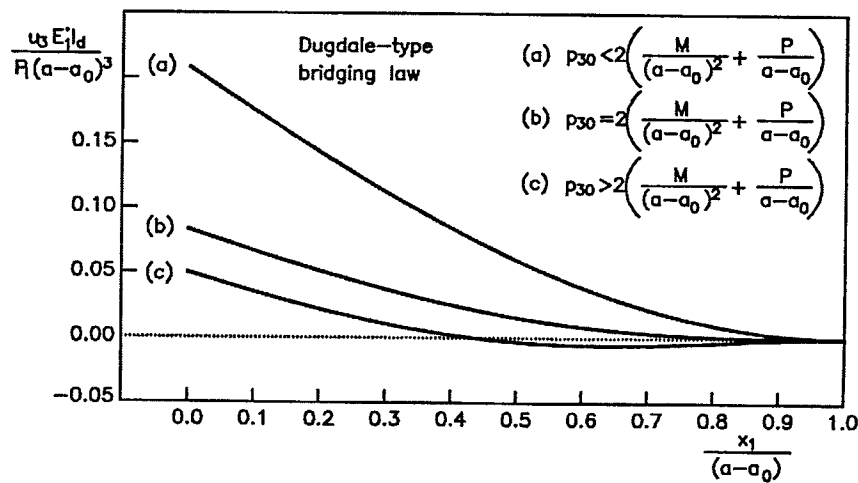


Figure 2-19: Crack profiles in the mode I problem with $M_I=0$ (Dugdale-type bridging law) (from Massabò and Cox, 1999c)

Results from the model of the ENF problem show that due to the bridging mechanisms, the sliding displacement can invert sign along portions of the crack during monotonic loading process. The mixed mode problem, combining all phenomena observed in mode I and mode II will create a varied range of crack configuration. For example, the

insertion of displacement sign can introduce locally cyclic loading conditions, which may alter the effectiveness of the through-the-thickness reinforcement. Due to the crack tip closure phenomenon, the loading conditions at the crack tip are likely to be modified by the presence of the stitches or Z-Fibres™.

2.3.4 Cox 'single ligament' model

Only one model considering the traction law of a single discrete bridging entity has been found in the literature (Cox, 1999a). After having identified the behaviour of the bridging tow by experimental observations, the state of the bridging tow is described by two variables of displacement, ξ , in the direction x_1 and ζ , in the direction x_3 (Figure 2-20).

The problem is solved in order to obtain the traction law $u=u(T)$ or $T=T(u)$, where $u = (u_1, u_3)$ are the displacement of the laminate near the tow and $T=(T_1, T_3)$ is the force resulting from the actions of the bridging tow (see Figure 2-20 for the nomenclature) (Cox, 1999b) (Cox, 1999c). Figure 2-21 compares various predicted traction laws with an experimental measurement of a stitch bridging a mode II delamination crack.

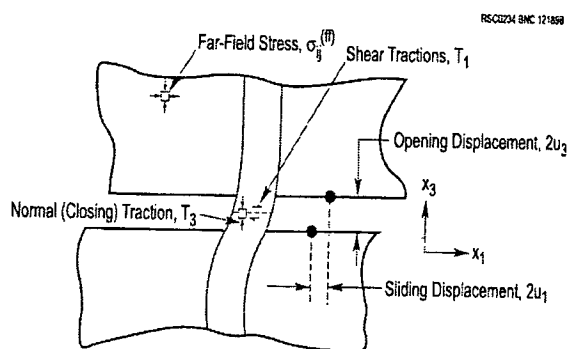


Figure 2-20: Bridging tractions and crack displacements (from Cox, 1999a)

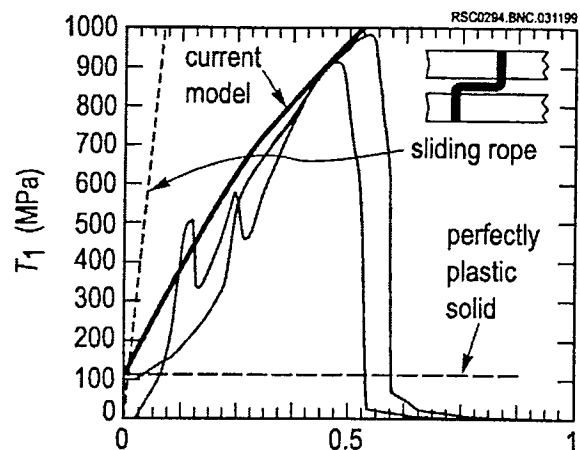


Figure 2-21: Mode II predicted tractions law compared with a direct experimental measurement (from Cox, 1999c)

2.4 Conclusions

The different test configurations for delamination testing of UD laminates have been reviewed and the data analyses based on LEFM briefly described. Through-the-thickness reinforcement has been shown to be a highly efficient solution to improve the delamination toughness of composite laminates.

The crack tip closure phenomenon revealed by Massabò's models is one clear manifestation of the inadequacy of LEFM.

The presence of energy absorbing mechanisms other than crack growth is another reason why the LEFM is not applicable as well as the extensive bridging, which is not yet included in the data analysis. However, this review shows that the models proposed, although being very accurate, are complex and require some considerable calculation time. They cannot be applied easily to each single delamination test to obtain bridging laws or crack growth resistance.

Jain and Mai models quantify the bridging actions in terms of K_{IR} . From an experiment and with the knowledge of some properties of unstitched laminate, they deduce the resistance of the bridging tows.

In the Massabò forward model, G_{IIC} of the laminate is determined from an experiment and assumption of the bridging law in term of localised shear stress. In Massabò inverse model, the bridging shear stress is calculated from the knowledge of the shear displacement field for a given crack length and a given load.

Cox has proposed theoretical models for the prediction of the interlaminar fracture toughness of stitched composites subjected to static and fatigue bending (mode I) loads and shear (mode II) loads. These models can be used to determine the minimum stitch density needed to suppress delamination cracking (Cox et al, 1997) (Cox et al, 1996) (He and Cox, 1997).

Chapter 3 Manufacturing with Z-Fibres™

This chapter will concentrate on the practical aspects of the manufacture of Z-Fibre™ reinforced laminates. The different types of Z-Fibre™ will be listed and the insertion methods described. At the end of this chapter, section 3.5 collects information on the manufacturing problems which have been faced and solved while inserting Z-Fibres™ in different kinds of laminates.

3.1 Z-Fibre™ and Z-Fibre™ preform

Z-Fibre™ reinforcement is based on the insertion before cure of stiff rods through-the-thickness of composite laminates. To take a pictorial comparison, the Z-Fibre™ is a rod, which will physically nail the different layers of a composite laminate together. Doing so, Z-Fibres™, also called Z-pins, introduce an extra strength in the third direction of composites, producing after cure a real 3D composite.

Any material can be used to manufacture Z-Fibres™, as long as it can be manufactured as a small diameter long rod and is strong enough to resist the insertion process into the laminate. The range of pin diameters is from 0.15mm to 1mm. The materials used for the rods include SiC/BMI, T650/BMI, T300/epoxy, T300/BMI, P100/epoxy, S-glass/epoxy, Titanium, Stainless steel and Aluminium (Aztex, 2000):

The Z-Fibres™ are supplied inserted in a two-density two-layer foam and the foam filled with pins is called a 'preform' (See Figure 3-1). In the case of composite Z-Fibres™, Aztex Inc has developed a two-stage process to manufacture the Z-Fibre™ preform (Bonnington, 2000):

- 1- Pultrusion of continuous, small diameter composite rodstock;
- 2- Insertion of the rodstock into a two-part sandwich structure foam.

In the pultrusion process, the carbon fibres are pulled off a bobbin, into a small bath where the resin is held at an elevated temperature. The material exits the bath through a die and immediately enters a long oven. The cured material, exiting the oven, is wound

up on a spool, then post-cured if required. The rodstock is then ready to be inserted into the sandwich foam.

The number of carbon fibre tows used during the pultrusion determines the Z-Fibre™ diameter. Typically, 1k T300 carbon fibres produce a 0.28mm diameter pin rodstock, while 3k T300 carbon fibres produce a 0.50mm diameter Z-Fibre™.

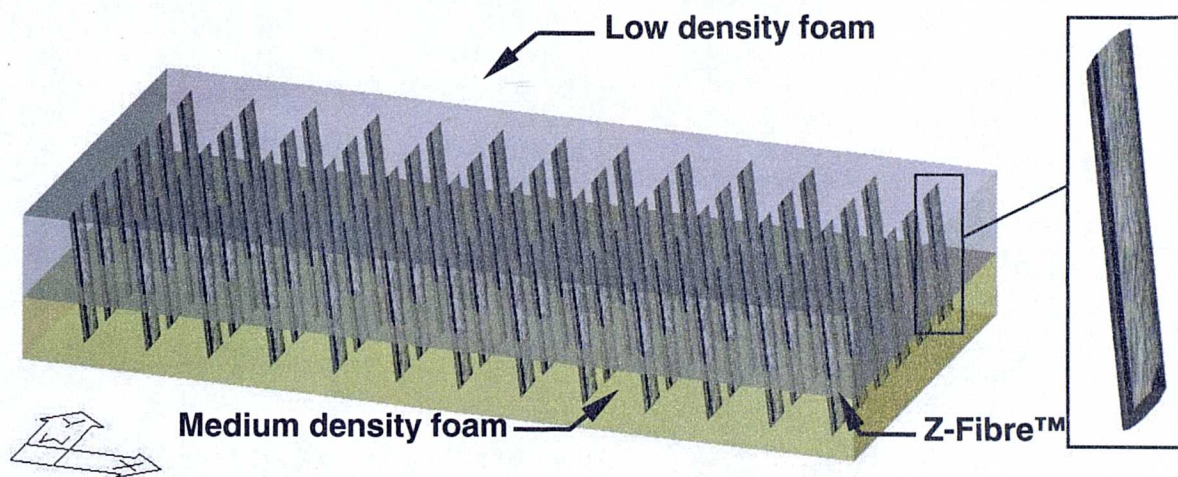


Figure 3-1: Z-Fibre™ Preform and a close-up of one pin

The preform's low-density foam, called 'support foam', is usually made from polystyrene and is located at the top. At the bottom, the medium-density foam, called 'base foam', is usually Rohacell LastaFoam material. The support foam is used to hold the pins prior to use, but is designed to collapse easily. In addition to locating the pins accurately, the base foam offers better stability to the lower part of the pins and prevents them from buckling during the insertion process.

Automated machinery cuts the long rodstock of pin material and inserts it directly into the foam. A cutting device shears the rodstock, leaving an acute angle at the ends of the pins. This angle assists the pin penetration into the part to be reinforced and minimises carbon fibre filament breakage and distortion.

The preforms are characterised by the following parameters: Z-Fibre™ material, Z-Fibre™ diameter, insertion angle, areal density of the Z-pins, type and thickness of support foam and type and thickness of base foam.

3.2 Specific preparation for Z-Fibre™ reinforcement

Laminate preparation

Z-Fibre™ technology can be used for reinforcement of most types of polymer matrix composites, in various manufacturing processes. Z-pins are to be inserted as a final processing stage, before cure in the case of pre-preg or RFI process or before injection in the case of RTM moulding. An extra debulk of one hour under vacuum is recommended before insertion of the Z-Fibres™ in order to be as close as possible to the cured laminate thickness. For dry fibre lay-ups with binder, a consolidation (compaction) of the lay-up is recommended to help hold the Z-Fibres™ in place.

Z-Fibre™ preform preparation

Pieces of preform are cut to the shape of the area to be reinforced. A layer of release film covering the whole laminate is needed in order to prevent contamination from the dust produced by the compaction of the polystyrene foam. A layer of non-porous Teflon coated glass fabric is cut slightly larger than the area to reinforce. This layer, located between the release film and the preform, will protect the laminate when the excess of preform is cut and discarded.

Because of the vibration of the horn, Z-pins pulling out of the preform are a common problem when reinforcing large areas. Indeed, despite being supported by the foam of the preform, Z-Fibres™ tend to vibrate and pull up when close to the activated ultrasonic horn. Covering the top surface of the preform with adhesive tape can prevent this effect, which is particularly important when smaller pin diameters or high pin

densities are used. Squares, slightly smaller than the horn footprint, are cut in the tape in order to facilitate the insertion.

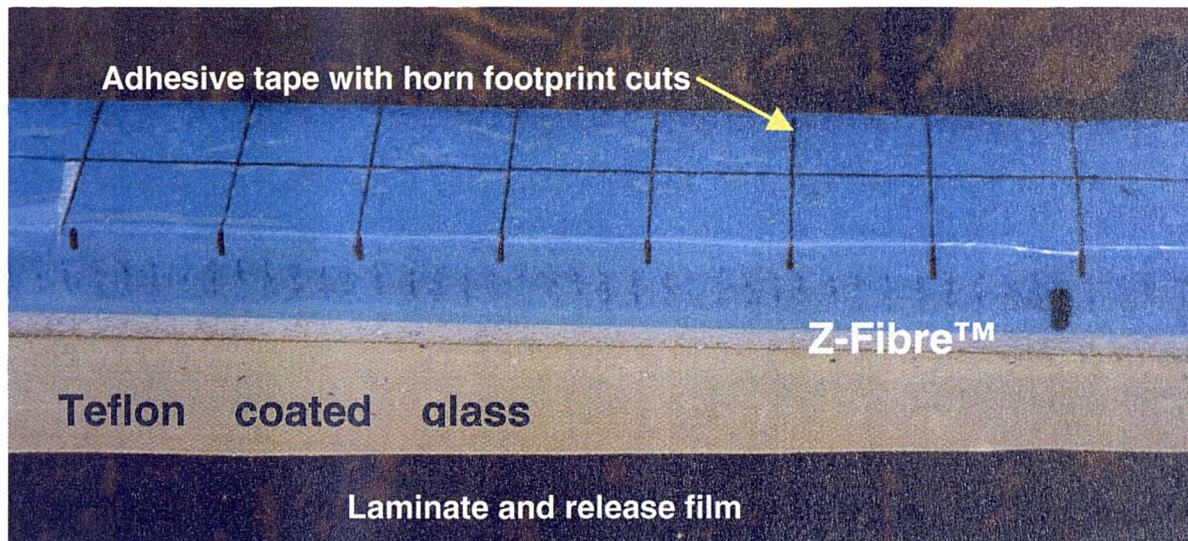


Figure 3-2: Preparation of the laminate stack

Figure 3-2 above shows the set of items needed for Z-Fibre™ reinforcement. The release film is placed on the surface of the laminate. The Teflon coated glass fabric is located on top of the release film, over the area to be reinforced. The Preform is laid on top, with the low density foam with the adhesive tape facing up. The laminate stack is then ready for pinning.

3.3 Autoclave insertion

The autoclave insertion process, also called heat and pressure insertion process, was initially developed by Aztex Inc. to drive the Z-Fibres™ into laminates. In that process, outlined in Figure 3-3, the preform is placed on the top of the uncured laminate, using a release film between the laminate and the preform and a backing plate on the top. Combination of heat and pressure compacts the preform and pushes the Z-pins in. The residual foam is then removed and discarded at the end of the cure.

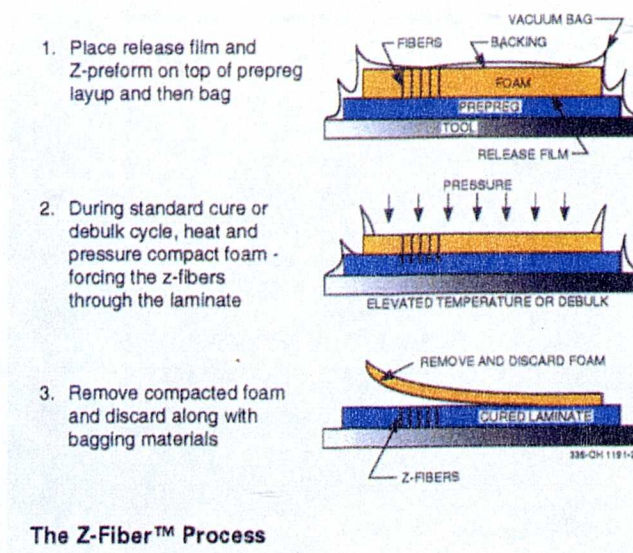


Figure 3-3: Heat and Pressure Insertion Process (from Aztex Inc.)

Large areas can be reinforced in one autoclave cycle using this method. On the other hand, because of the high pressure required, only relatively low pinning density can be used ($\leq 1\%$). The method is now rarely used, the UAZ™ insertion becoming the preferred option.

3.4 UAZ™ (Ultrasonically Assisted Z-Fibre™) insertion

An alternative solution to 'heat and pressure' has been developed by Aztex Inc. The method, called Ultrasonically Assisted Z-Fibre™ insertion (UAZ™ insertion), requires some hardware that can be described simplistically as an ultrasonic hammer.

3.4.1 The UAZ™ device

The ultrasonic device is composed of a standard power supply (Branson 900BCA), and a sequence of transducer, signal booster and insertion horn. Normally, 20kHz transducers, with maximum amplitude of 20µm (0.8mils) at 100% output, are used. The horn, supplied by Aztex Inc., can be of different sizes, depending on the insertion work to be done. The most commonly used horn has a footprint of 25mm x 25mm

(1''x1''). More complicated horn shape can be designed for areas which are partially obstructed or difficult to access. Aztex Inc. has developed several types of UAZ™ devices, hand held units, semi-automated gantries and fully automated 6 axes robots. Completely automated insertion processes are currently under development.

In the case of Z-pins insertion using a hand held unit, the power supply is connected to the transducer, which is held in a “gun casing”. The insertion horn is directly screwed on the transducer (See Figure 3-4). Like a gun, the ultrasound is activated by pulling the trigger of the casing. The amplitude of the vibration can be modified by adjusting the settings on the power supply. Operators using hand held units have to make sure that the horn is perpendicular to the laminate surface.

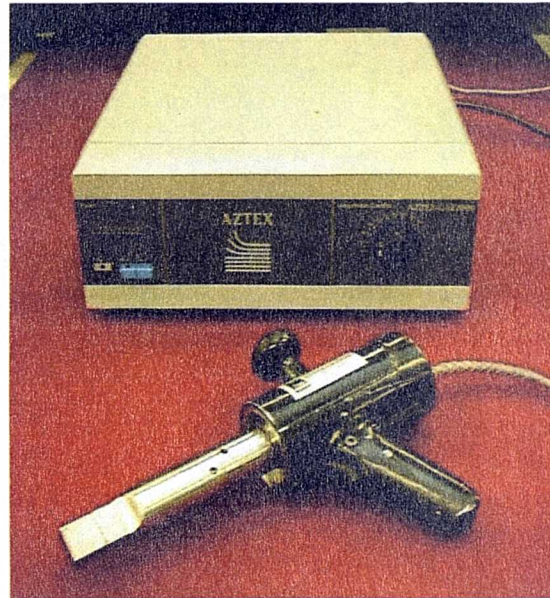


Figure 3-4 : Hand held UAZ™ Unit

The pressure applied is not controllable, however a better feel of the insertion process is achieved. An experienced operator will know the pressure to apply and feel the onset of insertion. Completion of the insertion can be noted by feeling the crushing of the end of the pins against the back plate.

The set-up of a gantry is more complicated (See Figure 3-5). Compared to a hand held system, the ultrasonic stack of the gantry includes a “booster”, which allows the amplitude of the vibration of the horn to be changed (Inset picture of Figure 3-5). The use of the booster is made possible by the fact that the transducer and the booster are fixed on a rigid platform. The booster is mounted on the gantry at a node point of the signal (point of the wave signal where the amplitude is zero). The insertion horn is connected to the booster. The change of the amplitude (or gain of the booster) can be calculated by applying energy conservation laws to the booster, the transducer and the horn; the masses on each side of the fixed node being different, but known.

The total amplitude yield by the ultrasonic stack is calculated by a simple multiplication of the amplitude of the transducer by the gain of the booster and the gain of the horn. Usually, amplitudes from 25 to 50 μm (1 to 2mils) are used for the insertion of composite Z-Fibres™ and 25 to 90 μm (1 to 3.5mils) for metal Z-Fibres™ (Aztex, 1996).

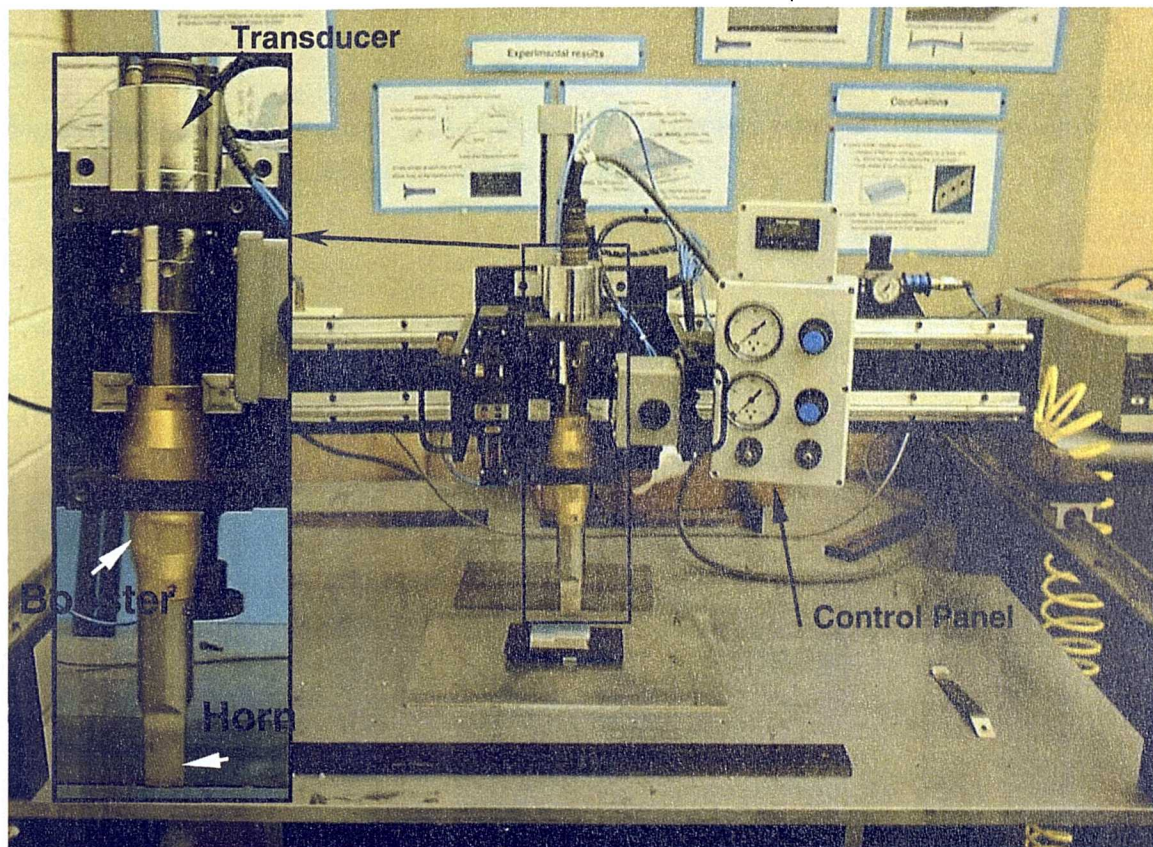


Figure 3-5: New gantry currently in use at Cranfield

A foot pedal activates the ultrasonic device and the compressed air system, which drives the whole ultrasonic assembly down and presses against the laminate stack for insertion. The pressure to be applied, as well as the speed of travel of the head can be tuned to optimise the insertion of the pins. Using a gantry offers the advantage of being sure that the horn is accurately perpendicular to the laminate. It also allows controllable and reproducible insertion pressure and speed to be achieved. A digital gauge, mounted on the ultrasonic carriage, allows the pinning depth to be checked.

3.4.2 Insertion using UAZ™

Composite Z-Fibres™

Once the laminate stack is prepared, the insertion starts by locating the horn footprint on the top of the first area to reinforce. The first stage of insertion consists of inserting the pins by activating the ultrasonics (See Section 3.4.1). The combined effect of the ultrasonic vibrations and the applied pressure collapses the support foam and drives the Z-Fibres™ through the thickness of the laminate (Figure 3-6). Insertion is carried out, inserting small areas corresponding to the cut squares of the adhesive tape, until the required depth is reached. Usually, in the case of composite Z-Fibres™, the maximum insertion depth is determined by the thickness of the support foam.

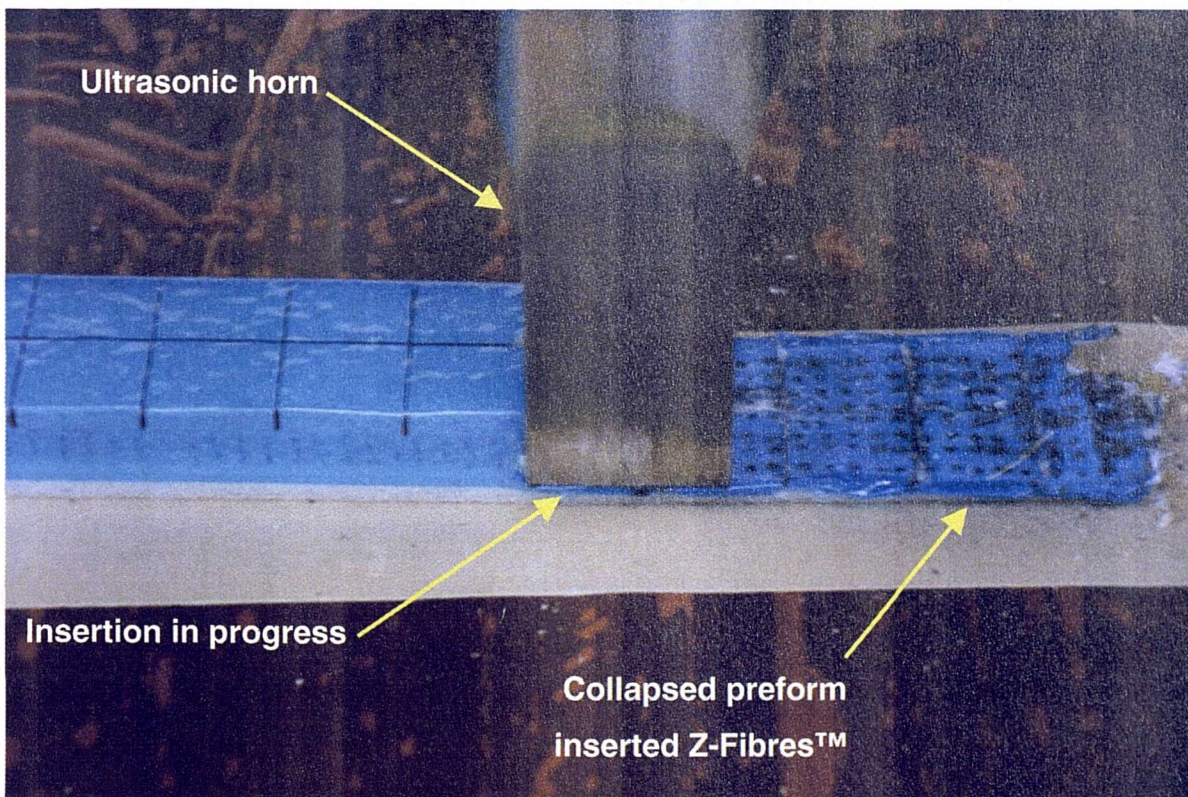


Figure 3-6: Z-Fibre™ insertion

The next stage consists of cutting the excess pin length flush with the laminate surface using a specially designed sharp tool (Figure 3-7). Extra care has to be taken to cut the

Z-Fibres™ on the surface of the Teflon coated glass fabric film without damaging the laminate or moving the pins already inserted in the laminate.

If the support foam is not thick enough for the desired pinning depth, insertion is stopped when the foam is fully compacted. Then the remaining foam can be removed, leaving a short pin length unsupported. A second insertion stage for deeper reinforcement is then possible.

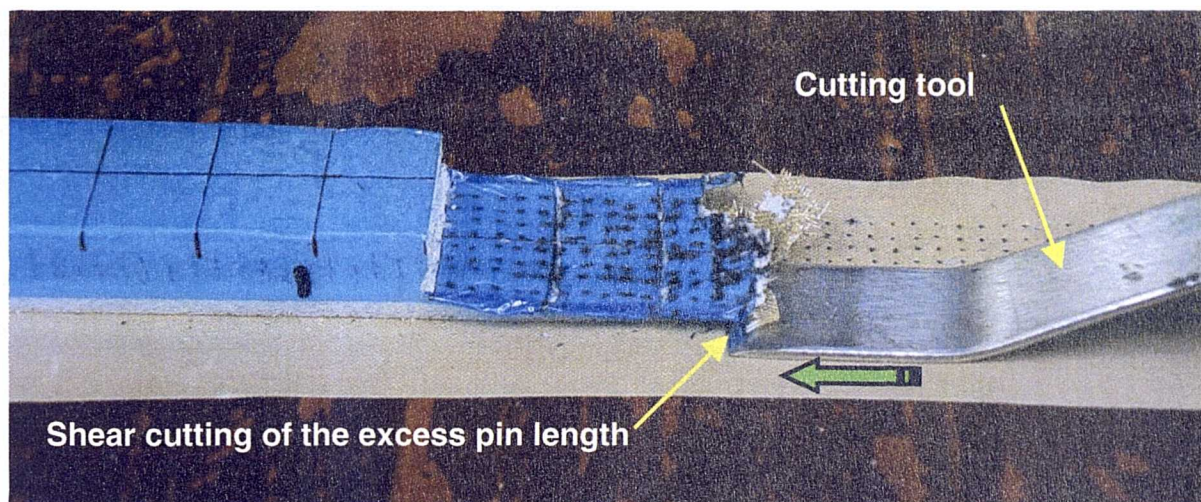


Figure 3-7: Cutting of the excess pin length and foam removal

Metal Z-Fibres™

The first stages of the insertion are very similar. The preform is located on the laminate in the same way. The difference in the process comes from the fact that for Z-Fibres™ made from metal, the shear-cutting phase is not possible. Therefore the pins are manufactured to the final insertion length. Insertion is carried out to the total compaction of the preform foam (Left hand of Figure 3-8). The remaining foam is then removed, leaving the pin in place and the excess length unsupported. Final insertion is done by driving the pin flush to the surface of the laminate (Right hand of Figure 3-8).

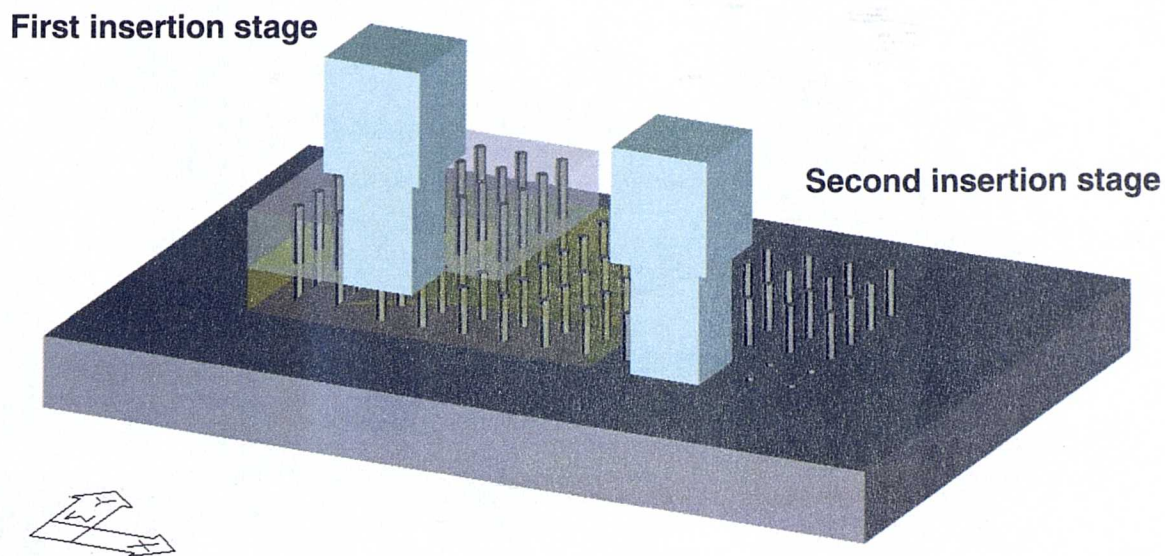


Figure 3-8: Schematic of metal Z-Fibre™ insertion

3.5 Operator experience

UAZ™ insertion is totally independent of the cure process, any parameters can be modified in order to optimise insertion of the Z-pins without affecting the cure parameters. Compared to autoclave insertion, higher areal densities of reinforcement can be achieved (up to 5% for normal applications), as well as deeper insertion (up to 25mm). Furthermore, UAZ™ insertion makes local reinforcement easy and the process can be automated for the reinforcement of large areas.

One of the main advantages of this process is that **access to only one side of the part** is required. The insertion can be made directly on the curing tools.

When using UAZ™ insertion for composite Z-Fibres™, it is very important to hold the laminate and the preform firmly during the initial stage of the insertion. The slightest movement can create instabilities, which can induce failure of the pins by buckling.

The use of fully automated insertion machine (as seen in Figure 3-9) solves the variability due to the operator and reduces cost and manufacturing time, when compared to other through-the-thickness reinforcement or equivalent attachment methods.

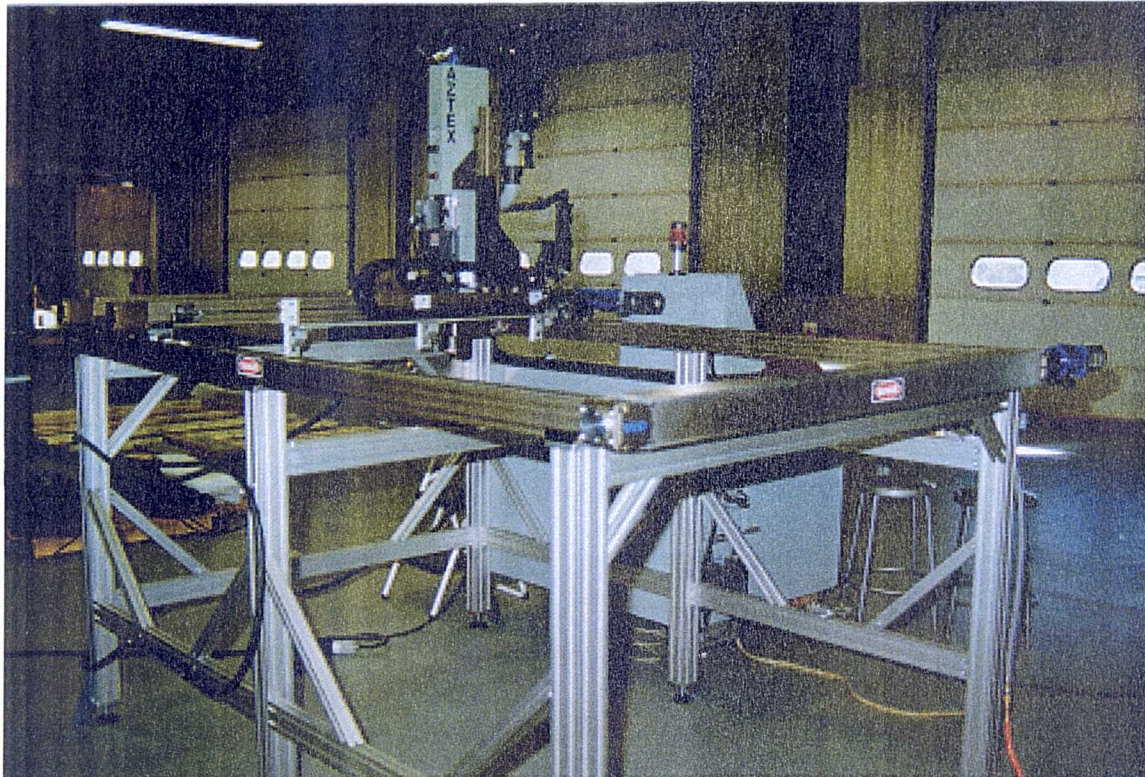


Figure 3-9: Fully automated Z-Fibre™ insertion machine (Picture Aztex Inc.)

To help shearing the excess length of composite Z-Fibres™, the temperature of the laminate can be lowered by putting the panel in a deep freeze for a few minutes. The matrix stiffens and the pins do not move during the cutting phase.

In the case of UD laminate, it is easier to cut the pins following the laminate fibre direction, but the chances of moving the pins are greater. Cutting can be very difficult in the case of pins inserted in dry fabrics. While being achievable if a binder is used, it is very difficult to cut the Z-Fibres™ in a completely dry and not compacted preform. Operator care and patience are the only virtues to solve the problem.

If too much pressure is applied, the Z-Fibres™ break by buckling without penetrating the composite laminate. Using lower pressure and lower speed would allow the ultrasonic vibration to heat up the pins and soften the laminate enough to allow the pins to penetrate more easily. Not enough pressure would heat up the Z-pins, without inserting them. Too much heat may burn the preform.

Because of the vibration of the horn, some pins can pull up from the cuts in the tape while an area nearby is being reinforced. A multi-stage insertion process can be used. During a first stage, the ultrasound is applied for a short period in order to insert the Z-Fibre™ through the very first layers of the laminate, just enough to hold them, but not long enough to allow the surrounding Z-pins to “escape”. The final insertion to the required depth can then be achieved in a second longer stage without losing any pins. If some Z-Fibres™ “escaped”, they are replaced in their original location, one by one, with help of a pair of tweezers.

Sometimes, the two stage process, described above, cannot be used because having been heated-up by the first insertion stage and cooled down naturally, the pins adhere to the laminate and the second insertion stage is not possible, adhesion between the pin and the laminate being too strong.

There are no strict rules on the way to insert the Z-Fibres™. Many unregulated parameters, like temperature of the laboratory and air humidity, affect the insertion process. Other parameters, like the pressure applied and the insertion speed, can be selected so as to optimise the insertion. At the present time, in non-automated processing, the quality of Z-pinning is highly dependent on the experience of the operator. Parameters are set-up by trial and error as well as operator's experience until the insertion is perfect.

In case of insertion of unsupported lengths of composite Z-pins, the insertion has to be slow and pressure light in order not to break the unsupported pin length by buckling or brushing.

In the case of high pin density, insertion parameters have to be tuned carefully because the ultrasonic vibration can produce enough heat to partially cure the laminate and induce some damage (See Figure 3-10).

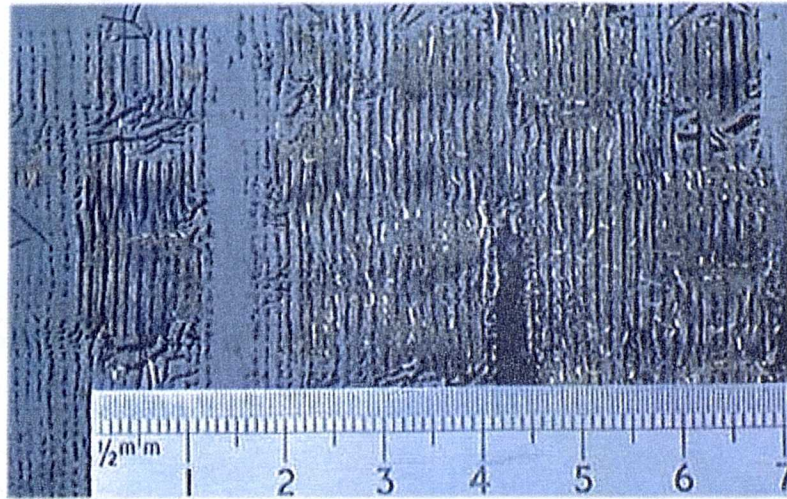


Figure 3-10 : Damage to the laminate due to too much heat generated during pin insertion

Criterion for the end of insertion:

When using hand held units or a gantry, the criterion for completion of the insertion varies depending on the operator. Someone can consider the insertion finished when some marks are visible on the back face of the laminate, others consider the insertion complete when the pins are completely through and the lower end of the pin is crushed. As will be shown in Section 8.4.1, the performance of the reinforcement will vary depending on which criterion has been selected.

As seen above, the quality of the manufacturing is highly dependent on the operator experience. Once an operator has been trained, the pinning quality is easily reproducible and the reject rate of unsatisfactory parts becomes minimal.

Chapter 4 Materials and Test Methods

4.1 Materials

4.1.1 IMS/924

For the experiments reported here, the pre-preg used was made from Tenax IMS carbon fibres and 924-epoxy resin supplied by Hexcel Composites Ltd, Duxford, UK.

From reception, the roll was stored in a deep freeze in a sealed bag, until needed. The pre-preg was allowed to defrost for about 8 hours before the bag was open in order to prevent moisture pick up. To manufacture unidirectional 3mm thick samples, 24 plies were laid up by hand, following the usual procedure. A debulk phase of 30 minutes under vacuum was applied every four plies. For interleaved specimens, the interleaf was created by laying-up several layers of the 924 resin, supplied by Hexcel as a thin film on a backing paper. The interleaf thickness was determined by the number of resin film layers. A 12.5 μ m polyimide film was laid-up in the centre plane of the laminate when needed as a crack initiator.

Following Hexcel Composites Ltd. recommendations, the laminates were cured at 180°C and under pressure of 6 bars for 2 hours. The panels were post-cured free standing in an oven at 180°C for 2 hours. After cure, the integrity of the panels was checked by C-scan. The C-scan prints are shown in Appendix A.

Table 4-1: Tenax IMS fibre properties (from Hexcel Composites Ltd.)

Fibre diameter	7 μ m
Tensile Strength	5400 MPa
Elongation at break (%)	1.7%
Tensile Modulus	295 GPa
Density	1.79 g/cm ³

Table 4-2: 924 neat resin properties (from Hexcel Composites Ltd.)

Compression Strength,	175 MPa
Tensile strength	65 MPa
Tensile Modulus	3.80 GPa
Tensile Strain to Failure, ϵ_{fm}	2.4%
Calculated Shear Modulus, G_m	1.40 GPa
Poisson's Ratio	0.41
Fracture toughness, K_{IC}	0.83 MPa $\sqrt{m}$
Mode I Critical strain energy release rate, G_{IC}	150 J/m ²
Glass transition temperature, T_g	190 °C
Cured Density at 22 °C, ρ_m	1.30 g/cm ³

Note: Operators should always be aware of the safety sheets supplied with the materials. Gloves should be worn in order to prevent health hazards as well as contamination of the pre-preg by human grease.

4.1.2 Z-Fibres™

In this study, only pultruded T300/BMI Z-Fibres™ were used. The Bismaleimide resin system used for manufacturing the pins was CytecFiberite 5250-4, usually used for resin transfer moulding applications. 5250-4 has a higher T_g than the temperature required in order to cure the 924 resin system. Therefore, the cure cycle of the laminate does not affect the integrity of the Z-Fibre™ matrix.

Two pin diameters were used, 0.28 mm diameter, made from 1k tows, and 0.50mm made from 3k tows. Two different areal densities have been used to reinforce the laminate with 0.28mm pin diameter; 0.5%, giving a pin-to-pin spacing of 3.5mm and 2%, giving a pin-to-pin spacing of 1.8mm. For the 0.50mm diameter Z-Fibres™, only the density of 2% has been used. The pin-to-pin spacing was 3.1mm (Pin-to-pin spacing denotes the distance between the centres of the two nearest neighbour pins in the preform).

The bulk of the experiments reported in this thesis were carried out before the purchase of the gantry, hence the pins have been inserted using the hand held UAZ™ 1000 insertion unit. The insertion horn was, in all cases, kept as perpendicular to the laminate as possible. A steel back in plate was used underneath. The backing paper was kept on the bottom face, between the laminate and the steel plate.

The aim of these experiments was to study the effects of Z-Fibre™ reinforcement on a **running crack**. In order to achieve that, the pins have been inserted 5mm beyond the starter film, in a 25mm wide band. The insertion was carried out until the pin imprints were visible on the backing paper. The insertion was stopped as soon as the paper was marked. In both cases, the chamfered ends of the pins were not damaged. However, because of the differences of pin diameter and the relatively thin laminate used, the difference of the effective length of the pins in the two different configurations is almost 10% (Figure 4-1). This fact will need to be taken into account during the results analysis (See section 8.4.1).

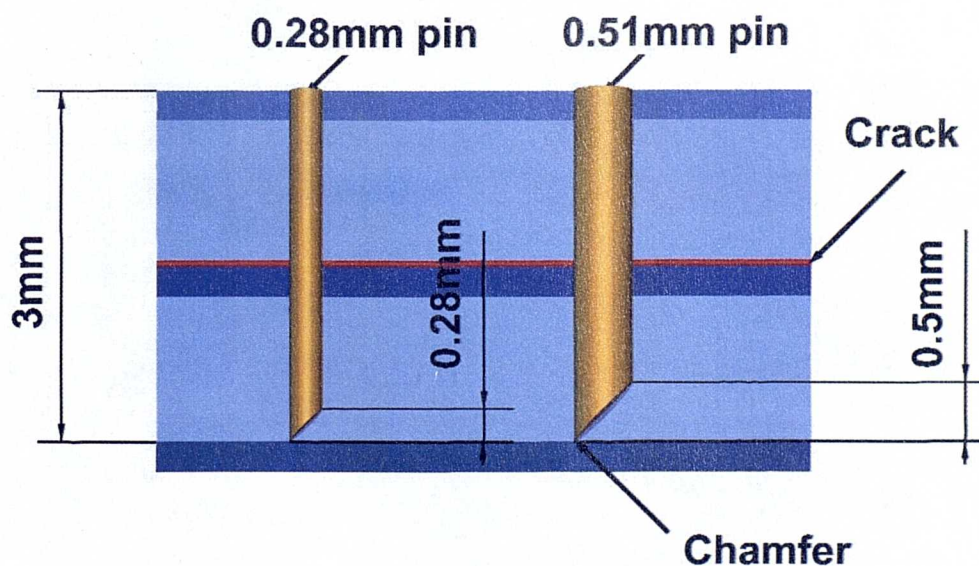


Figure 4-1: Effect of the chamfer on the Z-pin effective length

Some specimens have been manufactured in such a way that the Z-Fibres™ reinforce only the 1mm out of the whole thickness, at the centre of the laminate. Eight layers

were laid-up and debulked. The Z-Fibres™ were inserted through the thin laminate and then sheared off. The remaining layers were then laid-up on the already pinned laminate in a symmetrical fashion, in order to complete the 24 plies required.

4.2 Delamination testing of Z-pinned laminates

4.2.1 Specimen preparation

Specimens 20mm wide and with nominal thickness of 3mm were cut from UD panels, using a dry diamond coated saw. The specimens were cut so as to maintain an identical longitudinally centro-symmetric pin pattern in each coupon. This configuration was chosen to avoid edge effects if the pins were too close to the edge of the specimen and to maintain a constant number of pins per row, for a given pinning density. Figure 4-2 describes the dimensions of the delamination test beam and the location of the Z-Fibres™. The edges of the beams were coated with white correcting fluid to facilitate crack growth measurement.

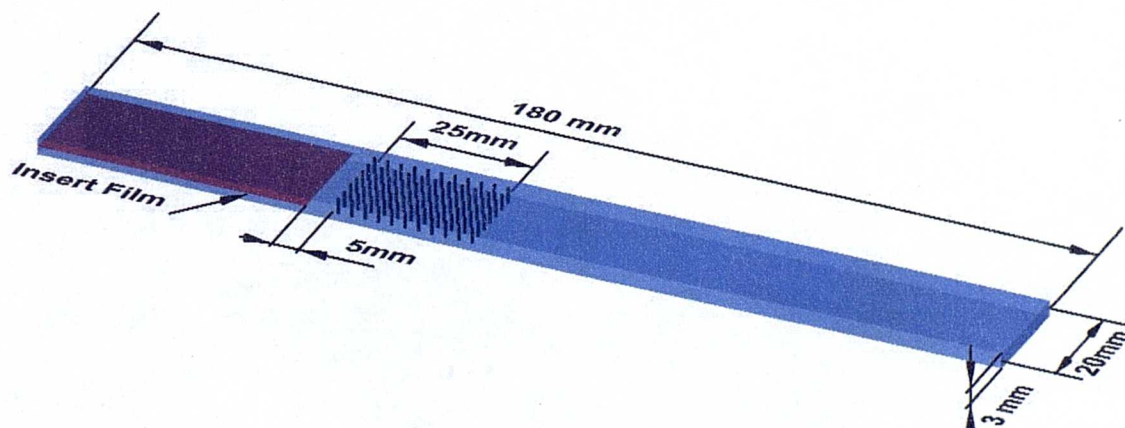


Figure 4-2: Delamination test beam, film and pin position

Only DCB and MMB specimens required the bonding on of end-blocks to introduce the load (Figure 2-4 and Figure 2-11). Prior to bonding the specimens were lightly abraded using 240-grade sandpaper and cleaned with acetone. The loading blocks were bonded with either cyanoacrylate glue in the case of control specimens, or with Araldite Redux

420, a two-component room temperature cure adhesive from Ciba Plastics, in the case of Z-Fibre™ reinforced specimens.

All delamination tests were performed on an Instron 5500, computer controlled, screw driven tensometer having a load cell of a maximum capacity of 5kN.

4.2.2 Pre-cracking

The mode II and mixed mode I/II specimens were pre-cracked in mode I. Loading blocks had been glued on using cyanoacrylate glue. Samples were loaded in mode I with a cross head speed of 1mm/min. As soon as the load versus displacement curve started to deviate from linearity, the loading was stopped and the crack tip was marked on the specimen edge. Then, coupons were unloaded and end blocks removed.

Despite the fact that this study concerns mainly the crack propagation resistance, the 5% or MAX initiation values have also been determined in order to cross-check the quality of the material of the different panels. As will be shown in the following chapter, the pins, being 5 mm beyond the end of the starter film, do not affect the propagation of the crack for the first few millimetres.

4.2.3 Stick-slip behaviour

In Chapter 5 it will be shown that the presence of Z-pins can introduce instabilities in the delamination behaviour of the laminate, particularly under mode I loading conditions. Although interlaminar testing standard suggests to use arrest values only in the case of stick and slip behaviour, it was considered important to record data from both initiation and arrest values during the test, in order to collect the maximum information possible. A testing procedure developed to achieve the best use of the computer data logger for this kind of behaviour has been used for the all tests.

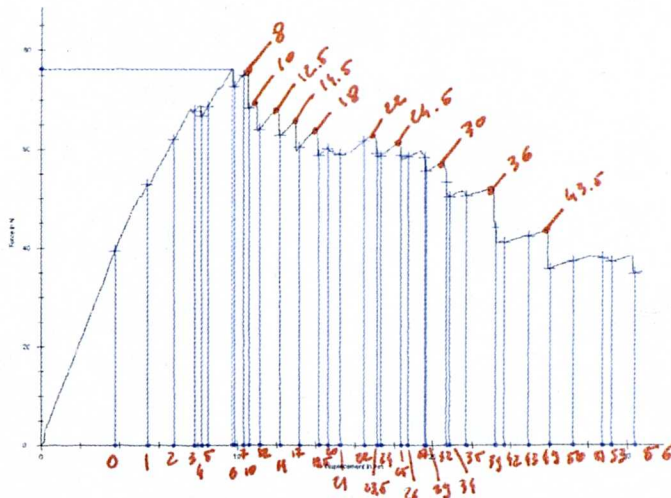


Figure 4-3: Load/Displacement trace of an unstable DCB specimen test

Tear of [0/40]_{cs} # 3 (710 f/6 X24-22)

0	6	19.5	25	35	51
1	7	20	26	39	53
2	10	4	27	42	56
3	12	22	29	43	
4	14	23.5	32	49	
5	17	24	34	50	

Figure 4-4: Extract of the lab book records for the same test

Older testing machines incorporated chart recorders. These were very convenient, as the operator could mark directly on the chart paper, during the test, the crack propagation and eventual stick-slip behaviour. With computer controlled testing machines, it is impossible for the operator to know and 'click' exactly the initiation values because the event is too fast and computer event markers work in real time, not a posteriori. Only regular crack growth in the case of stable behaviour or arrest values in the case of unstable behaviour can be marked. During the test, careful and systematic recording of the 'clicked' events as well as initiation values for eventual fast crack growth is therefore necessary. Figure 4-3 is an example of a load-displacement trace of an unstable DCB test with the crack length reported a posteriori from the lab book records shown in Figure 4-4. The arrows with SS above mean stick-slip behaviour from the initial crack length value circled to the arrest point 'clicked' with the event marker. All these data points are then usable for the analysis of the test.

4.2.4 Test conditions

Delamination tests under mode I (opening) loading conditions were carried out following the ISO 15024 for mode I delamination testing of UD laminates. Using the normal double cantilever beam (DCB), the crack was propagated from the starter film,

through the reinforced area and stopped when the crack had passed the pinned region. As the insert film used as a crack initiator was 12.5 μm thick, no pre-cracking has been performed. Figure 4-5 illustrates the test set-up and specific specimen dimensions. The loading rate for the DCB tests was set at 1mm/min.

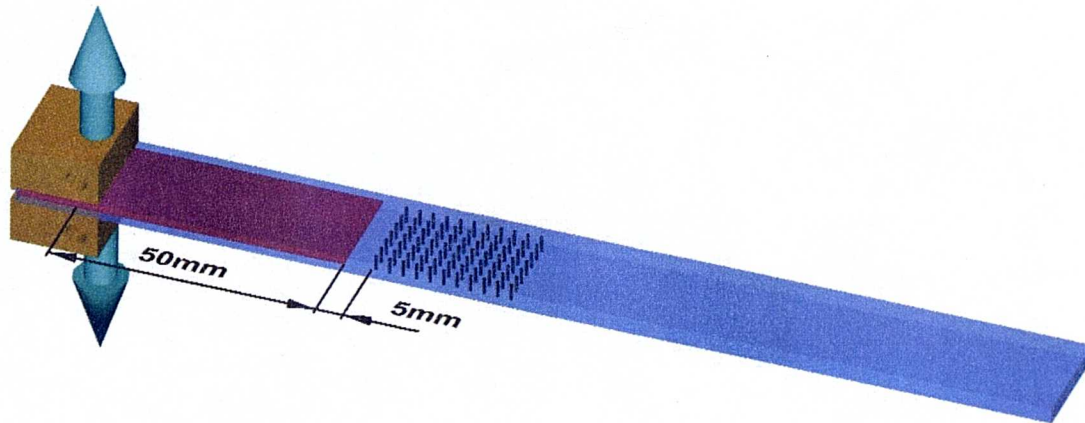


Figure 4-5: Schematic representation of Mode I DCB specimens

Mode II loading condition delamination tests were carried out following the ESIS TC4 recommendations for 3-point end notched flexure (ENF) testing (Moore, 2000). The nominal loading conditions, span and pin locations are given by Figure 4-6. The crack was propagated from a mode I pre-crack with a cross-head speed of 0.5mm/min.

For data analysis of the test results, the stiffness E and the compliance parameter m of the specimen need to be determined experimentally (see Section 2.2.2.1). The test protocol suggests that this experimental determination of the stiffness/compliance of the specimen can be carried out before and/or after the delamination test. In the present case, because of the presence of the Z-FibresTM in the wake of the crack after fracture of the specimen, the compliance determination has been carried out after pre-cracking and prior to testing.

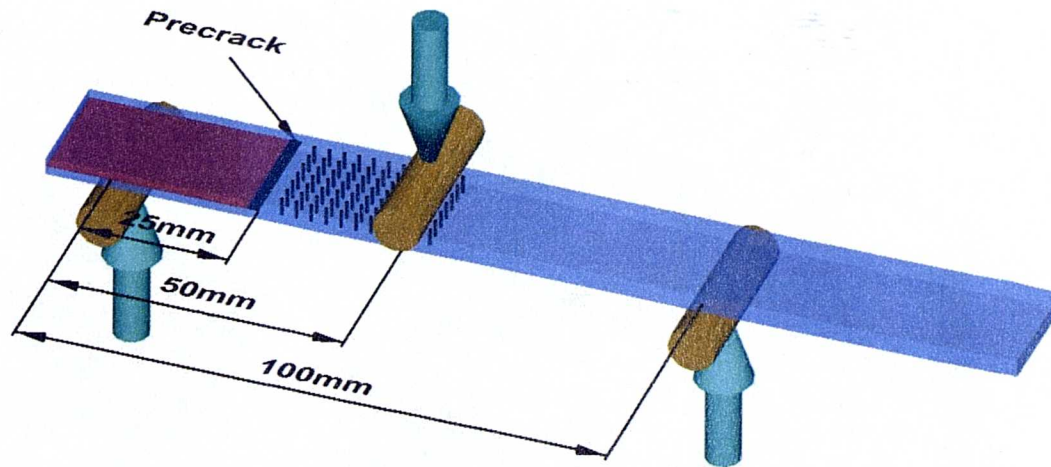


Figure 4-6: Schematic of Mode II 3pt ENF specimen and loading conditions

Mixed mode I/II loading condition delamination tests were performed following the ASTM draft standard for mixed mode bending (MMB) test of uni-directional composites (Reeder, 1998). Three representative Mode I / Mode II ratios were selected: MMB 20%, MMB 50% and MMB 80%, which denote the proportion of mode II loading out of the total loading. Table 4-3 gives the loading saddle positions for each mixed mode ratio, calculated accordingly to the draft standard, with the test configuration described by Figure 4-7.

Table 4-3: Loading saddle position

G_{II}/G	20%	50%	80%
Lever length 'C'	97 mm	44 mm	27 mm

The cross-head speed was set at 0.5mm/min and the crack was propagated from a short mode I pre-crack.

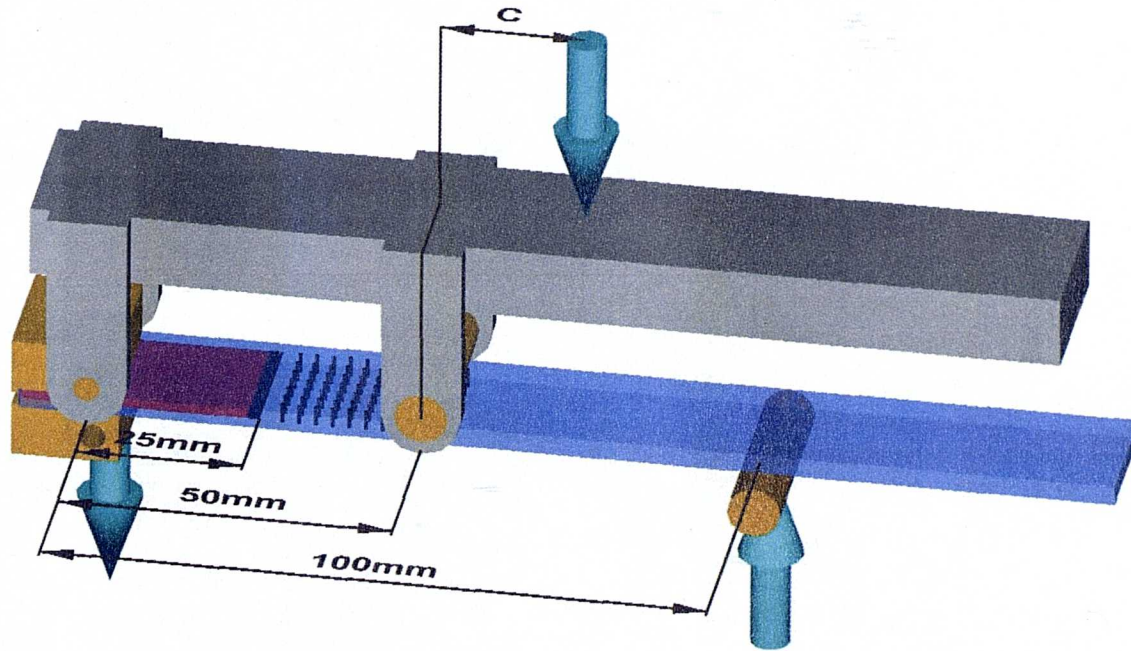


Figure 4-7: Schematic of mixed mode I/II MMB specimen and loading conditions

For analysis of mode II and mixed mode tests, the specimens were cracked open after the test and the real pre-crack length measured on at least five points, as the crack front produced by mode I pre-crack is unlikely to be straight. The average pre-crack length has been computed and a correction to the crack length applied to all the measured points.

4.3 Acoustic emission

Acoustic emissions have been recorded in some of the delamination tests. The equipment was easily accessible and had been used here largely as a matter of interest. No extensive analysis has been carried out. The acoustic emission instrumentation was a MISTRAS 2001 system, made by Physical Acoustics Corp. The system records time, counts, energy, duration and amplitude of each hit (noise). Being a digital system, it can also record the entire waveform for each hit for later analysis.

Due to the simple geometry of the specimens, only one channel was connected to an acoustic emission sensor. The sensor was held on the specimen with a rubber band.

Silicone high vacuum grease was used as the coupling agent. For DCB tests, a piece of string was used to take the weight of the sensor off the specimens. For the tests carried out here, only time, count, energy and duration were recorded.

4.4 Crack propagation imaging

During some of the tests, a Fuji MX700 digital camera was used to take pictures of the tests from a fixed point at regular time intervals. This method allowed digital 'videos' to be reconstructed and the behaviour of the different specimens to be compared qualitatively. Differences in crack propagation speed and different modes of failure have been observed and documented by this method. The knowledge of the sequence of the events in terms of pin deformation and pull-out is important in the modelling of the action of the pins, as will be shown in Section 7.4.

4.5 Experimental programme

A first series of tests, with only a limited number of specimens had been carried out in order to assess the manufacturing problems and testing feasibility. In this series, 16 specimens were tested in mode I and mode II, some of these having no reinforcement, reinforcement through the whole thickness or reinforcement in only 1 mm, in the centre of the thickness (see Table 4-4). Manufacturing problems having been solved and testing having proved successful, a more extensive study, involving different Z-reinforcement densities and diameters was then undertaken. Table 4-5 below summarises the different test condition chosen. The number of tested specimens of each kind is reported, as well as the number of tests performed with acoustic emission recording (in brackets). Only a relatively limited quantity of 0.28mm – 2% Z-Fibres™ preform was available; in consequence, only a limited number of this kind of specimens could be tested. Because of the behaviour of the mixed mode specimens, it was decided to concentrate on mode I and mode II delamination test for the specimens reinforced with 2% - 0.50mm Z-Fibers™.

Table 4-4 : Specimens tested for manufacturing and testing feasibility

	DCB	ENF
Control	3	2
0.5% - 0.28mm – Whole thickness	3	3
0.5% - 0.28mm – Partial thickness	3	2

Table 4-5 : Number of specimens tested for the second series

	DCB	MMB 20%	MMB 50%	MMB 80%	3-pt ENF
Control	3 (1)	4 (2)	3	4 (1)	4 (1)
0.5% - 0.28mm	4 (1)	4 (1)	4	4	7 (2)
2% - 0.28mm	3 (2)	2	2	2 (1)	4 (1)
2% - 0.50mm	5	0	0	0	5

Table 4-6 summarises the different tests performed in order to study the effects of Z-Fibres™ combined with interleaving. The interleaved specimens were manufactured in the second series of tests.

Table 4-6 : Specimens tested for interleaving trials

	DCB	ENF
Interleaved Control	4	3
Interleaved 0.5% - 0.28mm	5	3

In total, 94 specimens have been tested in this part of the overall study. For comparison purposes, all the test results in Chapter 5 reporting apparent toughness 'G_C' of the Z-pinned laminates have been analysed using the corrected beam theory methods, independently of the loading conditions.

Chapter 5 Delamination and Compression After Impact Test Results

5.1 Introduction

In addition to the results of the experiments listed in Chapter 4, results from separate studies of compression after impact performance of Z-pinned laminates will be presented. These results will be used at a later stage for discussions on the use and effectiveness of Z-Fibres™ in more realistic structures.

The delamination tests have been performed following the test protocols developed by the ESIS TC4 (DCB and 3pt-ENF) and the ASTM (MMB). Modifications have been made in this work in order to adapt the test procedures to recording stick-slip behaviour to obtain sets of data which are as complete as possible. The data will be presented under the format of load vs. displacement traces for the analysis of the behaviour of the beam regarding its load carrying capability. Resistance curves (energy release rate vs. crack length) will be used as a tool to analyse the crack propagation behaviour. Data analysis methods based on corrected beam theory have been used to compute the toughness of the specimens tested under mode I and mixed mode I/II loading conditions. In the case of mode II loading conditions, the toughness values have been obtained using the experimental compliance method. As discussed in chapter 2, LEFM based methods are not valid in the case of large scale bridging created by the Z-Fibres™. To date, analysis of bridging due to through-the-thickness reinforcement requires iterative procedures and long computing times. It is not applicable for the analysis of each single specimen. Therefore, LEFM data reduction analyses have been used to characterise and normalise the crack resistance of the combination laminate / Z-Fibres™ with respect to external parameters like beam width, beam stiffness and beam thickness. The reader has to be aware that any 'G_c' values quoted here are not absolute toughness values. Despite having been assigned the unit J/m² the values given must not be used as delamination toughness values of the pinned laminates. They are meaningful only when compared to other values obtained the same way, from comparable materials.

The acoustic emission results are presented correlated to the force vs. displacement curves, which is possible due to the fact that the loading rates for the different tests are kept constant. The triggering of the recording of the acoustic emission has been marked

on the load history trace using the event marker in order to synchronise the two devices. The acoustic emission results combine the energy of the hits (bars) as well as a cumulative count of the hits. The scale on the right hand side of the figures is relative to the hit energy. The cumulative counts have been divided by constant factors indicated in the legend of each graph to fit in the scale.

‘Control’ refers to specimens without Z-Fibres™. The pinned specimens will be characterised by their reinforcement density followed by the diameter of the pins used.

5.2 Mode I

5.2.1 Initiation / propagation

As shown in Figure 5-1, load vs. displacement traces of mode I DCB tests on pinned samples compared to an unpinned control sample indicate that the crack initiation is unaffected by the presence of the pins (5mm ahead), whilst when the propagating crack encounters the discrete rows of Z-pins, the fracture load increases significantly in comparison with control samples.

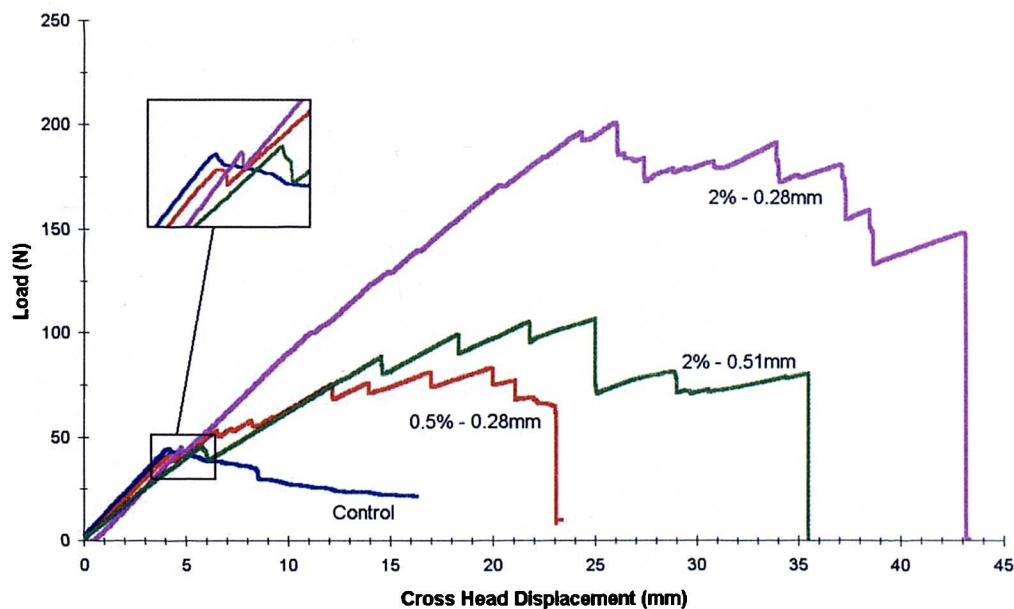


Figure 5-1: Typical force vs. displacement traces of mode I DCB tests

The load carrying capability of the specimens is improved up to 4 fold by using Z-Fibre™ pinning. The cracked beams are also able to withstand greater opening displacement than unreinforced samples, for the same crack length. However, the behaviour becomes unstable. The stick-slip behaviour reflects the mesostructure of the samples.

5.2.2 Mesomechanics

Figure 5-2 shows two Z-pins undergoing pull-out from the arms of a mini-DCB specimen. The photo was obtained from a small sample made especially for in-situ testing on the SEM microscope at the Engineering Department of the University of Cambridge. A resin-rich region surrounding the Z-pin is visible on the bottom arm of the DCB. The in-situ SEM observations confirm that the crack runs from one discrete row of Z-pins to the next, arresting temporarily at each row. A more macroscopic view is provided by the digital camera picture shown in Figure 5-3. The pins gradually pull out of the composites as the crack opening displacement increases.

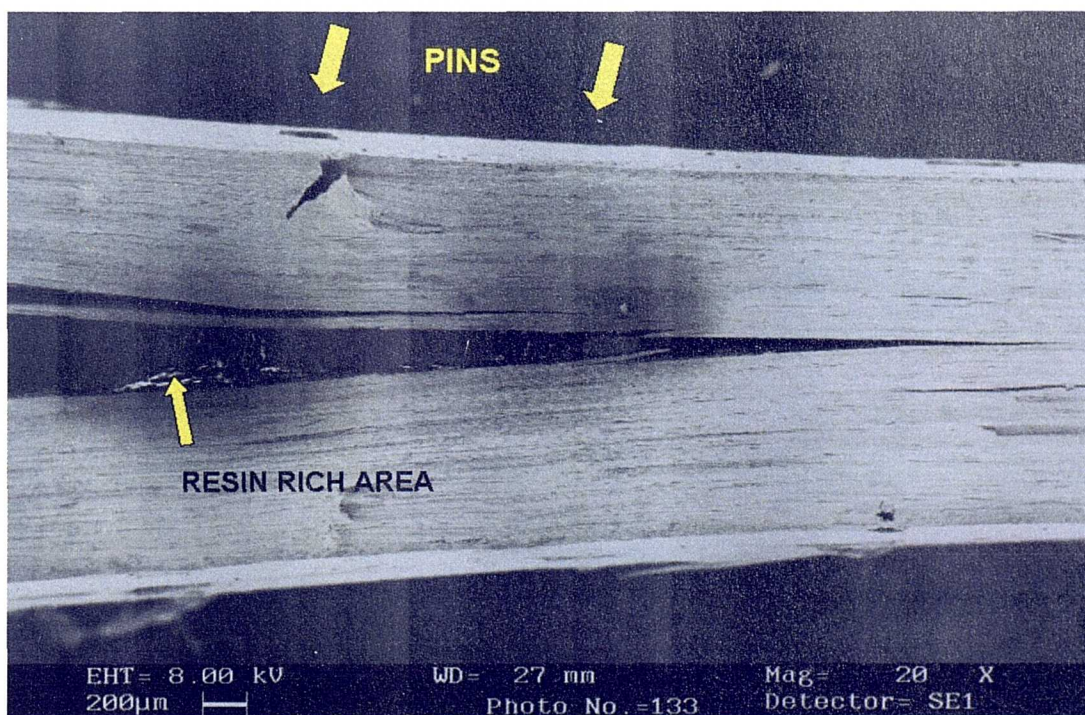


Figure 5-2: In situ SEM photo of a mini-DCB test in progress

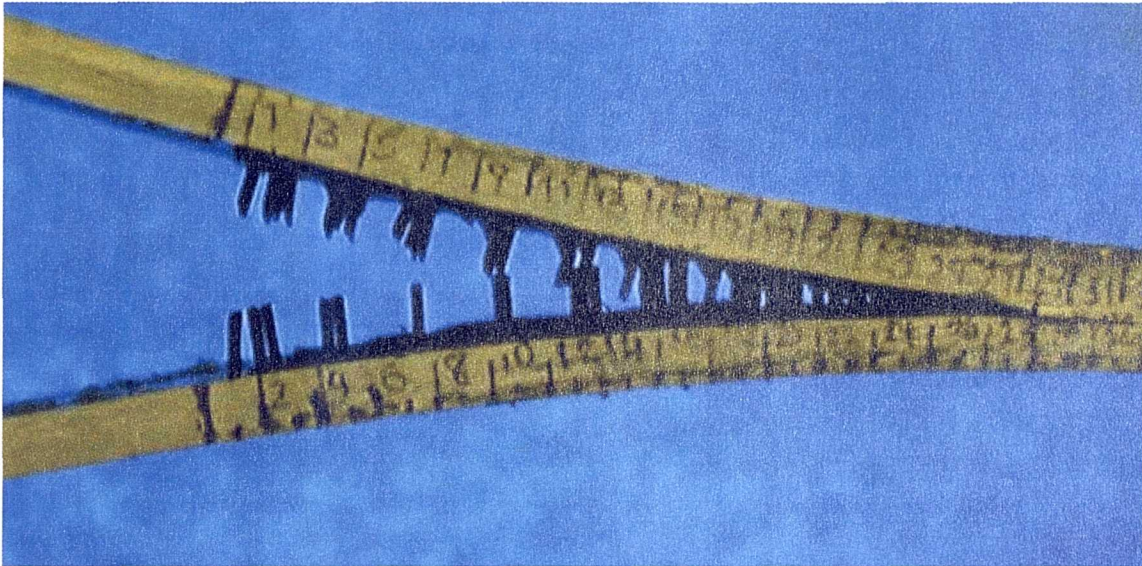


Figure 5-3: Pins pulling out of the arms of DCB samples (2% - 0.28mm)

5.2.3 0.5% - 0.28mm - pin-to-pin 3.5mm

A typical R-curve of a pinned specimen 0.5%-0.28mm is shown in Figure 5-4 with the fracture surface photograph of the corresponding specimen. The magnification of the photograph has been adjusted in order to obtain the same scale as the R-curve crack length axis.

The crack propagation is clearly unstable. The locations of the pins marked on the graph tend to indicate a clear relationship between the specimen mesostructure and the crack propagation behaviour. From an initiation toughness of about 200J/m^2 , the apparent propagation resistance increases to about 1200J/m^2 in an unstable manner. When the crack encounters a row of pins, the resistance is increased and the crack stops. This phenomenon is illustrated by the presence of 'river lines' on the fracture surface (bottom of Figure 5-4). The river lines are a change in the coloration of the fracture surface due to the fact that the crack stops and initiates. Indeed, the brighter river line locations correspond to initiation points on the R-curve. The river lines are parallel to each other and parallel to the edge of the starter film. This indicates that the crack front is not deviated by the pins. Edge effects are visible by a little curvature of the river

lines near the edges of the specimen. Once the crack has passed the pinned region, the delamination propagation resistance reverts back to that exhibited by the control samples.

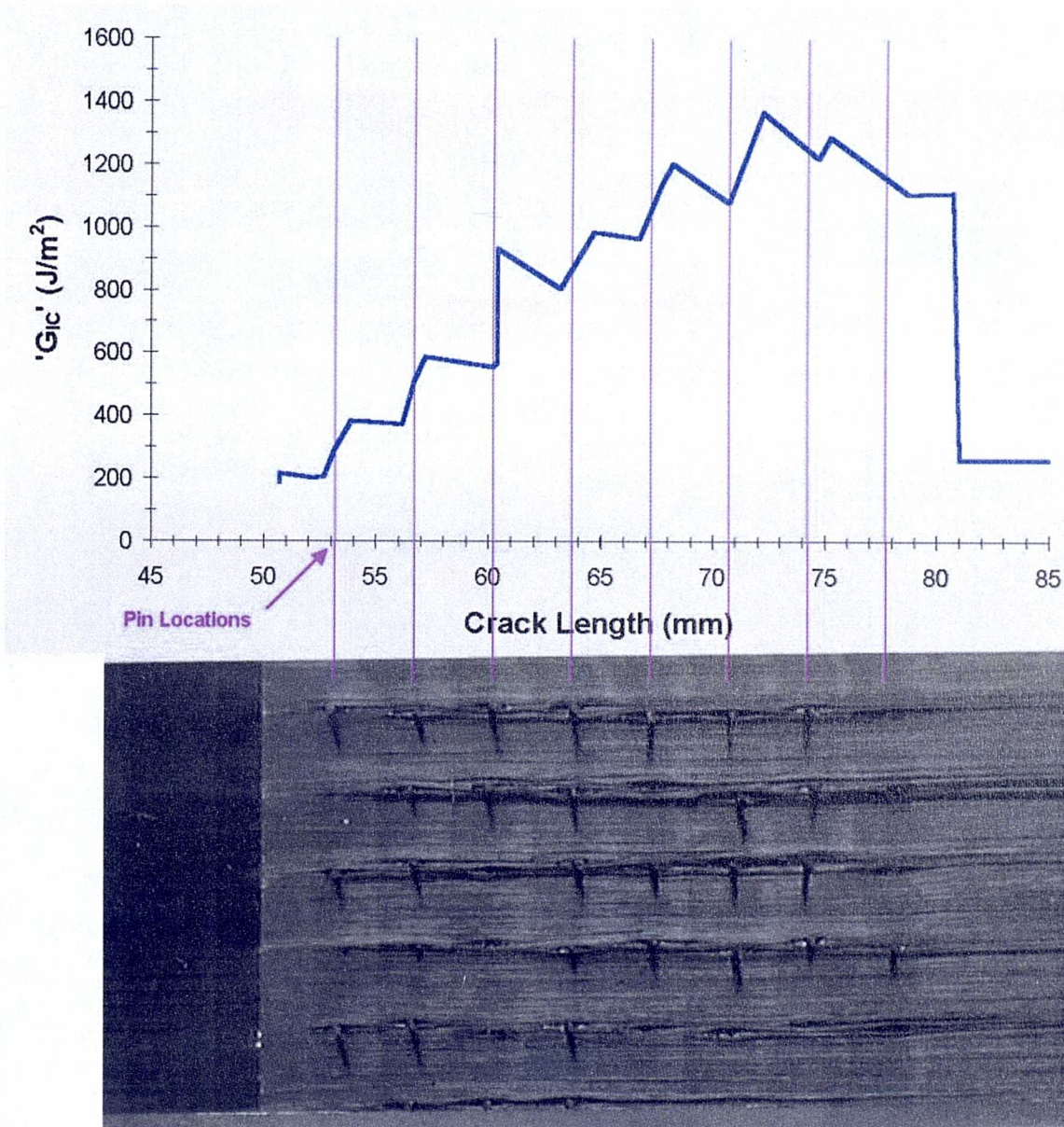


Figure 5-4: Mode I R-curve and fracture surface of a 0.5%-0.28mm DCB specimen (Sample ref. GRE10)

5.2.4 2% - 0.28mm - pin-to-pin 1.75mm

The delamination resistance of the 2%-0.28mm pinned specimens increases from 225J/m^2 to a plateau value of 5000J/m^2 in a short crack propagation distance (about 6mm), which is shown in Figure 5-5 by the steep initial slope of the R-curve. Once that plateau values is reached, the crack propagates in a steady-state fashion. The number of working rows of pins is believed to be constant, one row being reached as another one is fully pulled out (Figure 5-3)

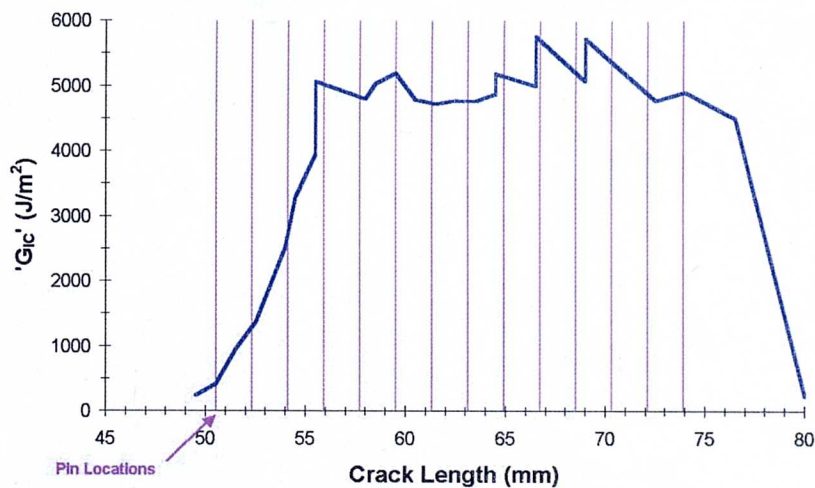


Figure 5-5: Mode I R-curve of a 2% - 0.28mm DCB specimen

As before, once the crack has passed the pinned region, the delamination propagation resistance reverts back to that exhibited by the control samples, however, the load and opening displacement are sufficiently high to propagate the crack rapidly to the end of the specimen. Due to the fact that the spacing between each row of pin is very small, no river line is visible.

5.2.5 2% - 0.51mm - pin-to-pin 3.1mm

Similarly to Figure 5-4, Figure 5-6 shows a plot of the delamination R-curve of 2%-0.51mm pinned specimens in combination with its fracture surface.

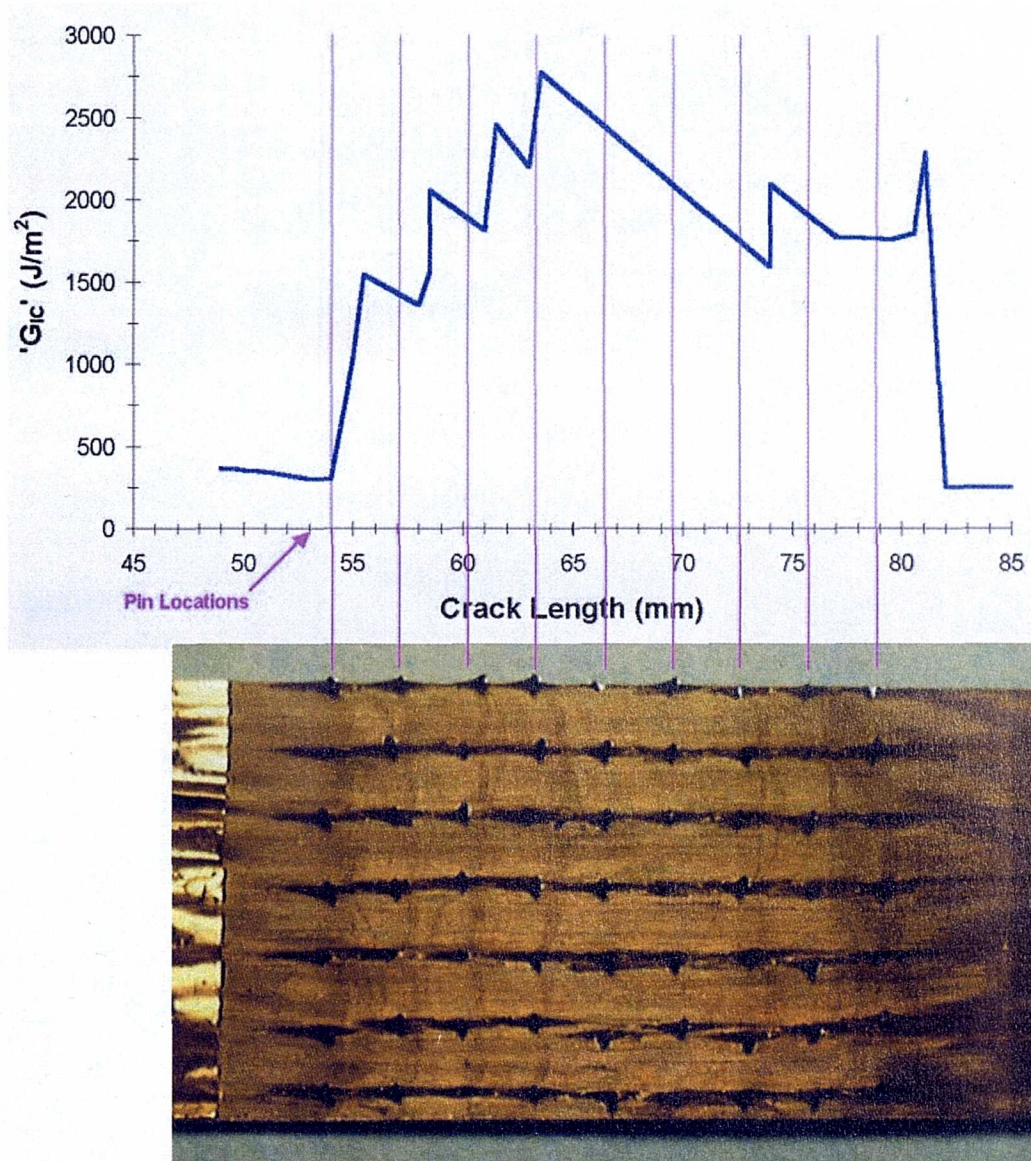


Figure 5-6: Mode I R-curve and fracture surface of a 2%-0.51mm DCB specimen (Specimen ref. GTE1)

The crack propagation behaviour of 2%-0.51mm pinned laminates is intermediate between the two previous pinning configurations described above. It presents the pronounced unstable stick-slip behaviour of the 0.5%-0.28mm reinforced specimens

and the steep rising initial slope of the R-curve of the 2%-0.28mm pinned samples. River lines are visible on the fracture surface. It is visible on the R-curve that the crack jumped from 64mm to 73mm rapidly. There is no river line on the corresponding part of the fracture surface.

Mesostructural effects of the larger pin diameter can be seen on an optical micrograph of the fracture surface of a specimen (Figure 5-7). On this micrograph, the large chamfer is visible. Extensive resin rich pockets are created at the base of the pins where the laminate fibres are pushed apart. During fracture, the resin rich pockets fail in such a way that the foot of the pin is surrounded by a block of resin.

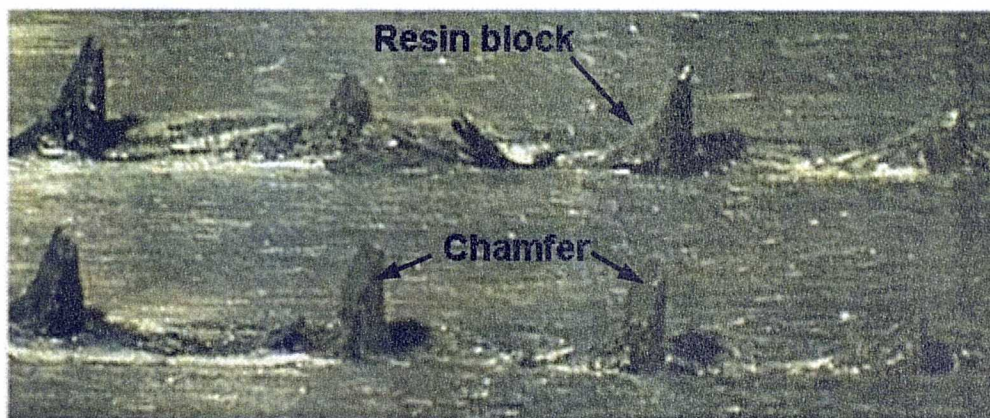


Figure 5-7: Optical micrograph of the fracture surface of a 2%-0.51mm DCB specimen

The investigation of the fracture surfaces revealed that one specimen (specimen ref GTE9) showed some 'river lines' not perpendicular to the laminate fibre direction, but diagonally across from one pin to another (Figure 5-8). When this phenomenon occurs, the crack propagation behaviour is changed from being unstable stick-slip to being apparently stable with increase of the toughness (crack lengths from 62mm to 70mm). This indicates that, in this particular case, the crack front was not always parallel to the edge of the starter film. This may be caused by misalignment of the specimen in the test apparatus. However, because of the care taken during testing and the fact that the crack apparently propagates faster in an area where the pins are shorter, it is believed that the variable bridging actions due to different insertion depths of the Z-Fibres™ altered the crack propagation path in this particular case.

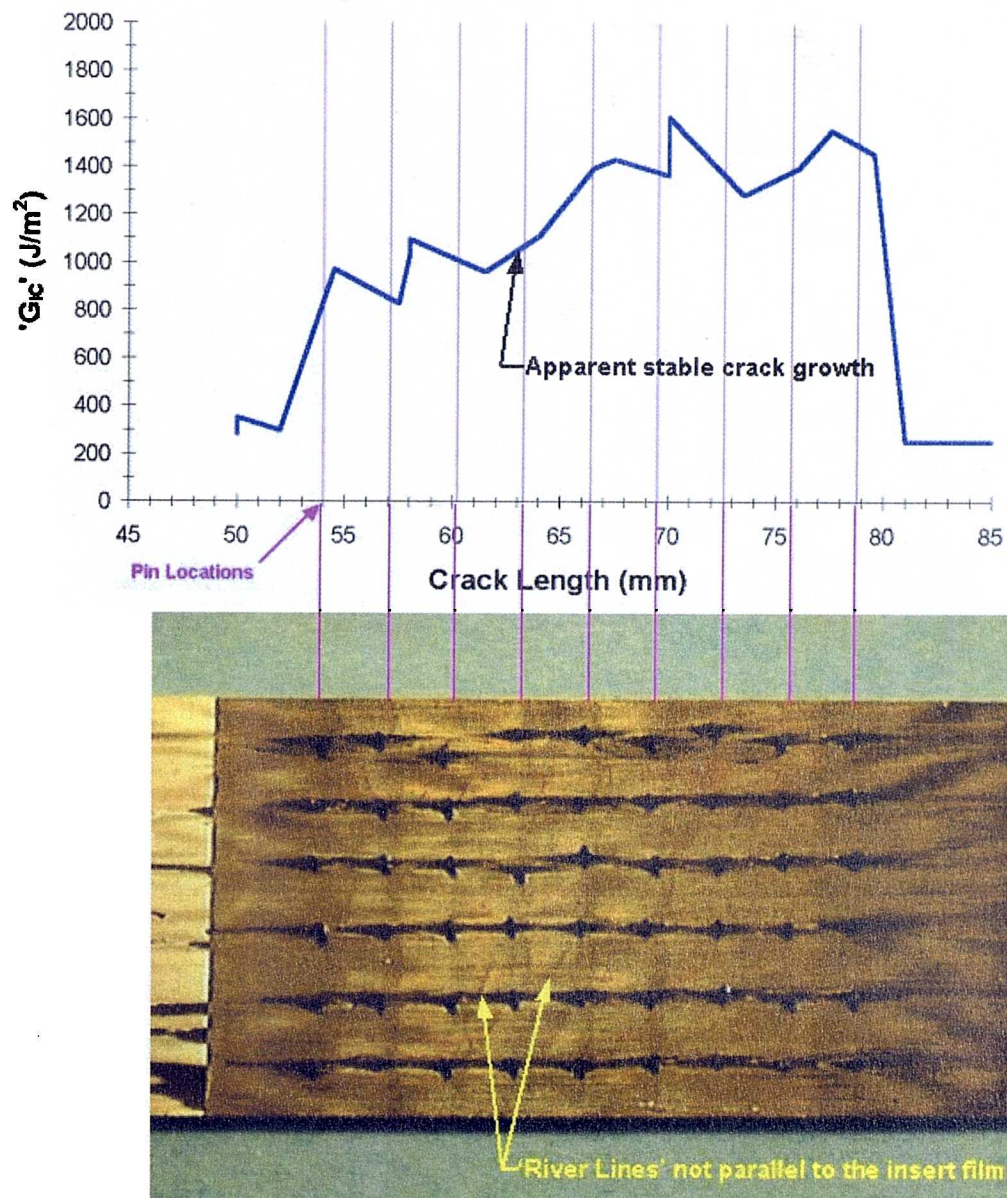


Figure 5-8: R-curve and fracture surface of a 2%-0.51mm DCB specimen (Specimen ref. GTE9)

5.2.6 Pin depth or pin length

The study of the effects of the pin length has been carried out simultaneously with the first series of specimens manufactured. For comparison purposes, only results from the first series of tests are presented in this section. The initiation toughness for all the specimens is nominally 230J/m², a value that would be expected for 924 matrix based

composites. The propagation resistance increases for the control sample up to 400J/m^2 . Visual observation of the tests shows that extensive fibre bridging occurred, which ‘artificially’ increased the propagation toughness of the control specimens. Such fibre bridging has not been observed in the pinned specimens or in the tests of the second series.

The results called ‘partial thickness’ have been obtained by testing specimens in which only 1mm at the centre of the laminate has been pinned. It is clear that the crack propagation resistance is directly related to the length of the pins, the longer the pins are, the greater is the toughness. From 600J/m^2 for the samples reinforced partially through-the-thickness, the delamination resistance increases up to 900J/m^2 for specimens pinned through the whole thickness. In contrast to the crack propagation behaviour of laminates reinforced through the entire thickness, which is unstable, the crack propagation of the ‘partial thickness’ reinforced laminate is stable, in this particular case.

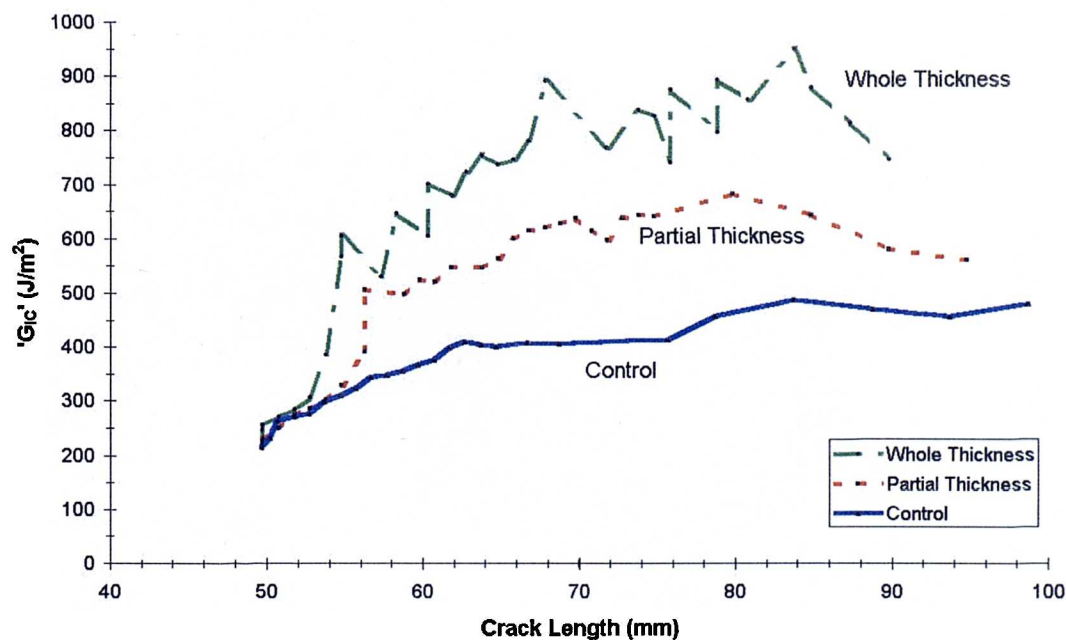


Figure 5-9: Effect of Pin Length on Mode I R-Curves

5.2.7 Interleaving

As shown in Table 4-6, only a few specimens with self-same-resin interleaving have been manufactured. The effectiveness of the resin interleaf placed at selected interfaces has been shown to be strongly dependent of the interleaf thickness (Singh and Partridge, 1995a) (Aksoy and Carlsson, 1992) (Bradley, 1990). Figure 5-10 shows typical R-curves of DCB specimens with and without interleaving, in both cases, without pins. The R-curves are flat and interleaving increases the toughness of the laminate by approximately 20% (from 250J/m² to 300J/m²). In this case, data reduction methods based on LEFM are valid, thus the quoted values can be considered as correct.

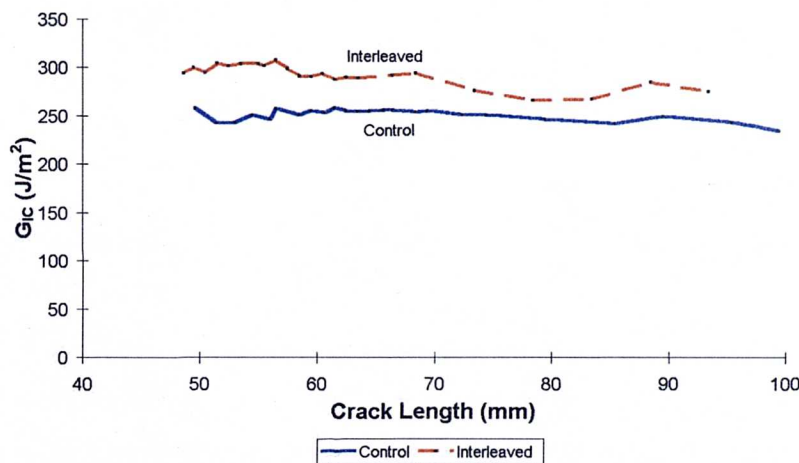


Figure 5-10: Effects of Interleaving on Mode I R-Curves

As illustrated by Figure 5-11, self-same-resin interleaving also improves the performance of Z-pinned laminates. The crack propagation behaviour of the interleaved and pinned laminate is similar to the one of the pinned only laminate. Due to the unstable nature of the crack propagation, it is difficult to quantify the improvement due to interleaving. It is therefore difficult to determine if interleaving improves the bridging action of the Z-Fibres™ or if the improvement is only due to a tougher material, which is the interleaved IMS/924.

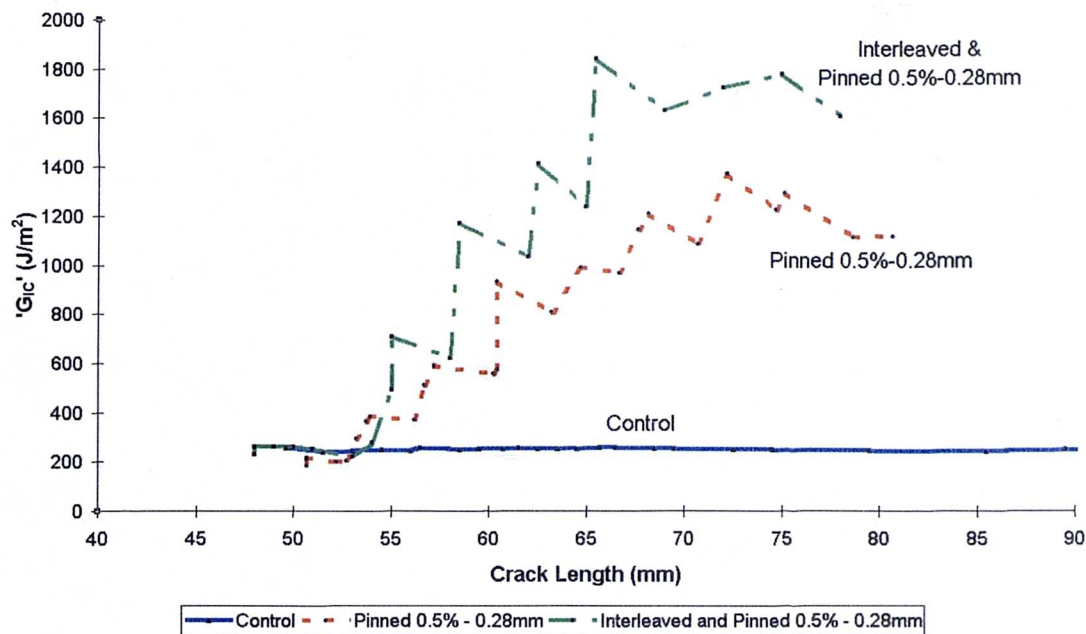


Figure 5-11: Effect of interleaving on pinned specimens (0.5% - 0.28mm)

5.3 Mode II

5.3.1 Behaviour

In the case of the mode II 3pt-ENF test, the failure mode is modified by the presence of the Z-pins. Unlike the sudden catastrophic failure in the control sample, the delamination in the pinned beams propagates in a stabilised and measurable way (Figure 5-12). The presence of Z-pins at a sufficiently high density allows the 3pt-ENF beam to carry load even after the crack initiates. For the 2% pin density, the load carrying capability is higher than the crack initiation load. In contrast to mode I, no stick-slip behaviour was observed. The crack propagation was either catastrophic or progressive and stable.

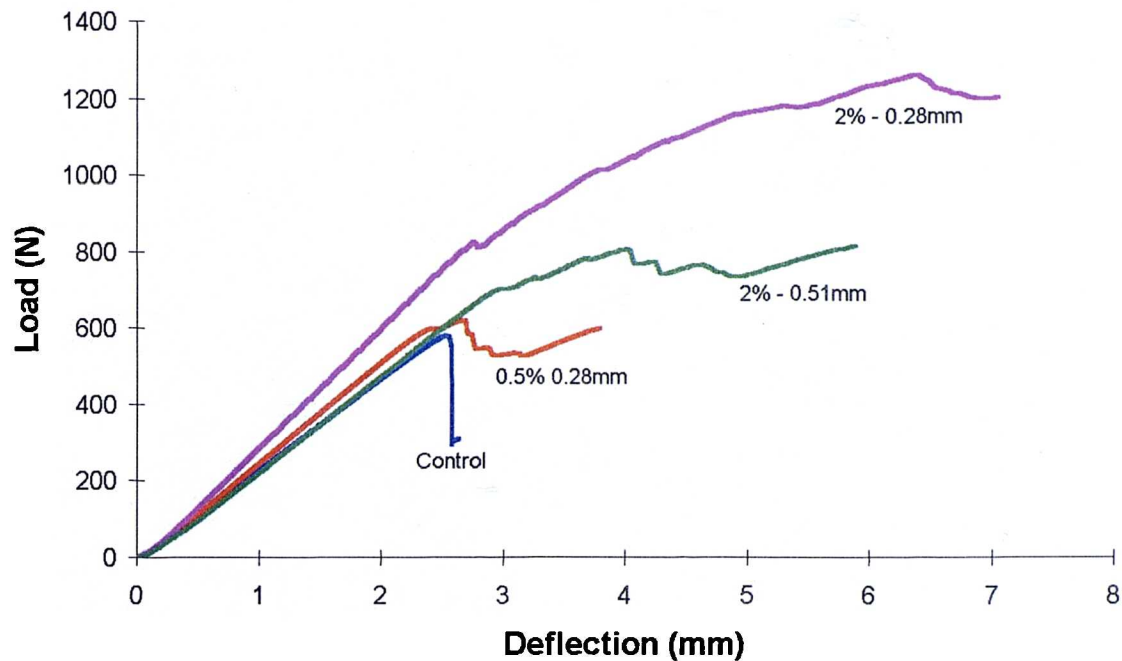


Figure 5-12: Mode II load vs. displacement traces

5.3.2 Mesomechanics

In-situ SEM micrograph of a mini-ENF test specimen, shown in Figure 5-13, shows two Z-pins pulling out from the beam arms and twisting with respect to their initial positions, in the wake of the crack front. The image indicates the existence of a significant proportion of crack opening displacement in the deformation of this sample. This is consistent with the observation of both pulled-out and sheared Z-pins on the fracture surfaces of failed 3pt-ENF samples, such as shown in Figure 5-14.

No river lines are visible on the fracture surface of the specimens tested under mode II loading conditions. The mode I pre-crack is visible near the edge of the starter film. It is also apparent that the first two rows of pins have been sheared off as opposed to being pulled out. This can be explained by the fact that the different rows of pins have been subjected to different shear displacements (the nearer a row is to the crack tip, the smaller the shear displacement), therefore different failure modes of the pins can occur.

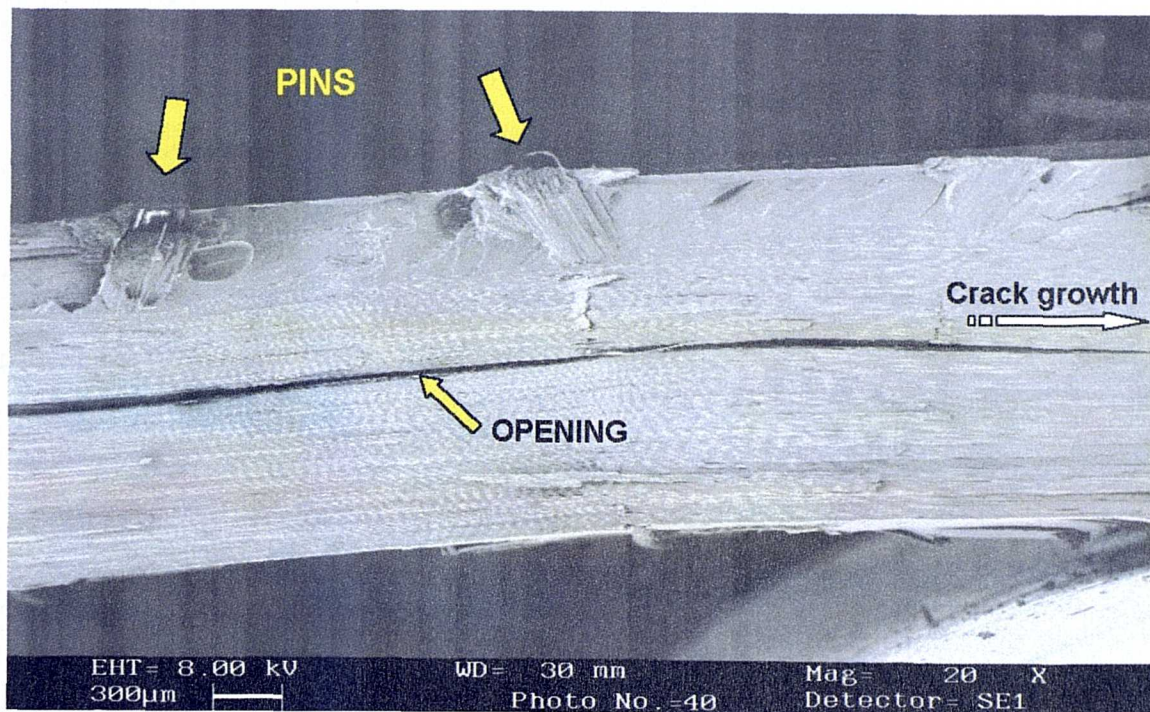


Figure 5-13: In situ SEM photo of a mini-ENF test in progress

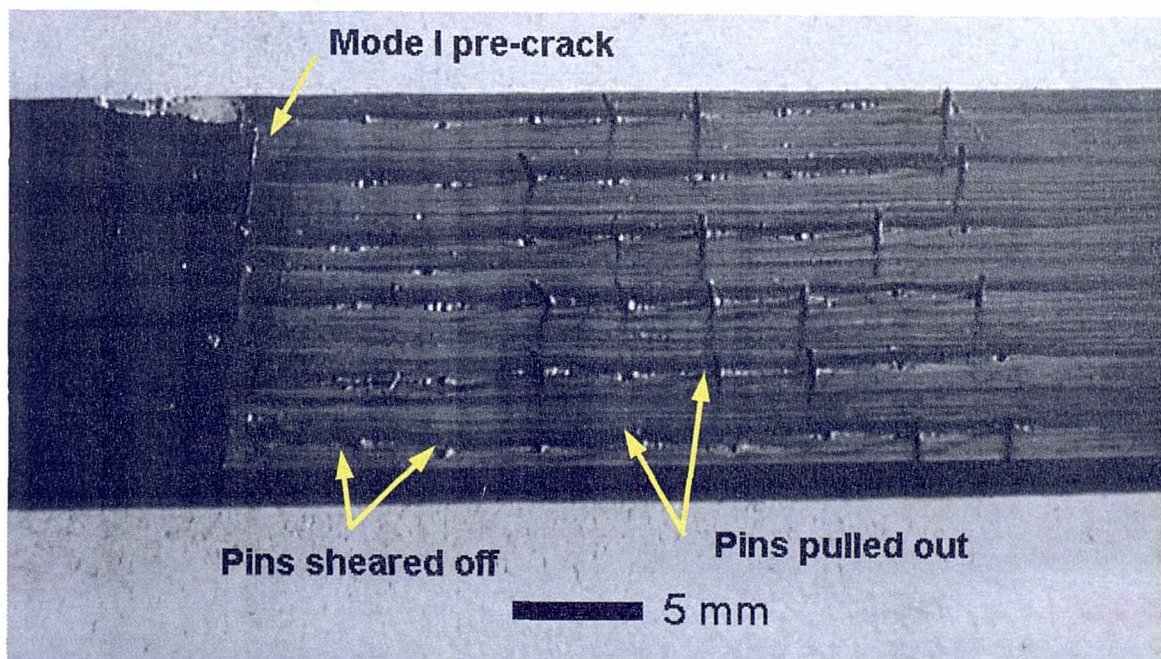


Figure 5-14: Fracture surface of an 3pt-ENF specimen (0.5% - 0.28mm)

Figure 5-15 illustrates that in the area where the crack has not propagated (area A), the pins are not subjected to any shear displacement in the centre plane of the laminates. As

the crack propagates, shear displacement is applied to the pin on the crack plane. The Z-Fibres™ debond from the laminate and then shear and pull out (Area B) until the relative crack face displacement becomes too high and the pins fail by shear (Area C).

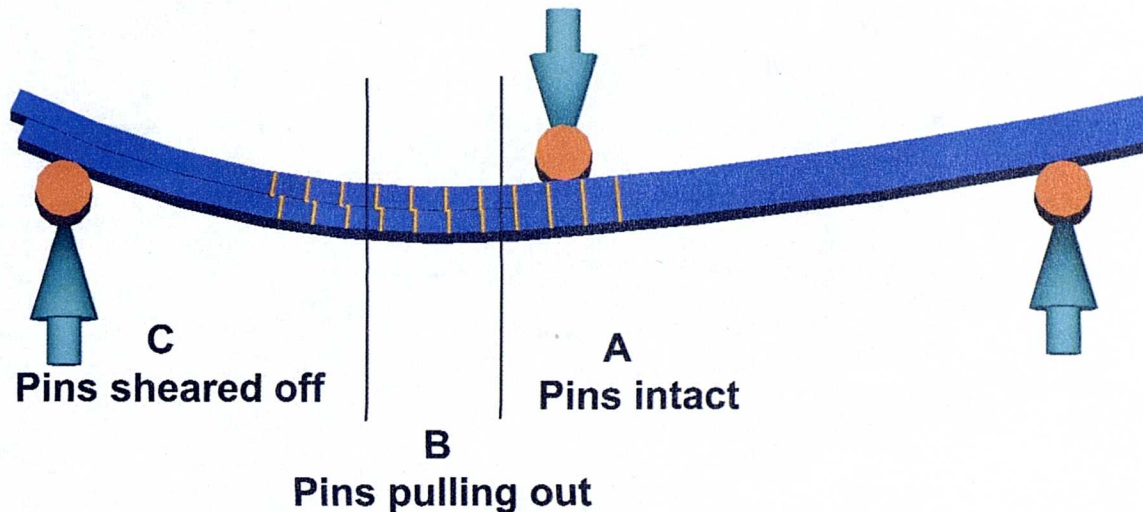


Figure 5-15: Schematic of the different failure modes of the pins subjected to shear displacement

5.3.3 Resistance curves

As can be seen in Figure 5-16, when the crack propagation is stable, the shape of the R-curves for the pinned 3pt-ENF specimens is similar. They can be described as constantly rising R-curves. The greater the pin density, the steeper is the R-curve. The selected R-curves plotted here are close to the average value determined from all the specimens of any given type.

In contrast to the Mode I case, there is no obvious effect of the Z-pin diameter, at the given areal density, on the Mode II crack growth resistance, although the use of the small diameter pins still leads to slightly better performance, i.e. for a given crack extension through the pinned area the propagation resistance offered by the 0.28mm

samples is typically 15% higher than the 0.51mm samples. For the geometry of the specimens and the location of the reinforcement, no plateau value or steady-state crack propagation has been reached.

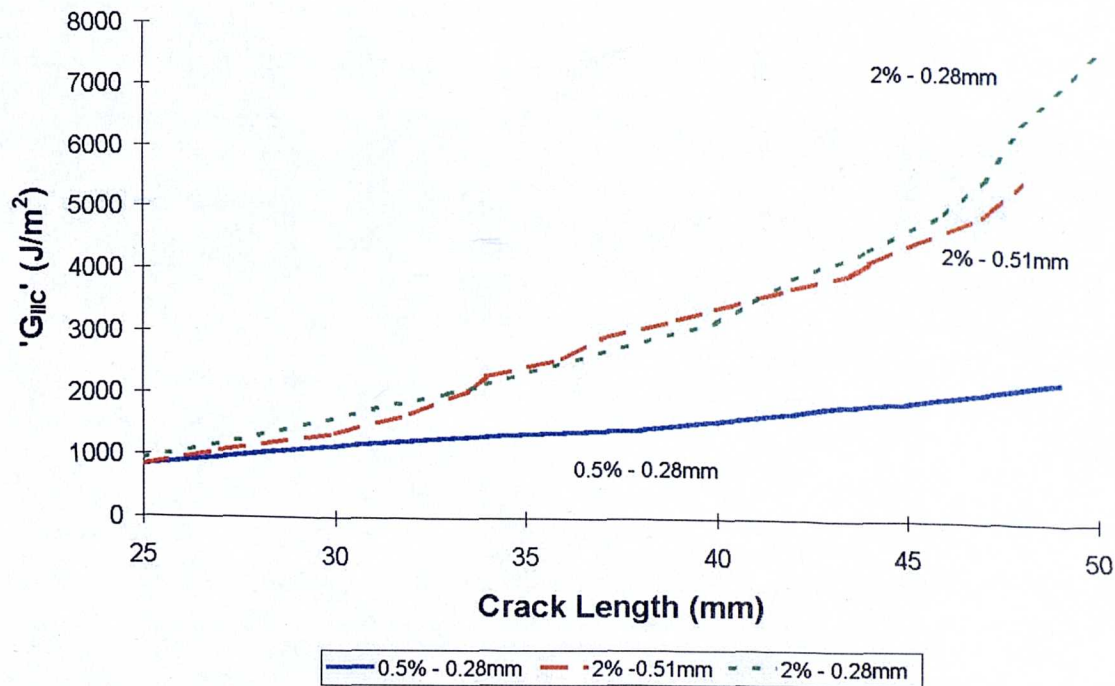


Figure 5-16: Typical mode II R-curves for stable samples

5.3.4 Inconsistency with 0.5% - 0.28mm

Some inconsistency of the behaviour of 3pt-ENF specimen pinned with a density of 0.5%-0.28mm pin diameter has been observed. Of the seven specimens of this kind tested, four had a stable behaviour. The other three exhibited unstable behaviour. On average, a specimen with an unstable behaviour reached a greater load before the crack started to propagate. Their G_{IIC} initiation value was therefore higher.

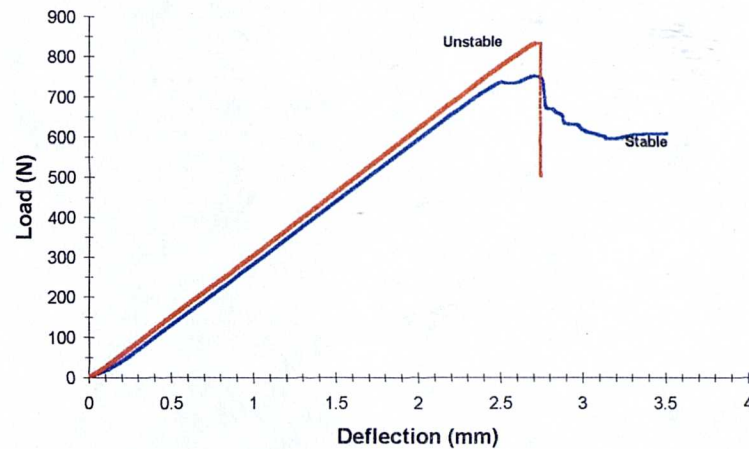


Figure 5-17: Inconsistency on the stability of the 3pt-ENF specimens pinned with 0.28mm density 0.5%

In the experiments to date, a density of 0.5% is the lowest pin density which has been shown to stabilise the crack propagation of the 3pt-ENF specimens in this configuration. It is probable that any density smaller than 0.5% would not be able to stabilise the 3pt-ENF tests. Table 5-1 below summarises the initiation values for the different types of behaviour observed.

Table 5-1: Initiation toughness of 0.5%-0.28mm pinned 3pt-ENF specimens, with samples separated by fracture behaviour type

	Stable	Unstable
' G_{IIC} ' (J/m^2)	865	1200

5.3.5 Acoustic emission

Figure 5-18 shows the typical behaviour of an unpinned specimen and its acoustic emission. The load increases linearly until the crack initiates. Noise hits of small energy (under 50) can be recorded. Catastrophic failure is preceded by a high number of greater energy hits (up to 4000).

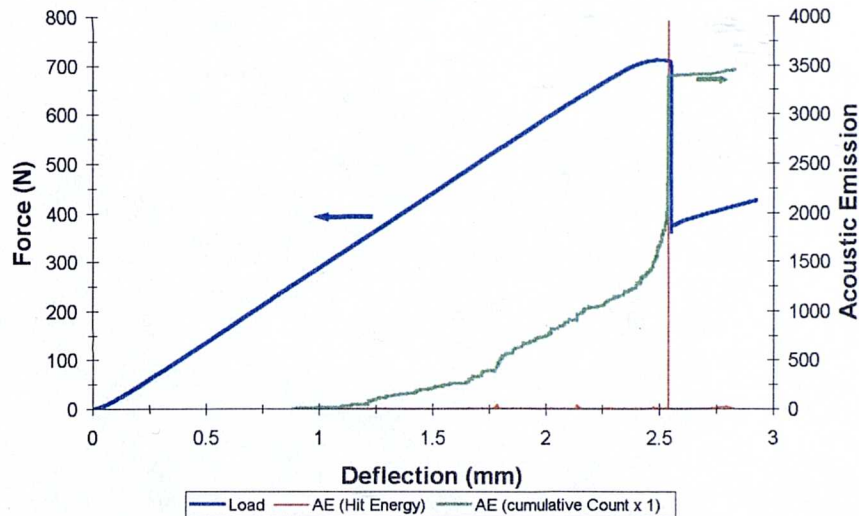


Figure 5-18: Behaviour of a control specimen under mode II loading conditions

For the 2%-0.28mm pinned specimens (Figure 5-19), the low energy noise (around 50) is still present after initiation of the crack. In contrast with the high energy hits during the catastrophic failure, some medium energy hits (between 400 and 1000) are present. These noises correspond to fluctuations on the force history graph. The cumulative number of hits at the end of the test is 66500, to be compared with 3500 hits recorded during the test of the control specimens.

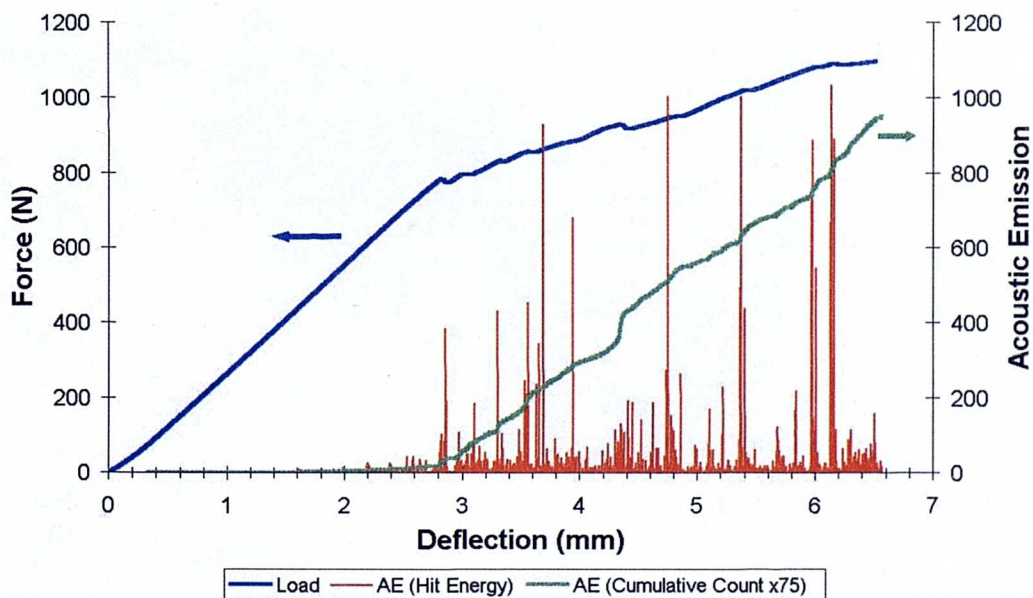


Figure 5-19: Typical mode II load vs. displacement trace 2%-0.28mm

5.3.6 Pin length

In the pinning configuration tested here, the bridging due to the short pins was not sufficient to prevent the crack from propagating catastrophically. The load histories of the 3pt-ENF tests of the laminate reinforced through the partial thickness were no different than the load vs. displacement curves of the control specimens.

5.3.7 Interleaving

Similarly to mode I, the interleaving increases the mode II delamination toughness, although the behaviour of the interleaved 3pt-ENF beam is still unstable (Figure 5-20). Nevertheless, the combination of interleaving and 0.5%-0.28mm pins leads to slightly greater initiation toughness values, as shown in Table 5-2. Like the standard 0.5%-0.28mm pinned specimens, when the initiation values are high, the density of 0.5% is not sufficient to stabilise the crack growth. The batch sizes of the samples tested are 4 specimens for control and 3 samples for both 'Interleaved' and 'interleaved & pinned' 0.5%-0.28mm. The values quoted in Table 5-2 are the maximum initiation values determined from the maximum point. As seen in section 5.3.4, the initiation toughness of pinned 0.5% - 0.28mm samples ranges between 840 and 1200J/m². Interleaving by itself increases the initiation toughness to 2375J/m². The improvement are additive, to some degree.

Table 5-2: Effect of interleaving on mode II delamination toughness (initiation)

	Control	Interleaved	Interleaved & 0.5% - 0.28mm
$G_{II\text{Cini}}$ (J/m ²)	700 (±50)	2375 (±300)	2590 (±300)

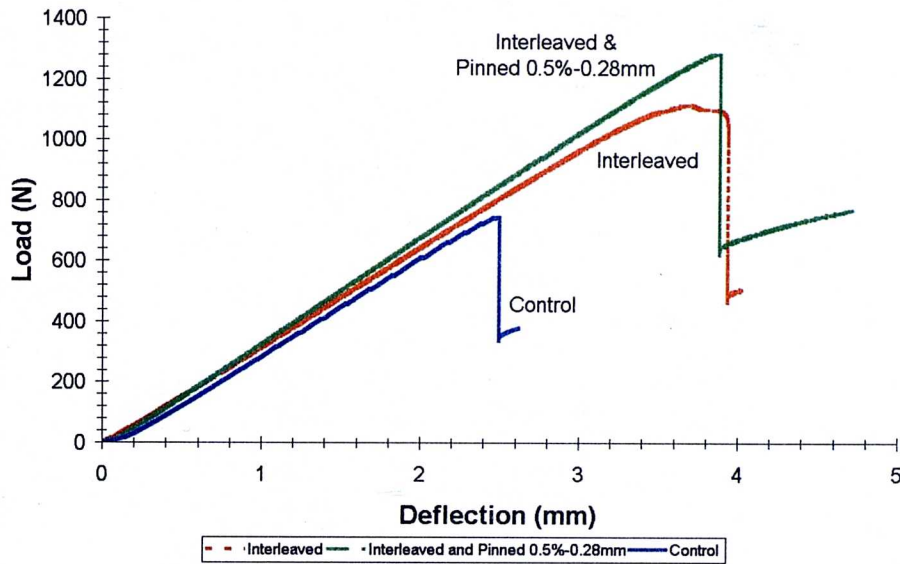


Figure 5-20: Effect of interleaving on Mode II load traces

5.4 MMB

5.4.1 MMB 20% - $M_I/M_{II}=4/1$

Figure 5-21, Figure 5-22 and Figure 5-23 are force vs. displacement traces of a control, a 0.5%-0.28mm pinned and a 2%-0.28mm pinned MMB samples, respectively, with their corresponding acoustic emission recordings. A series of pictures taken at regular intervals during these tests is shown in Appendix B. The difference of behaviour between the different types of reinforcement is clearly visible. The shape of the force history graph of the control specimen is characteristic of the behaviour of the delamination crack growth of an UD specimen under mode I dominated loading conditions (Figure 5-21). After a linear loading, the load drops as the crack propagates. The acoustic emission hits of an energy lower than 200 are recorded constantly. The total number of recorded hits is 114000.

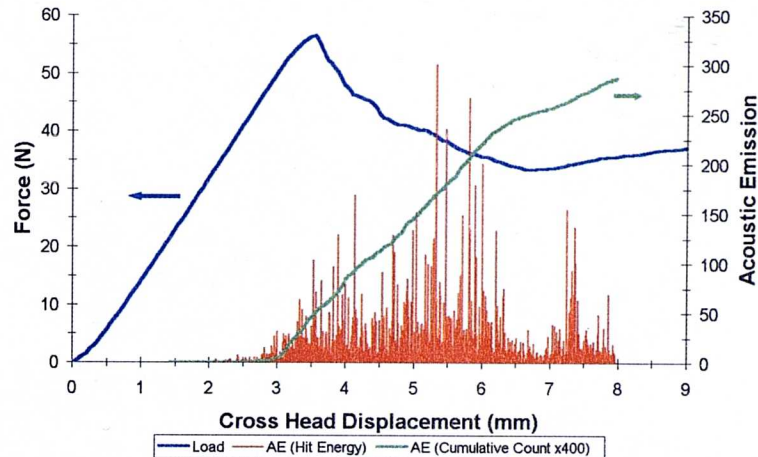


Figure 5-21: Force vs. displacement curve of a control MMB specimen, $M_I/M_{II}=4/1$ and its acoustic emission trace

The behaviour of the 0.5%-0.28mm samples is very similar to the behaviour of the same samples under mode I loading (Figure 5-22). The force history is unstable. Each load drop is accompanied by a number of higher energy acoustic emission hits (up to 2500). The overall number of recorded hits is 74100.

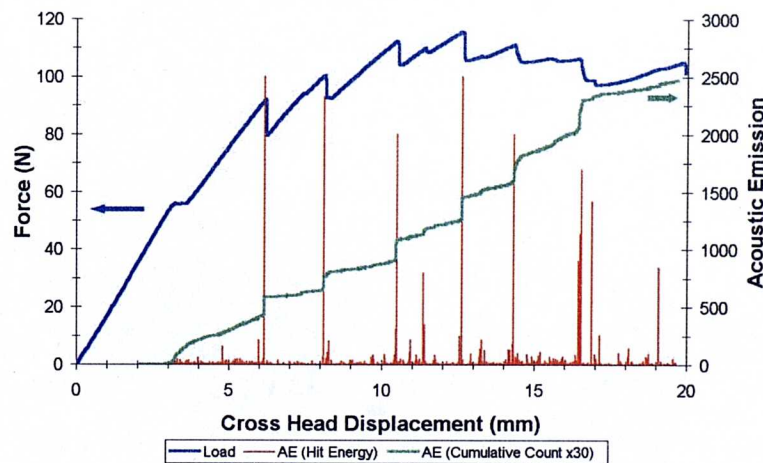


Figure 5-22: Force vs. displacement curve of a pinned 0.5% - 0.28mm MMB specimen, $M_I/M_{II}=4/1$ and its acoustic emission trace

Crack propagation in the 2%-0.28mm pinned specimens is more stable (Figure 5-23). No drops are visible in the force vs. displacement traces. The fluctuation in the force are accompanied with acoustic emission hits of an energy of about 1000. Under these specific loading conditions, with this reinforcement, the crack is stopped after a

propagation of about 15mm and the upper arm of the MMB beam fails in flexure (Figure 5-24).

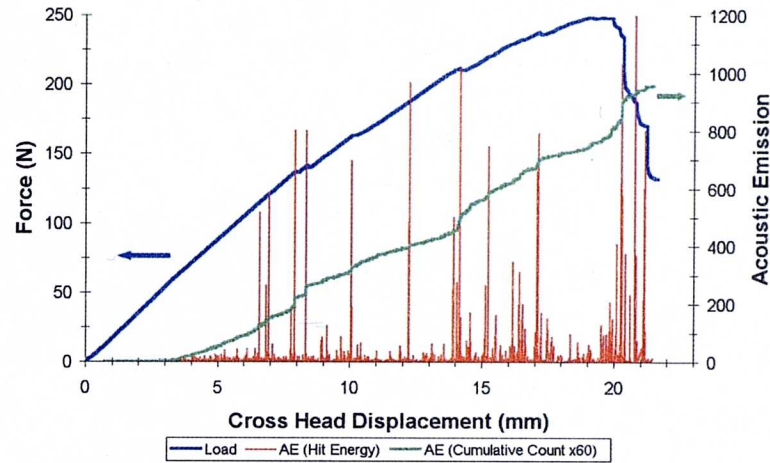


Figure 5-23: Force vs. displacement curve of a pinned 2% - 0.28mm MMB specimen, $M_I/M_{II}=4/1$ and its acoustic emission trace

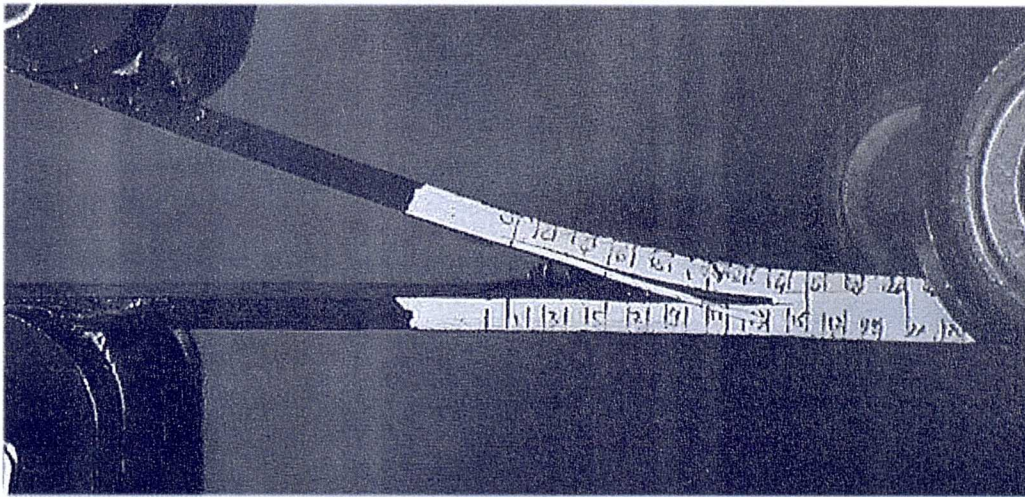


Figure 5-24: Arm failure of specimen under mixed mode loading conditions ($M_I/M_{II}=4/1$) Pin Density 2% Pin Diameter 0.28mm

In the present loading configuration, the opening displacement of the crack faces was sufficient to allow visual observation of the Z-Fibres™ pullout. It appears that the pins were mainly pulled out of the upper arm of the beam, the arm being subjected to the greatest bending. This can be explained by the fact that the bending of the arm may

initiate an early debonding of the pins from the laminate, which would induce their pullout from the upper arm.

Figure 5-25 is a surface plot of the force vs. displacement traces of the MMB 20% samples. The batch sizes are 4 samples for both control and 0.5%-28mm pinned specimens and 2 samples for 2%-0.28mm pinned specimens. This form of plot has been chosen to represent graphically the good reproducibility of the behaviour of the samples.

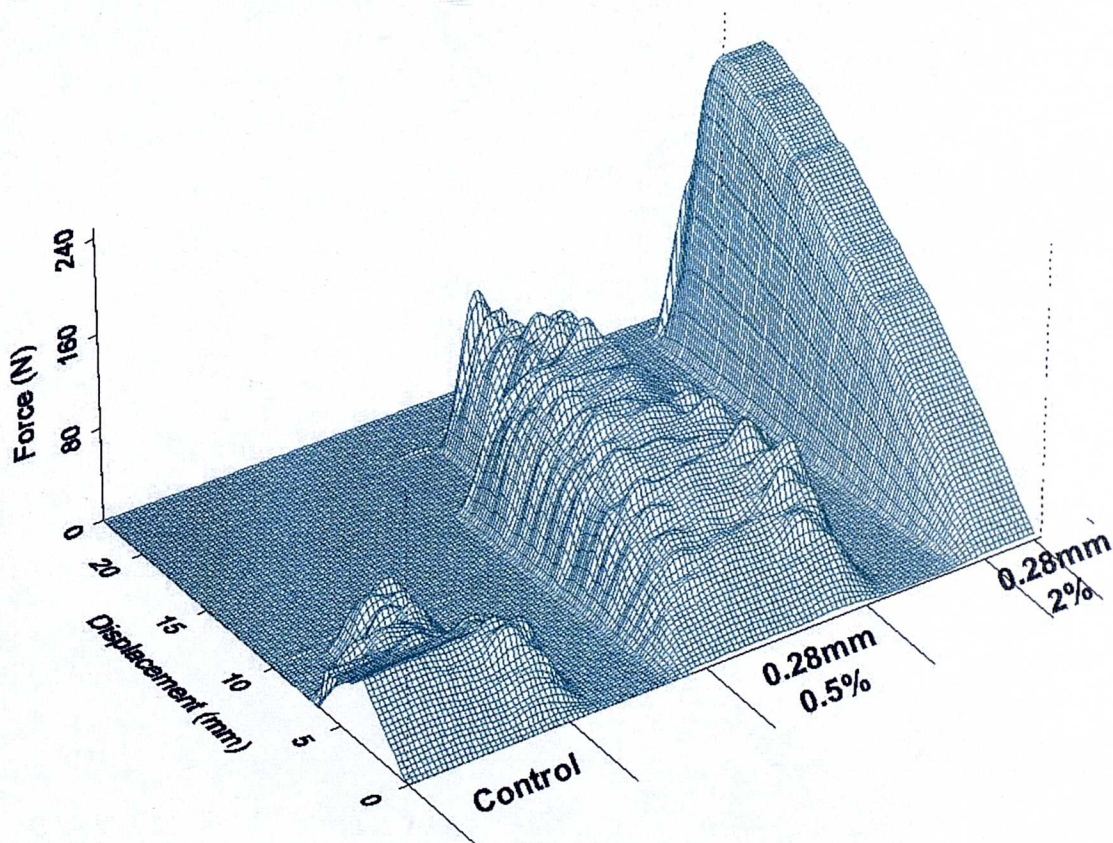


Figure 5-25: 3D plot of the force vs. displacement traces of the MMB specimens for $M_I/M_{II}=4/1$

5.4.2 MMB 50% - $M_I/M_{II}=1/1$

Like Figure 5-25, Figure 5-26 has been chosen to show the good reproducibility of the MMB 50% tests. The batch sizes are 3 samples for the control specimens, 4 for the 0.5%-0.28mm pinned specimens and 2 samples for 2%-0.28mm pinned specimens. The tests have been stopped when the crack had reached the centre loading roller for all MMB specimens. In the control specimens, a shorter opening displacement needed to propagate the crack to the roller indicates that the crack propagation is faster than when the ratio of mode I/mode II is 4/1.

The stick-slip behaviour of the 0.5%-0.28mm specimen is illustrated by the protrusions in the shape of the surface. The shape of the load history of the 2%-0.28mm is very similar to the force history of the corresponding specimens tested in either mode I or mixed mode bending with a mix ratio of 4/1.

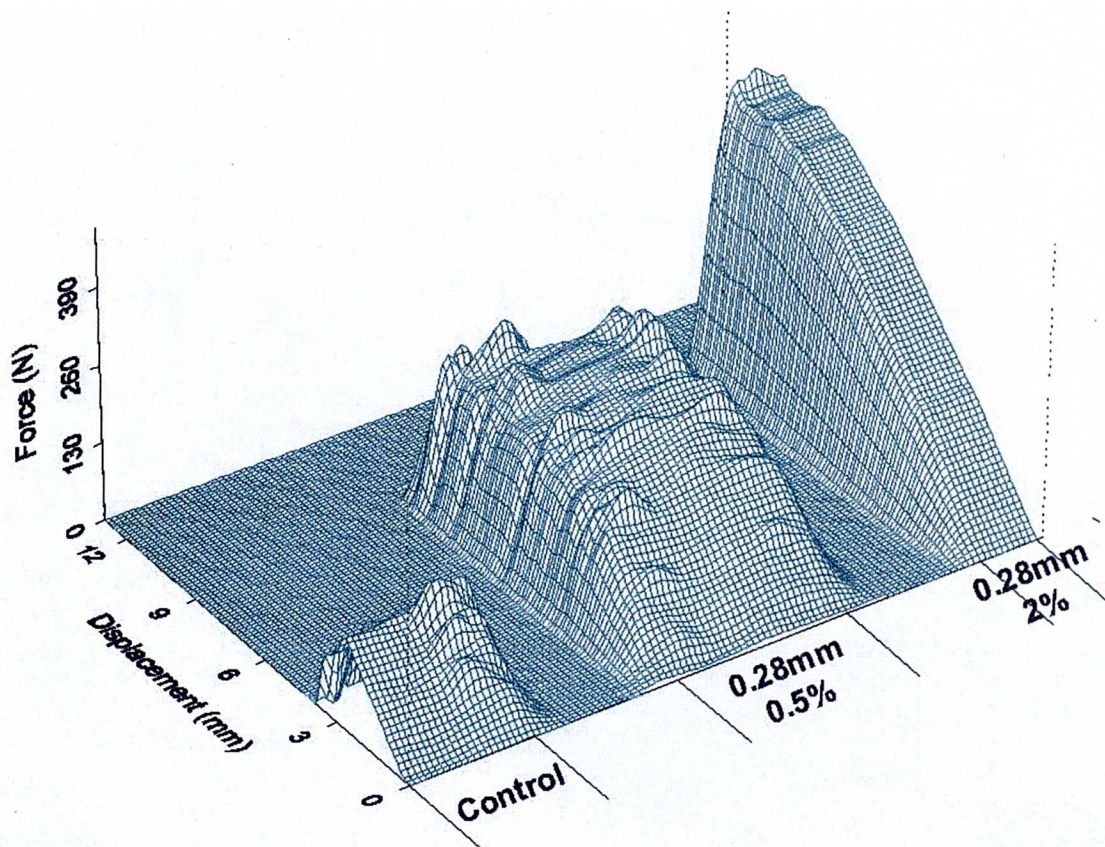


Figure 5-26: 3D plot of the force vs. displacement traces of the MMB specimens for $M_I/M_{II}=1/1$

5.4.3 MMB 80% - $M_I/M_{II}=1/4$

As the proportion of mode II loading becomes dominant, the behaviour of control specimens becomes unstable, as illustrated by the sudden drop in the load vs. displacement traces in Figure 5-27. 0.5%-0.28mm pinning conditions induce enough bridging actions to stabilise the crack growth. The shape of the surface does not present the protrusions characteristic of stick-slip behaviour.

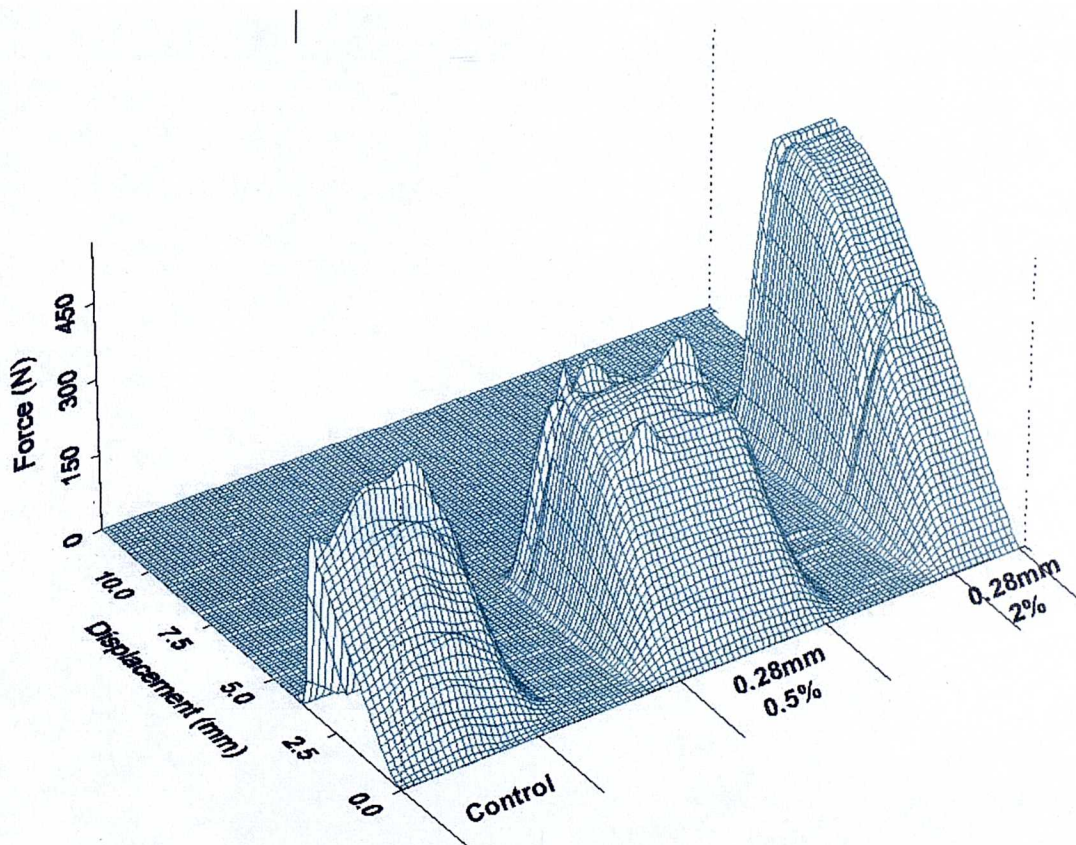


Figure 5-27: 3D plot of the force vs. displacement traces of the MMB specimens for $M_I/M_{II}=1/4$

5.5 Summary of the delamination behaviour

As summarised in Table 5-4, for loading conditions where mode I is dominant (pure mode I, MMB $M_I/M_{II} = 4/1$ and MMB $M_I/M_{II}=1/1$), the R-curves change from a flat R-

curve in unpinned samples to a shallowly rising R-curve in the 0.5%-0.28mm and 2%-0.51mm pinned samples, to a steeply rising R-curve in the 2%-0.28mm pinned samples. The effect of increasing areal density of pinning, for a fixed pin diameter $\phi = 0.28$ mm, is shown in Figure 5-28. This form of surface plot was chosen to give a graphical indication of the reproducibility/variability of the fracture behaviour. The batch sizes are 4 samples for both control and 2% pinned density samples and 5 samples for 0.5%-0.28mm pinned samples. The steeply rising R-curves of the high pin density samples ($D = 2\%$) are to be compared with the flat R-curves of the unpinned control samples. At initiation point the mode I (G_{IC}) delamination toughness are comparable ($\sim 250\text{J/m}^2$), whilst when the propagating crack encounters the discrete rows of Z-FibresTM, the G_{IP} increases to 5000J/m^2 compared to 300J/m^2 for the control samples. At the lower pin density (0.5%), the R-curves are considerably less steep, reaching a plateau value of 1200J/m^2 .

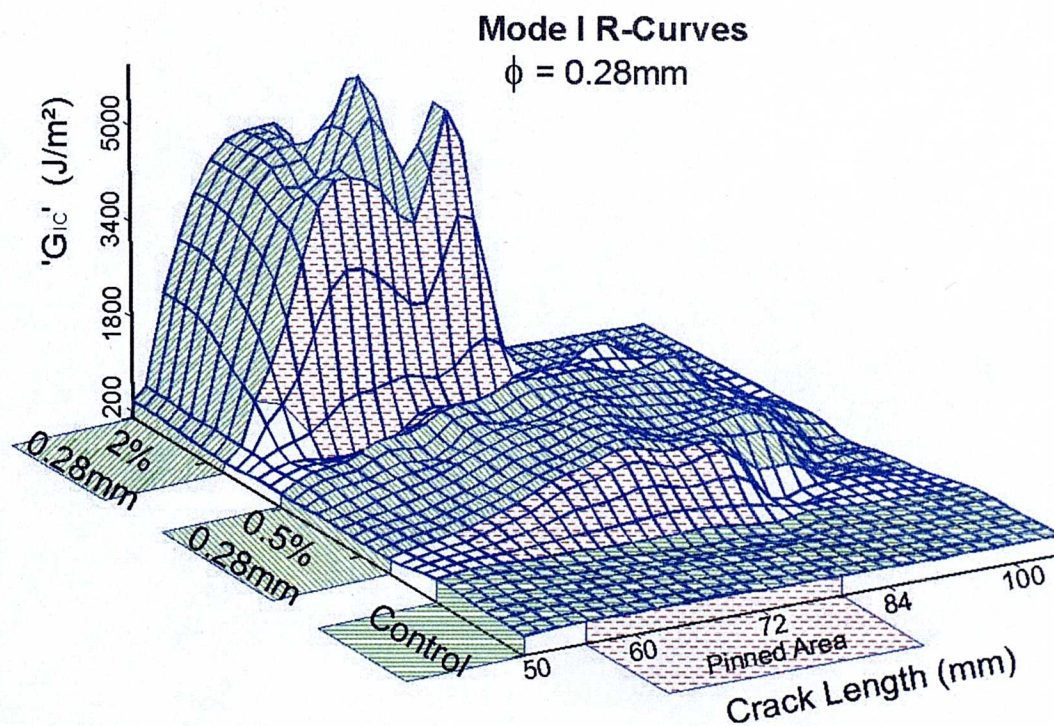


Figure 5-28: Effects of Pin Density on Mode I R-Curves

Some of the data presented in Figure 5-28 are re-plotted in Figure 5-29 in order to achieve a comparison of the effects of doubling the Z-Fibre™ diameter. The comparison clearly suggests a significant benefit from use of the smaller diameter Z-pins in this material.

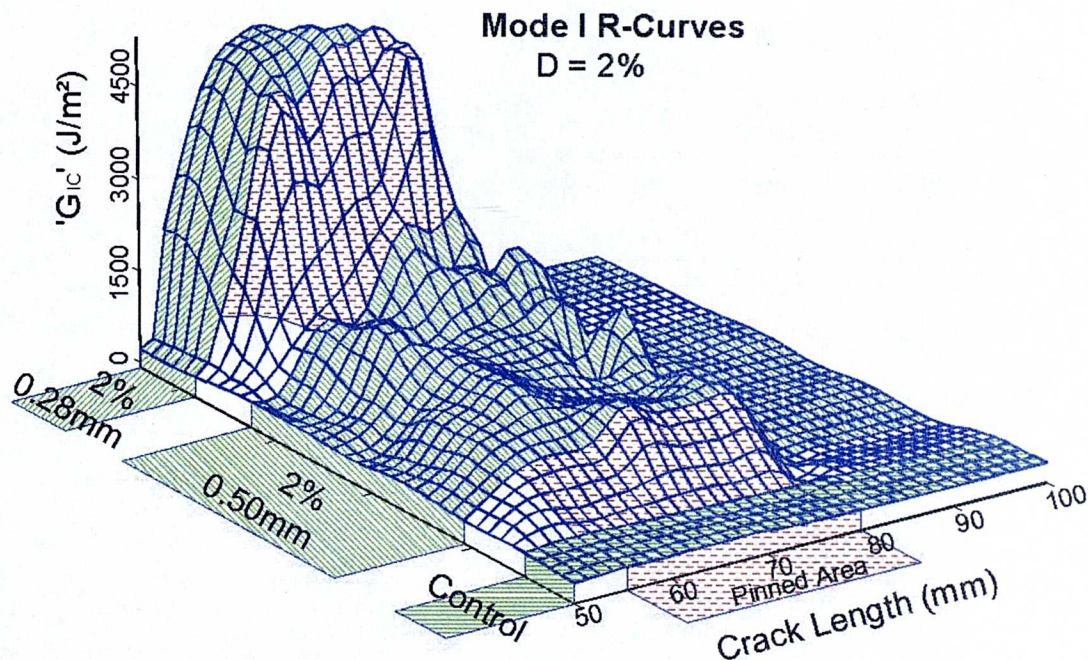


Figure 5-29: Effects of Pin Diameter on Mode I R-Curves (Density 2%)

It is apparent in mode I loading conditions that once the crack has passed the pinned region the delamination propagation resistance reverts to that corresponding to the control sample (Figure 5-28 and Figure 5-29).

Typical test results for mode I DCB, mixed mode I/II MMB and mode II 3pt-ENF are shown in Appendix B. Table 5-3 illustrates the evolution of the correction factors with pin diameter and pinning density in the case of DCB testing. It is noteworthy that the control specimens show no dispersion in the value of Δ or n . In contrast, the error in determining these factors for pinned laminate is fairly high. However, as the apparent stiffness of the beams are increased due to the through-the-thickness bridging actions, the crack length correction factor Δ increases with increasing pin density. Conversely, the compliance parameter n decreases with increasing pin density.

Table 5-3: Correction factors Δ and n (case of mode I DCB tests)

	Control	0.5%-0.28mm	2%-0.28mm	2%-0.51mm
$ \Delta $ (mm)	4.1 to 4.9	9 to 14	7.4 to 21.6	1.5 to 7
n	2.80 to 2.81	2.43 to 2.58	2.1 to 2.6	2.7 to 2.9

The values quoted in Table 5-4 as well as in Table 5-5 and in Table 5-6 are not absolute values. They are to be used only comparatively to each other. As discussed in Section 2.4 and in Section 5.1, the data analysis methods are not valid. It is only a means of normalising the results with variable beam parameters. Propagation values quoted here are mean maximum ' G_P ' values corresponding to a crack length of 80mm for DCB tests and 45mm for MMB and 3pt-ENF tests.

Table 5-4: Crack initiation and propagation resistance for mode I, Mixed Mode $M_I/M_{II}=4/1$ and Mixed Mode $M_I/M_{II}=1/1$ loading conditions

	' G_C ' (J/m ²)	Initiation	R-Curve trend	Propagation
Mode I	Control	265 (± 20)		290 (± 40)
	0.5% - 0.28mm	200 (± 15)		1300 (± 100)
	2% - 0.51mm	300 (± 25)		1800 (± 300)
	2% - 0.28mm	225 (± 25)		5000 (± 400)
Mixed Mode $M_I/M_{II}=4/1$	Control	255 (± 20)		350 (± 15)
	0.5% - 0.28mm	280 (± 40)		2700 (± 500)
	2% - 0.28mm	320		10000
Mixed Mode $M_I/M_{II}=1/1$	Control	260 (± 10)		410 (± 10)
	0.5% - 0.28mm	336 (± 10)		2600 (± 155)
	2% - 0.28mm	360		7500

As mode II becomes dominant ($M_I/M_{II} \leq 1/4$), the control specimens are unstable. In contrast, rising R-curves are observed in the 2% density pinned specimens. All intermediate behaviours are observed in the 0.5% density pinned specimens (Figure 5-30 and Figure 5-31). Table 5-5 and Table 5-6 summarise the behaviour of the crack propagation behaviour under these loading conditions.

Table 5-5: Crack initiation and propagation resistance for Mixed Mode $M_I/M_{II}=1/4$ loading conditions

G_C (J/m ²) $M_I/M_{II}=1/4$	Initiation	R-Curve trend	Propagation
Control	560 (± 40)		0
0.5% - 0.28mm	470 (± 30)		1600 (± 180)
2% - 0.28mm	600 (± 40)		5600 (± 300)

Table 5-6: Crack initiation and propagation resistance for Mode II loading conditions

G_{IIC} (J/m ²) Mode II	Initiation	R-Curve trend	Propagation
Control	700 (± 50)		0
0.5% - 0.28mm	1200 (± 300) (3 samples)		0
	890 (± 100) (2 samples)		1300 (± 200)
	840 (± 20) (2 samples)		2100 (± 200)
2% - 0.51mm	850 (± 40)		5600 (± 1800)
2% - 0.28mm	930 (± 80)		7500 (± 800)

Figure 5-30 shows the dramatic increase in the crack propagation resistance in the 2% pinned beams under Mode II loading. The batch sizes are 4 samples for both control and 2% pinned samples and 7 samples for the 0.5% 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.

There is no obvious effect of the pin diameter on the delamination crack propagation under mode II loading conditions, although on average, the use of the 0.28mm diameter pins lead to slightly higher toughness values than of the 0.51mm diameter pins.

The tests were stopped soon after the crack front had passed through the pinned region, because of the proximity of the 3pt-ENF loading roller. It is therefore not possible, from this set of data, to draw quantitative conclusions regarding the persistence of the reinforcement effect beyond the pinned area, but the absence of sudden load drop must be noted.

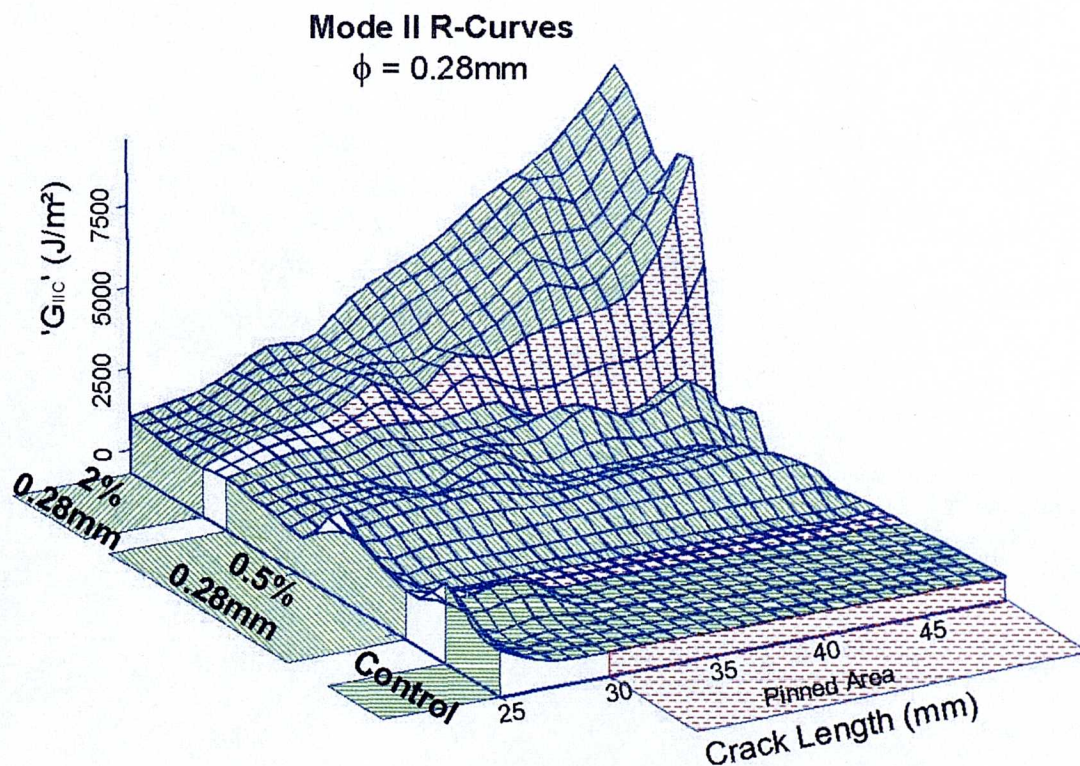


Figure 5-30: Effects of Pin Density on Mode II R-Curves (Pin Diameter 0.28mm)

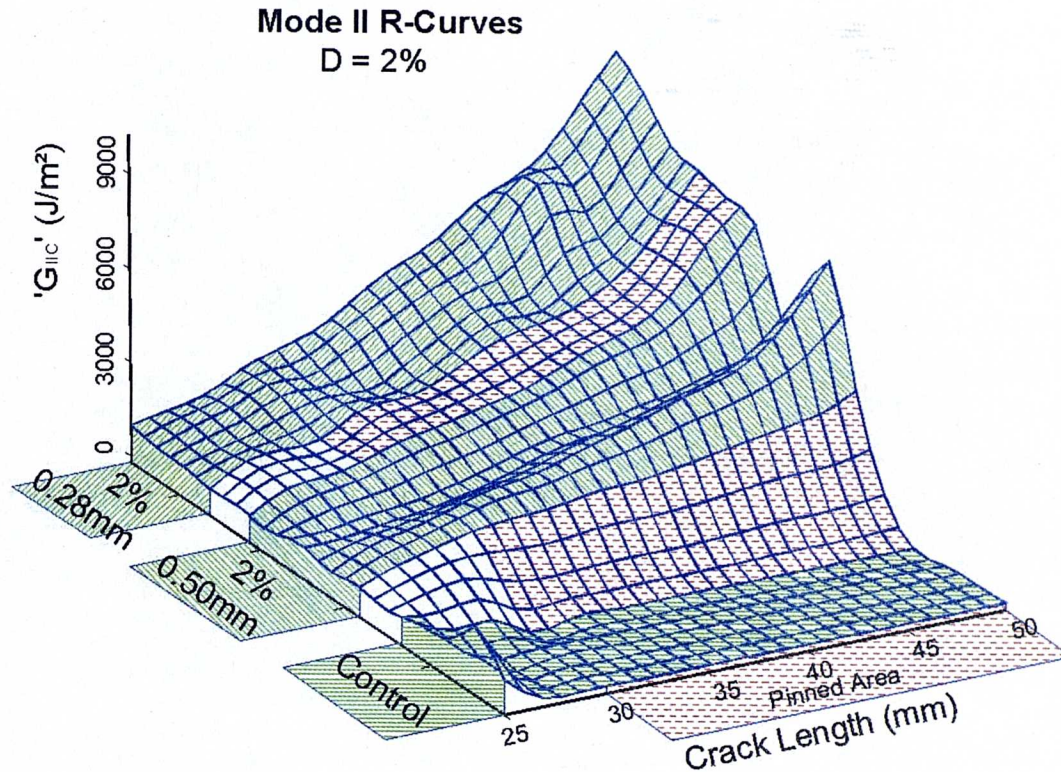


Figure 5-31: Effects of Pin Diameter on Mode II R-Curves (Density 2%)

5.6 Compression after impact results

Bitsianis (1999) carried out comparable delamination fracture tests on T300/914 composites. The present author was involved in all the experimental stages of this project. The experimental details can be found in (Cartié et al, 2000). T300/BMI Z-Fibres™ with diameters of 0.28mm and 0.51mm have been used as through-the-thickness reinforcement of 4 mm thick UD laminates, at 2% areal density. The pin configuration was similar to that shown in Figure 4-2 with a pin band width of pins of 50mm. Mode I DCB and mode II 3pt-ENF delamination tests were performed.

Figure 5-32 and Figure 5-33 show the R-curves of all the DCB and 3pt-ENF tests respectively. The batch numbers were in both cases three samples for the control specimens and five samples for the Z-pinned specimens.

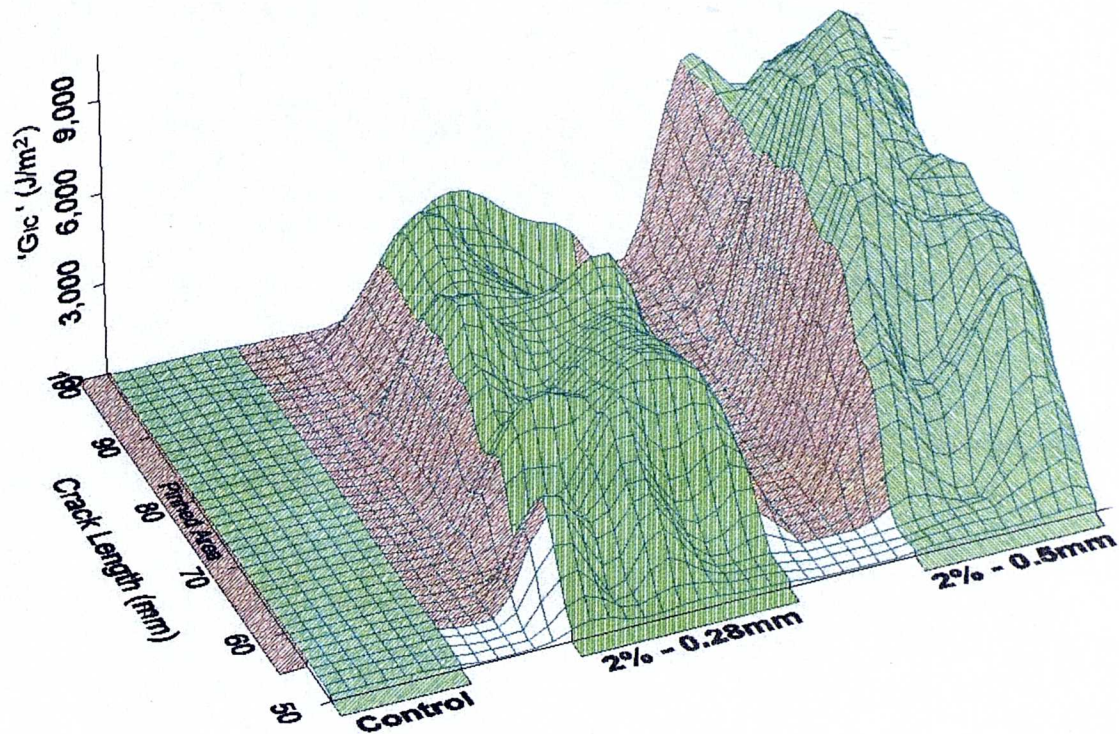


Figure 5-32: Mode I R-curves (T300/914)

(After Cartié et al, 2000)

Similarly to the results shown in Figure 5-29, the mode I delamination toughness is increased by using Z-Fibres™. However, the trend of the effects of pin diameter change is inverted in comparison to the results given in Section 5.5 . Here, the 2% - 0.28mm reached a ' G_{IC} ' plateau value of 3300 J/m², whereas the 2% - 0.51mm reached a plateau value of 6400 J/m².

As can be seen in Figure 5-33, the Z-Fibre™ diameter has relatively little effect on the ' G_{IIC} ' for this set of samples. Here, the ' G_{IIC} ' of the 2%-0.28mm samples increased to 3300 J/m² at a crack length of 45mm, whereas the 2% - 0.51mm specimens reached a value of 4300 J/m².

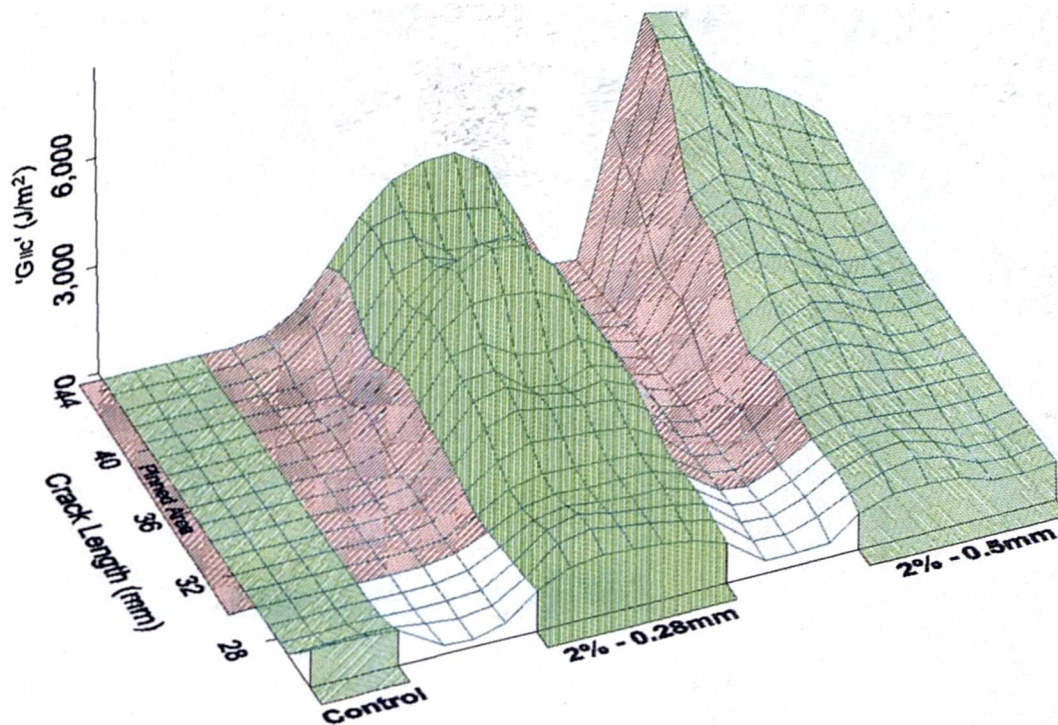


Figure 5-33: Mode II R-curves (T300/914)

(After Cartié et al, 2000)

Compression after impact (CAI) specimens were manufactured by (Bitsianis, 1999) using T300/914 and by (Negre, 2000) using IM7/8552, following the Boeing standard (Boeing, 1988). The stacking sequence was $[45/0/-45/90]_{4S}$. The pinning configuration is shown in Figure 5-34. A 25mm × 25mm square of Z-Fibres™ was inserted in the centre of the specimens. The samples were subjected to low velocity impact in the centre of the reinforced area. The force histories of the impacts were recorded for further analysis. The damage was assessed by C-scan. Therefore the term ‘delamination area’ means the projected delaminated area and not the calculated cumulative areas of the superimposed delaminated layers.

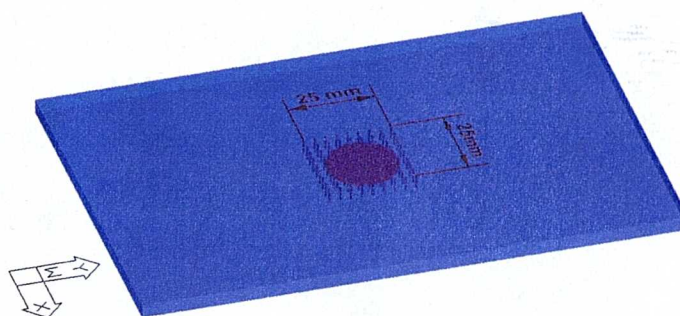


Figure 5-34: Pinning configuration in CAI specimens

The effects of the Z-Fibres™ on creation of the damage are shown in Figure 5-35. A reduction of the damage area of 30% can be achieved by using 2% - 0.28mm Z-pins in both T300/914 and IM7/8552 materials. The use of the larger pins at the same areal density (2% - 0.51mm) induces a reduction of the damage on T300/914 laminates between 10 and 20%. (This pinning configuration has not been tested on the IM7/8552 laminates.)

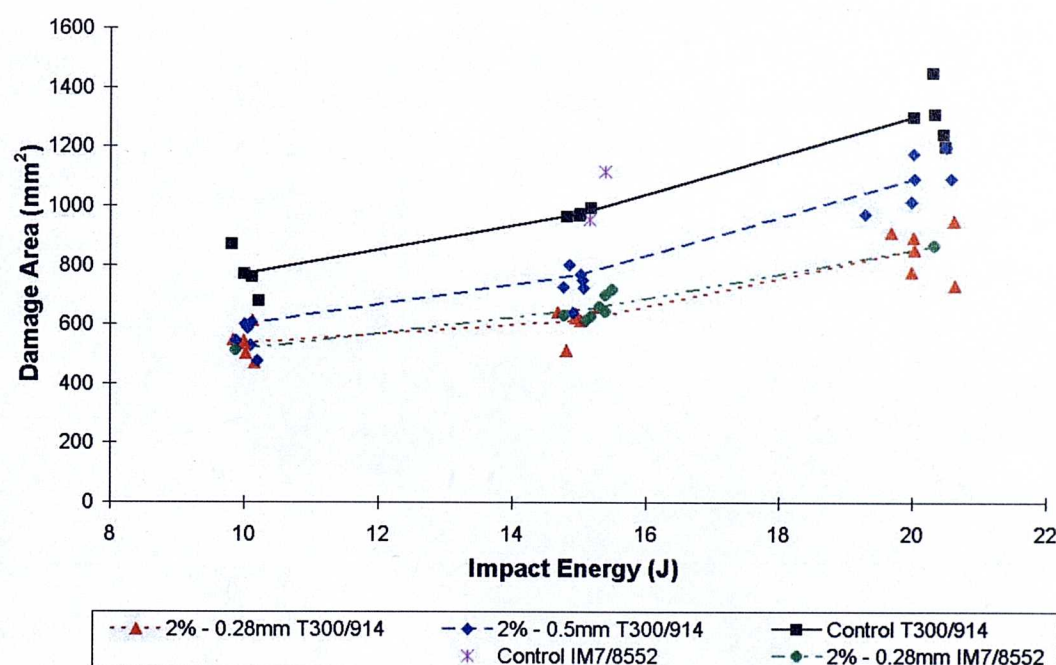


Figure 5-35: Impact performance of pinned laminates

Abrate (1991, 1994) and Schoeppnen & Abrate (2000) showed the existence of a damage of initiation threshold force on the load history traces of an impact event by

being the first load drop (See point A in Figure 5-36). This threshold force, P_c , is related to initial damage in the form matrix cracking, fibre breakage and mainly delamination. P_c is shown to be independent of the impact energy.

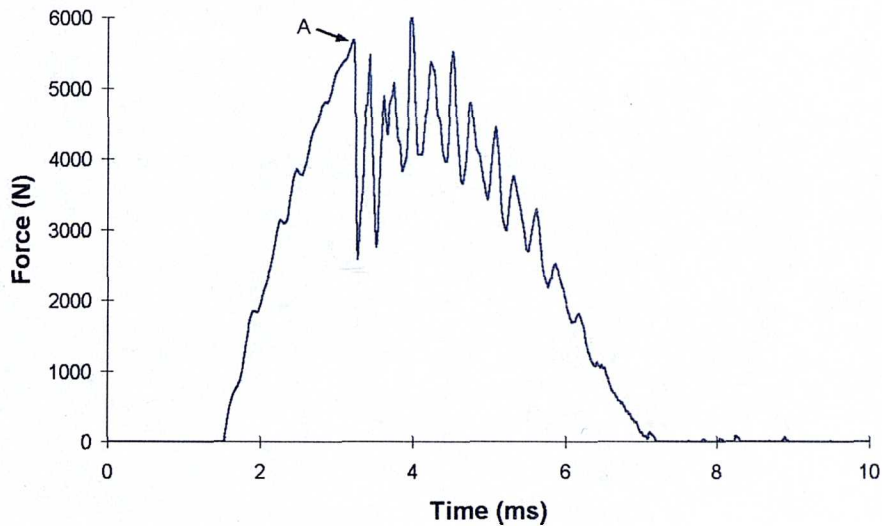


Figure 5-36: Force history of a 15J impact on T300/914

Table 5-7: Critical threshold force for impact damage initiation for pinned and control CAI samples

	Control	2% - 0.28mm	2% - 0.51mm
T300/914	5420 N ($\pm 6\%$)	4770 N ($\pm 8\%$)	4905 N ($\pm 5\%$)
IM7/8552	5620 N 2samples	4580 N ($\pm 3\%$)	Not tested

The values shown in Table 5-7 are average values of the threshold force for damage initiation for the specimens separated by their material and reinforcement without consideration of the impact energy. The variability of the threshold force is very low. It is clear that the presence of the Z-Fibres™ reduces the threshold force for damage initiation.

Figure 5-37 shows the compression after impact strength of the samples as a function of the delaminated area. This plot has been chosen to show that for a given damage, the Z-Fibres™ still improve the CAI strength. The Z-pins act twice during the compression

after impact test. They reduce the extent of the damage, for a given impact energy and they improve the CAI strength, for a given damage area.

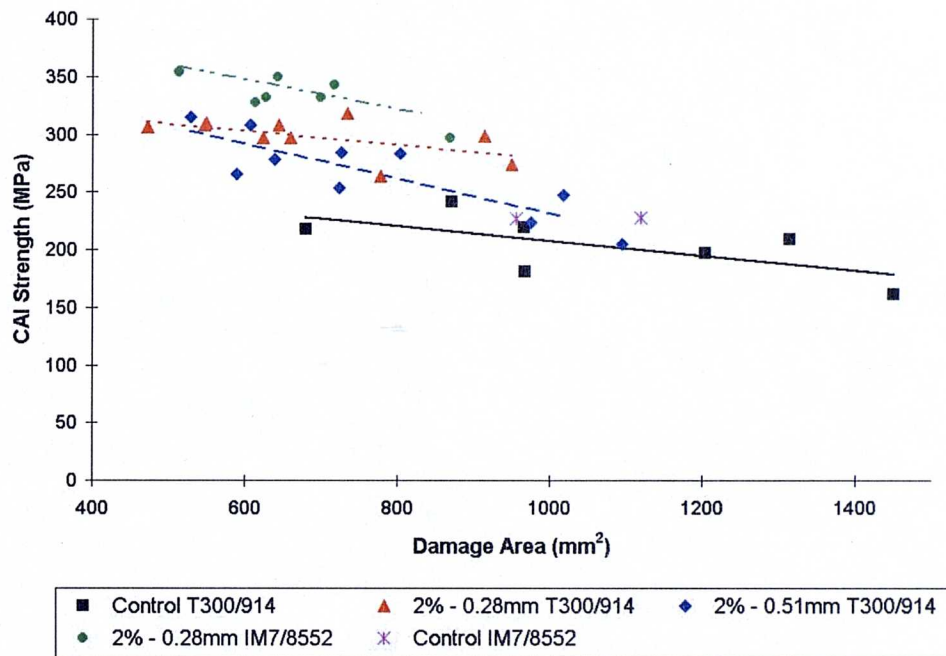


Figure 5-37: Compression after impact strength of pinned laminates

Chapter 6 Single Pin Testing

6.1 Introduction

As shown in Chapter 5, the use of Z-Fibres™ as through-the-thickness reinforcement proved to be very efficient for improving the crack propagation resistance under mode I, mode II and mixed mode I/II loading conditions. However, it is impossible to determine quantitatively the actions of each individual Z-Fibre™ from delamination testing as their loading conditions are not constant across the number of Z-pins acting. The objectives of this study, initiated during a three months secondment in the Engineering Department of the University of Cambridge, are to characterise and quantify the actions of a single Z-Fibre™ bridging an already existing crack, under mode I and mode II loading conditions.

6.2 Materials

For all the tests described below, titanium and/or T300/BMI Z-Fibres™ of a diameter of 0.51mm were used. For the first series, both titanium and T300/BMI Z-Fibres™ were used. Two 300mm×300mm panels were manufactured using IMS/924 pre-preg. Nominally 4mm thick, 32-ply UD laminates were laid up using the usual procedure. A **20µm thick PTFE release film** was located in the centre plane of the laminate in order to simulate a crack. Using the release film will avoid the need for introducing a crack, which, besides being difficult, may damage the Z-pins. The Z-Fibres™ were inserted one by one with a pin-to-pin spacing of about 30mm, using a hand held UAZ™ machine. The locations of the Z-pins were marked and individual specimens were cut out of the panel, with one single Z-Fibre™ in the centre.

In order to characterise visually the behaviour of the Z-Fibres™ under mode II loading conditions, polycarbonate was used as a ‘pseudo-laminate’. Polycarbonate also presents the advantage of being an isotropic material, which can potentially facilitate the analytical modelling of single Z-Fibre™ reinforcing a laminate. Two layers of 2mm thick polycarbonate sheet were used as a ‘delaminated’ laminate. It is impossible to insert the Z-Fibres™ in the polycarbonate using conventional methods (UAZ™), thus

the 'pseudo-laminate' was drilled using a titanium Z-pin as a drill bit on a fast electric drill. When using titanium Z-Fibre™ as through-the-thickness reinforcement, the drill bit/titanium pin was left inside in order not to break the bond between the pin and the polycarbonate created by the heat generated by the drilling process. The excess of pin length was removed using a bench grinder. For the study of the actions of T300/BMI Z-Fibres™ bridging the polycarbonate, the samples were drilled using the titanium pin as a drill bit, but the titanium pin was removed. A T300/BMI Z-pin was cut to length and inserted in the hole. This method gave good results for titanium pins. Unfortunately, the fit of the carbon/BMI Z-Fibres™ into polycarbonate was not reproducible, affecting the test results.

6.3 Pull-out testing

6.3.1 Theory on pull out testing

The extraction of the Z-Fibre™ from the cracked laminate can be described by two phases. Initially, the pin stretches elastically and gradually debonds from the laminate. When the pin is completely debonded, a frictional slip is activated: the pull-out.

It is believed that under mode I loading conditions, the action of a pin pulling out is controlled by friction. The objectives of the present tests were to determine the friction stress, τ_f , acting between the Z-Fibre™ and the laminate during pull-out. This exercise is similar to determining the interfacial shear stress during single fibre pull-out tests. Although a lot of work has been carried out on single fibre pull-out test from a resin matrix, it is still a debated topic (Gray, 84) (Chua & Piggott, 85-a) (Piggott, 99). The aim is not to interfere with the current debates, but to adapt existing theories to obtain the best possible information from the single pin pull-out tests.

During the elastic stretch and debonding, the load, F , applied to open the crack increases linearly to a maximum value, F_a , where the slip is initiated. An adhesion shear stress, τ_a , is defined by Equation 6-1.

$$\tau_a = \frac{F_a}{2\pi r L}$$

Equation 6-1

Here, $2r$ is the diameter of the Z-Fibre™ and L is the debonded length of the pins in the laminate (See Figure 6-1).

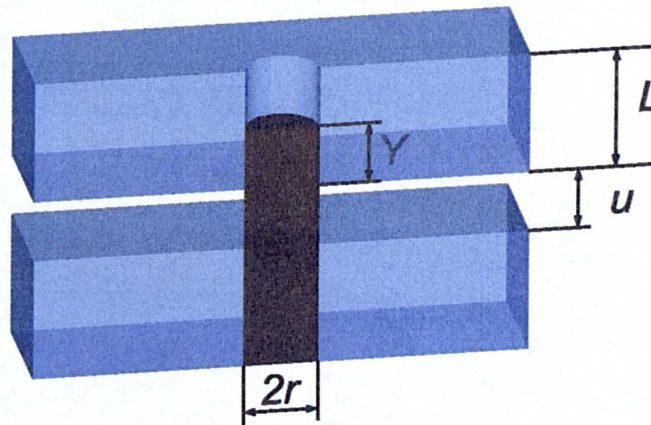


Figure 6-1: Schematic of a Z-Fibre™ pulling out of a laminate

Depending on the magnitude of the debonding force, F_a , compared to the friction-induced forces, the initiation of the frictional slip may be accompanied with a load drop if the debonding force is greater than the friction force (Gray, 1984). Figure 6-2 shows the possible behaviour types which can be observed.

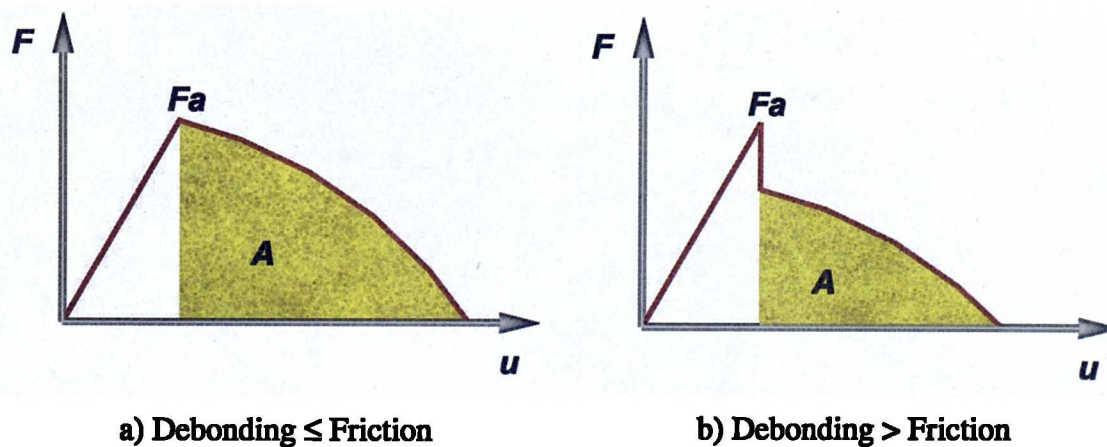


Figure 6-2: Typical pull-out curve

Once slip is initiated, the load decreases in a friction-controlled pull out behaviour. Assuming that the friction is uniformly distributed along the fibre, the force, F , required to pull the fibre out of the laminate is a function of the friction stress, τ_f , of the Z-Fibre™ diameter, $2r$, and of the length of the pin inside of the laminate, Y , (See Figure 6-1). F is given by Equation 6-2:

$$F = 2\pi.r.\tau_f.Y \quad \text{Equation 6-2}$$

In the case of fibres pulling out of a neat resin system, the slope is increasing. The maximum shear stress τ_i can be obtained from the steepest slope of the curve, ideally when $u=L$ (**Equation 6-3**) (Chua & Piggott, 85-b).

$$\tau_i = \frac{1}{2\pi r} \left(\frac{dF}{du} \right)_L \quad \text{Equation 6-3}$$

However, Z-Fibre™ pull-out experiments showed that the steepest part of the curve is not always when $u=L$. An average shear stress, τ_w , is calculated from the work, A , exerted during Z-pin pull-out with **Equation 6-4**. On the load-displacement curve, A is the area shaded in Figure 6-2.

$$\tau_w = \frac{2A}{\pi r L^2} \quad \text{Equation 6-4}$$

6.3.2 Design problem

The minimum bonding area between the specimen and the loading tab was assessed in order to prevent premature failure. The maximum bonding strength of cyanoacrylate glue was assumed at 1MPa from mode I DCB tests when Superglue was used to bond the loading blocks and the bond failed. At first it was believed that τ_f would be in the order of 50MPa, therefore, for a single pin of a diameter of 0.51mm bridging a 4mm thick laminate delaminated in its centre plane, the maximum load would go up to 160N.

The specimens dimensions were fixed to 12mm x 20mm in order to achieve a maximum bonding stress of 0.6MPa.

The specimens were glued between two parallel T shaped tabs. The arms of the tabs were directly gripped into the jaws of the testing machine. The tests were performed on a Zwick ZN10K digitally controlled screw driven testing machine. The grips of that machine are fixed rigidly to the testing frame in such a way that no displacement or rotation are allowed. Therefore, the two parallel sides of the tabs are forced to stay parallel during the whole test. The cross-head speed was set at 0.5mm/min.

6.3.3 Results

For the pull-out tests, the specimens were selected to have the Z-Fibres™ as perpendicular as possible from the X-Y plane. After each test, the pull-out length, L , was measured with an accuracy of $\pm 0.02\text{mm}$ using a travelling microscope. Visual observation showed that both titanium and T300/BMI Z-Fibres™ are pulling out from one side of the laminate only. In the case of T300/BMI Z-pins, the side pulling out is systematically the side showing the chamfered end.

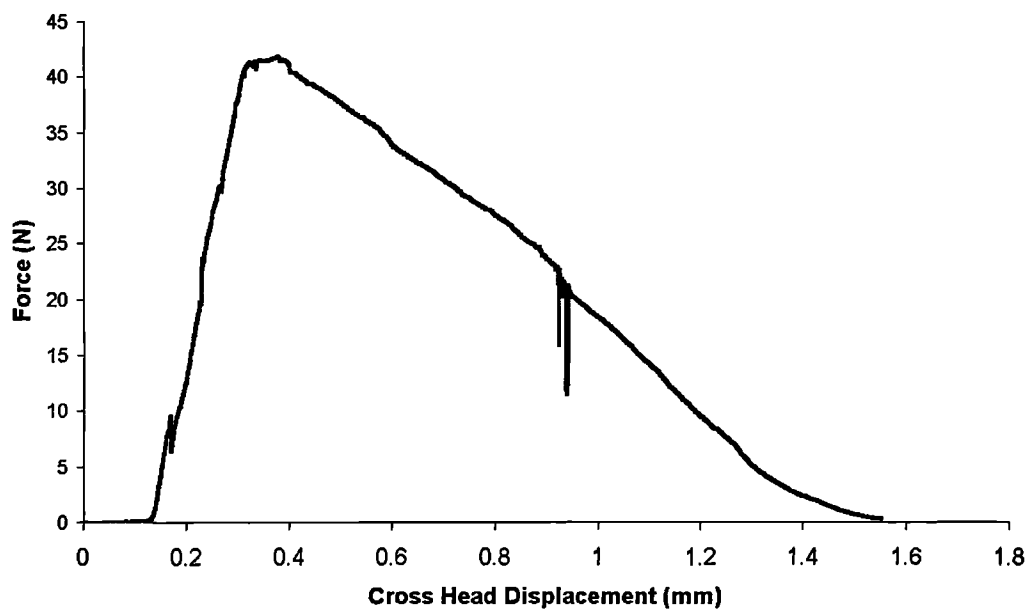


Figure 6-3: Typical pull-out curve of a T300/BMI Z-Fibre™ from a UD laminate

Figure 6-3 and Figure 6-4 show typical pull-out curves of T300/BMI and titanium Z-Fibres™ reinforcing an IMS/924 laminate. The elastic stretch of the composite Z-pin is consistently linear. For the titanium pin, the debonding is not always linear as shown by Figure 6-4.

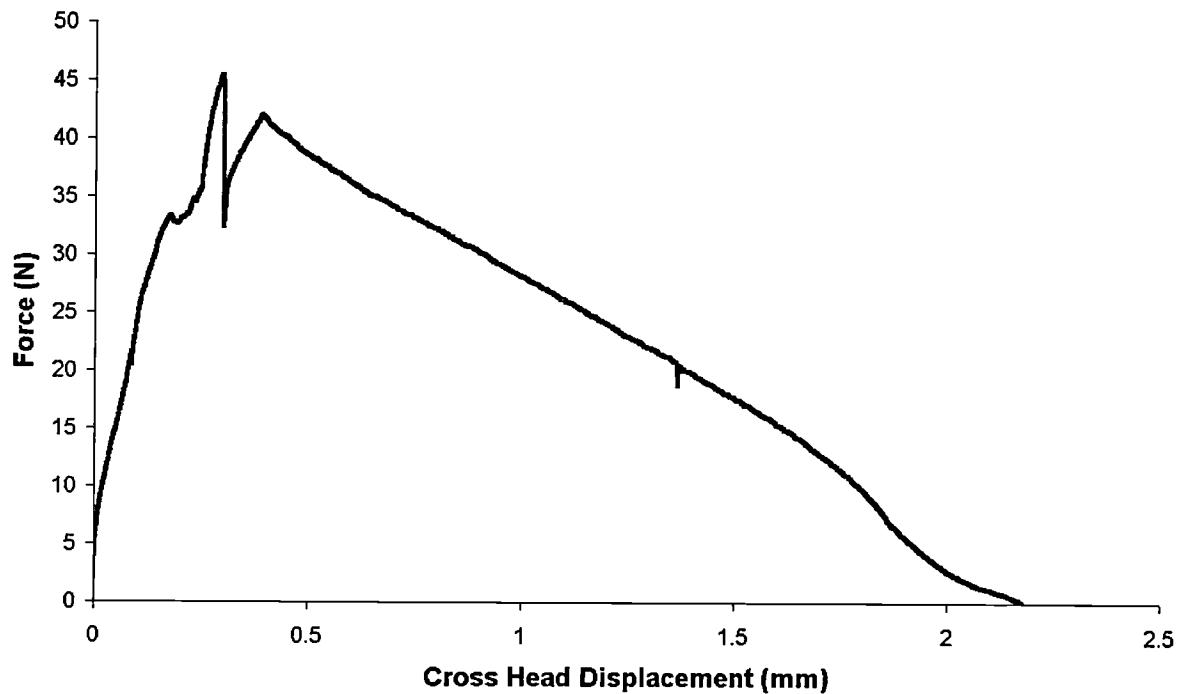


Figure 6-4: Typical pull-out curve of a titanium Z-Fibre™ from a UD laminate

The area, A , was calculated from the pull-out curve using a numerical trapeze integration method. Table 6-1 shows the average values of the adhesion shear stress, τ_a , and the friction shear stress, τ_w . The Z-Fibre™ material has little effect on the adhesion shear stress and the friction shear stress. The friction shear stress of the composite Z-Fibre™ is greater than the one of the titanium Z-pins.

Table 6-1: Pull-out results

	τ_w (MPa)	τ_a (MPa)
Titanium Z-Fibre™	15.4±4	7.4
T300/BMI Z-Fibre™	19.2±3	7.3

Due to manufacturing problems faced in the insertion of Z-Fibres™ in polycarbonate, no pull-out test of this kind was attempted.

6.4 Shear testing

Section 5-3 described the variety of behaviour types for a Z-Fibre™ subjected to mode II loading conditions. The pin may fail in shear at the crack plane. It may bend and pull out. Figure 5-13 also showed that in the 3pt-ENF test configuration, some opening displacement is visible. The objective of this study is to design a simple test to identify and characterise the deformation behaviour of a Z-Fibre™ depending of the applied loading conditions.

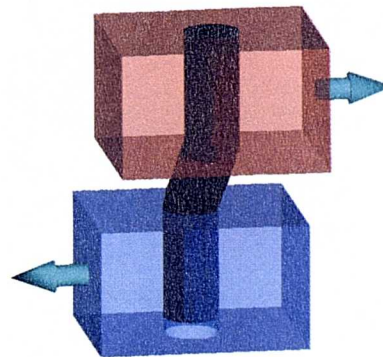


Figure 6-5: Z-Fibre™ deforming in shear loading conditions

6.4.1 Test design

A test rig was designed to apply shear loading conditions on a 10mm×10mm×4mm specimen containing a single Z-pin (Figure 6-6). The specimen is mounted in the loading blocks using cyanoacrylate glue. The load is applied via two forks mounted in the jaws of the testing machine, which are connected to the loading blocks via to stainless steel pins. In order to assure of the loading conditions, the loading pins have to

be located exactly on the crack plane. The thickness of the specimens is therefore critical. The specimens were sanded as required to be exactly 4mm thick. During the sanding procedure, care has been taken to insure that the crack plane stayed in the central plane of the laminate.

A U-shape piece was manufactured in order to constrain the opening displacement, if required. If the U-shape is not used, opening displacement is allowed (Figure 6-7). The U-shape piece can be glued to one of the loading blocks and a lubricant is used on the other loading block to limit the friction between the U-shape piece and the loading block. In this configuration, the opening displacement is constrained (Figure 6-8).

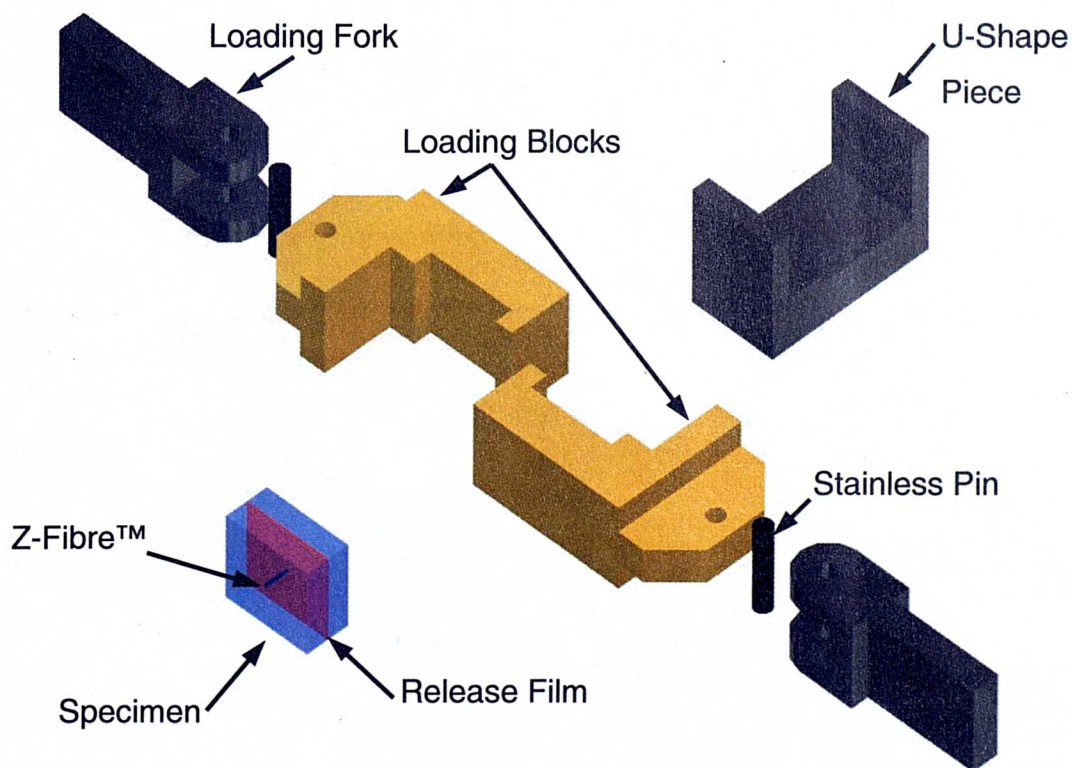


Figure 6-6: Exploded view of the shear pin test rig components

A special clamping tool was designed in order to cut and manufacture the specimens without damaging the Z-Fibre™.

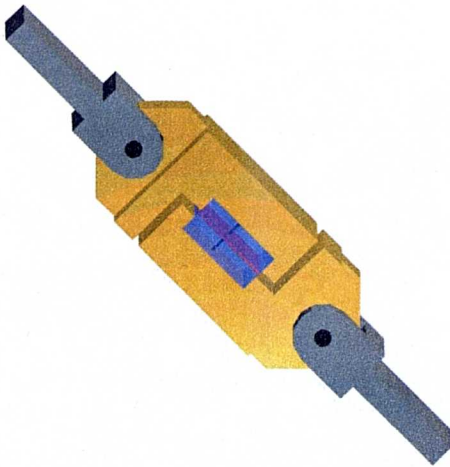


Figure 6-7: Shear test configuration with opening displacement allowed

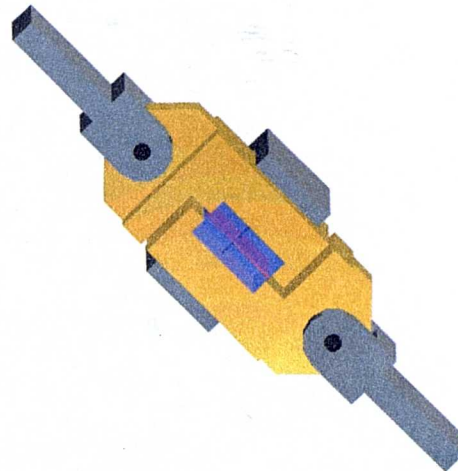


Figure 6-8: Shear test configuration with opening displacement constrained

As seen in section 3-5, it is difficult to make sure that the Z-Fibres™ are inserted normal to the plane of the laminate. The angle of the pin from the normal of the crack plane will have an influence on the behaviour of the bridging rod. Figure 6-9 illustrates the convention used here in relation to the loading conditions. If the angle from the normal to the pin goes with the loading conditions, as shown in Figure 6-9, the angle, ϕ , is positive and the pin direction will be called 'in the nap', as a reference to everyday experience of cat's fur (smoothing effect) (Cox, 2000). If the pin angle goes against the loading conditions, ϕ is negative and the pin is called 'against the nap' (hackling effect).

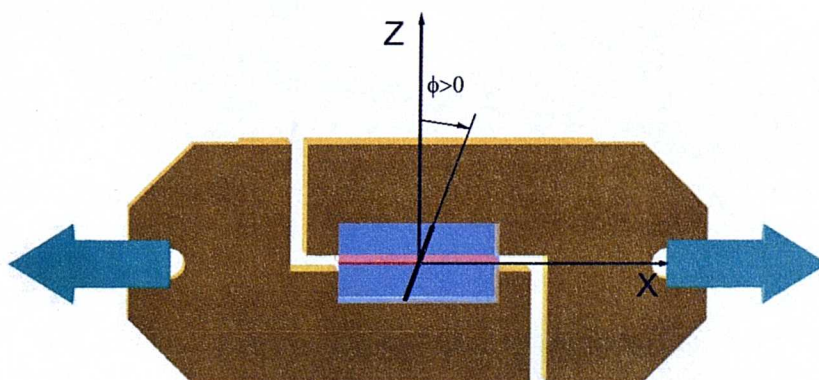


Figure 6-9: Coordinate system of the angle of the Z-Fibre™

6.4.2 Results

The results of the different shear tests are presented by material selections. Pictures characteristic of particular events, extracted from the videos of the tests, are shown in Appendix C, to illustrate the behaviour of the different samples.

6.4.2.1 Titanium Z-Fibre™ in polycarbonate laminate

Figure 6-10 shows force vs. displacement traces of shear tests of titanium pins reinforcing a polycarbonate 'laminate'. For these tests, the opening displacement was not constrained.

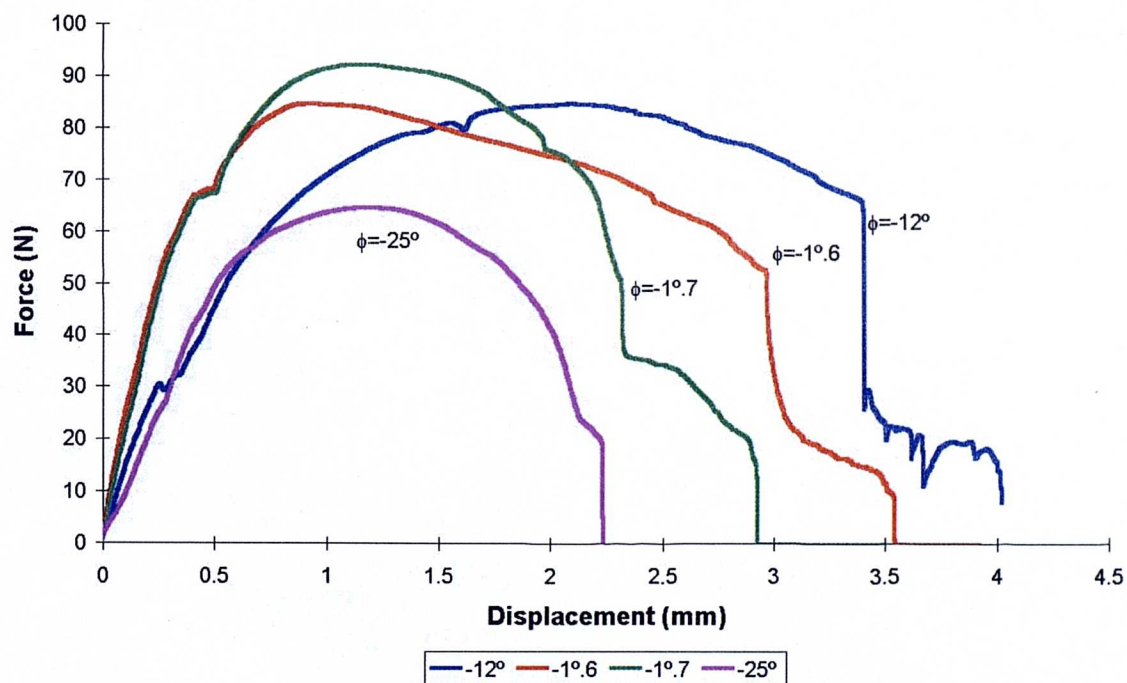


Figure 6-10: Force vs. displacement traces of shear tests of titanium Z-Fibre™ inserted in polycarbonate

The effect of the angle ϕ is clearly visible. The two specimens having a same angle ϕ close to 0° show a similar behaviour. After an initial bending of the pins, the mode I

opening displacement increases and the Z-Fibre™ pulls out. As the absolute value of the angle increases, the specimen apparent stiffness decreases. For the specimen where $\phi = -12^\circ$, visual observation shows that the Z-Fibre™ 'ploughs' through the polycarbonate matrix. The load carrying capability of the specimen is extended. For the specimen where $\phi = -25^\circ$, the initial 'ploughing' effect induces large deformations in the polycarbonate, which leads to extreme mode I opening and premature failure of the specimen.

Figure 6-11 below shows the deformation of the titanium Z-Fiber™ at the end of a test. During the test, the pin bends, 'ploughs' through the polycarbonate and pulls out. The shape of the hole left after the complete extraction of the Z-Fiber™ is highlighted on Figure 6-11.b. Figure 6-11.a shows the deformed titanium Z-Fiber™. It is also visible that the pin pulls out from both halves of the 'laminate'. No tensile fracture of titanium pins was observed.

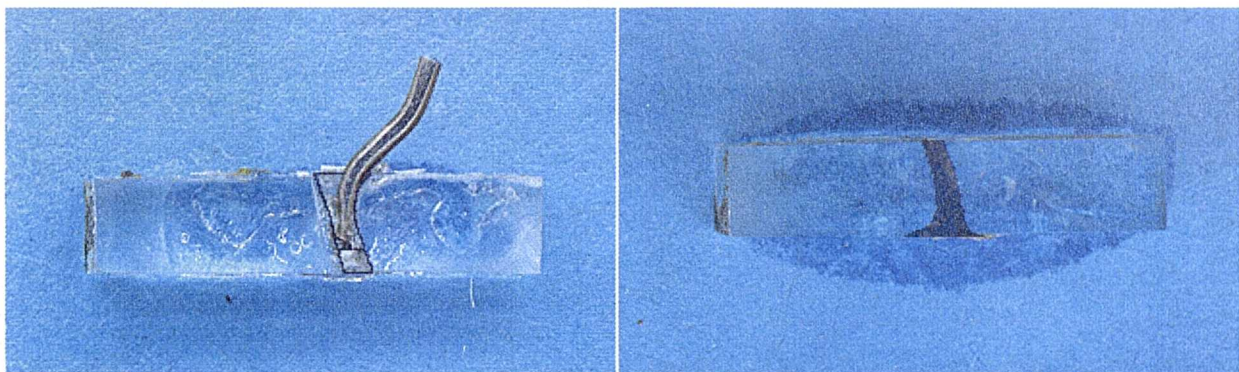


Figure 6-11 a and b: Post-mortem pictures of polycarbonate reinforced with a single titanium Z-Fiber™

6.4.2.2 Carbon/BMI Z-Fibre™ in polycarbonate laminate

Figure 6-13 shows the force-displacement traces of the shear test of carbon fibre/BMI Z-pins. Like in Section 6.4.2.1, the opening displacement is not constrained. As shown in section 6.2, the adhesion/friction of the T300/BMI pin with the polycarbonate was not reproducible. Figure 6-13 clearly shows that this adhesion/friction affects the test results. The friction of the Z-pin into the polycarbonate has been 'evaluated' qualitatively by trying to move the two halves of the specimens by hand. No friction means that the Z-Fiber™ could be pulled out of the matrix easily. High friction means that the two 'half laminates' very rigidly bonded. Medium friction means that the two polycarbonate parts could move but the pin could not be pulled out.

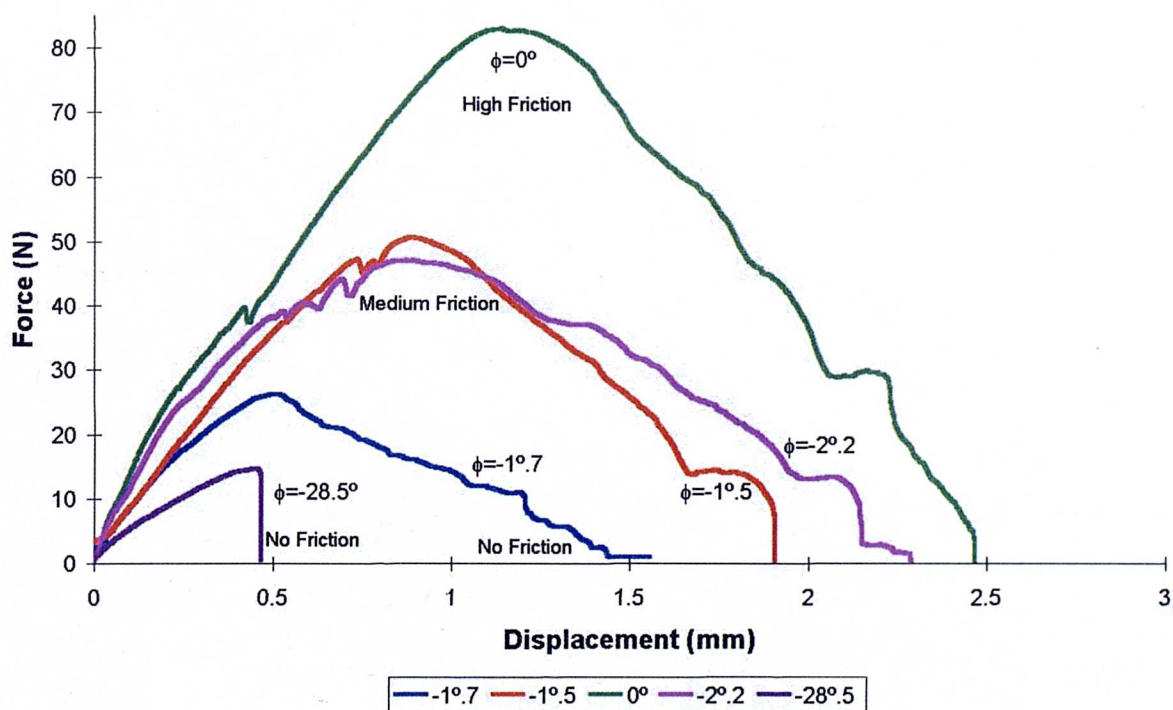


Figure 6-12: Force vs. displacement traces of shear tests of T300/BMI Z-Fibre™ in polycarbonate

For all the specimens but one, the Z-Fibre™ was inserted with an angle ϕ close to 0°. For these specimens, the force/displacement traces present a similar triangular shape.

The level of the force need to carry out the tests is related to the friction/adhesion of the Z-pin inside of the polycarbonate. When the friction is high, the maximum force reaches 83N, as when the Z-FiberTM moves freely inside of the matrix, the maximum load is 26N. On the fifth specimen with an angle ϕ of 28.5°, the excessive angle leads to a premature failure of the pin.

From the beginning of the test, opening displacement is apparent. The Z-FibreTM has enough space to pull out. Due to more shear displacement, the Z-pin starts to split near the crack plane. Figure 6-13, on the right hand side, is a picture extracted from the video of a shear test of a carbon Z-FiberTM. The pin splitting is visible (indicated by the arrow). Towards the end of the tests, the opening displacement increases and the broken pin pulls out completely.

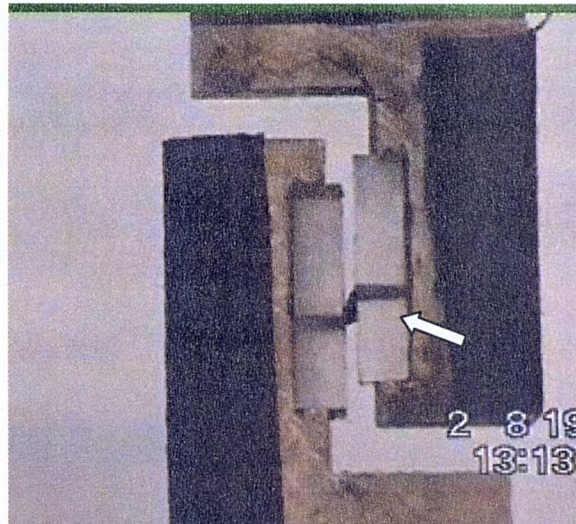


Figure 6-13: Shear test of a T300/BMI Z-FibreTM

Figure 6-14 and Figure 6-15 are SEM fractographs of the broken carbon fibre/BMI Z-pins. Large deformation and splitting damage of the Z-FibreTM are visible. It is also noticeable that the Z-FibreTM is coated by the cyanoacrylate glue used to fix the specimen in the loading blocks.

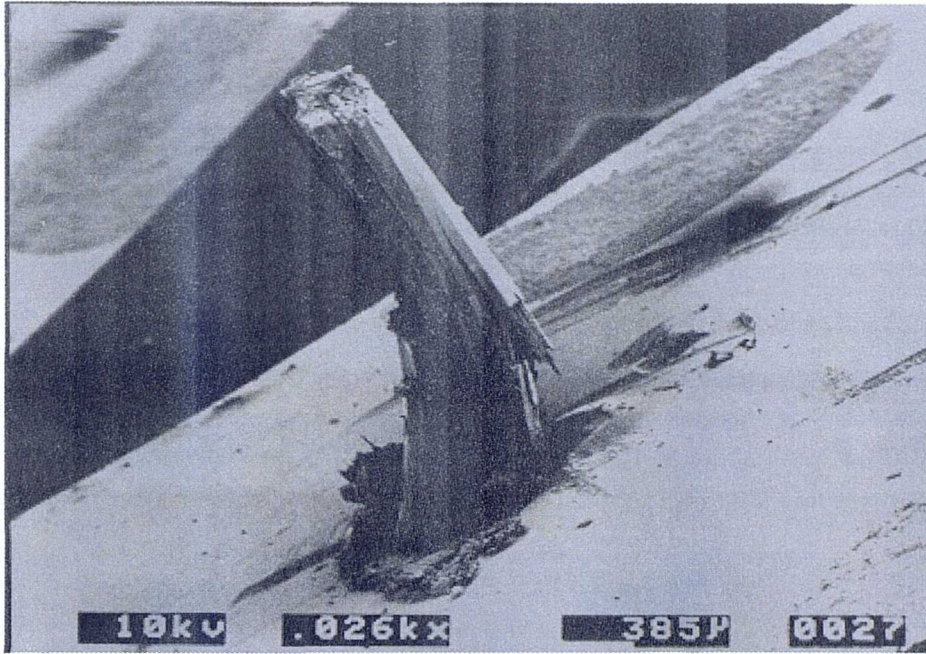


Figure 6-14: Post mortem SEM of a T300/BMI Z-Fibre™ in polycarbonate

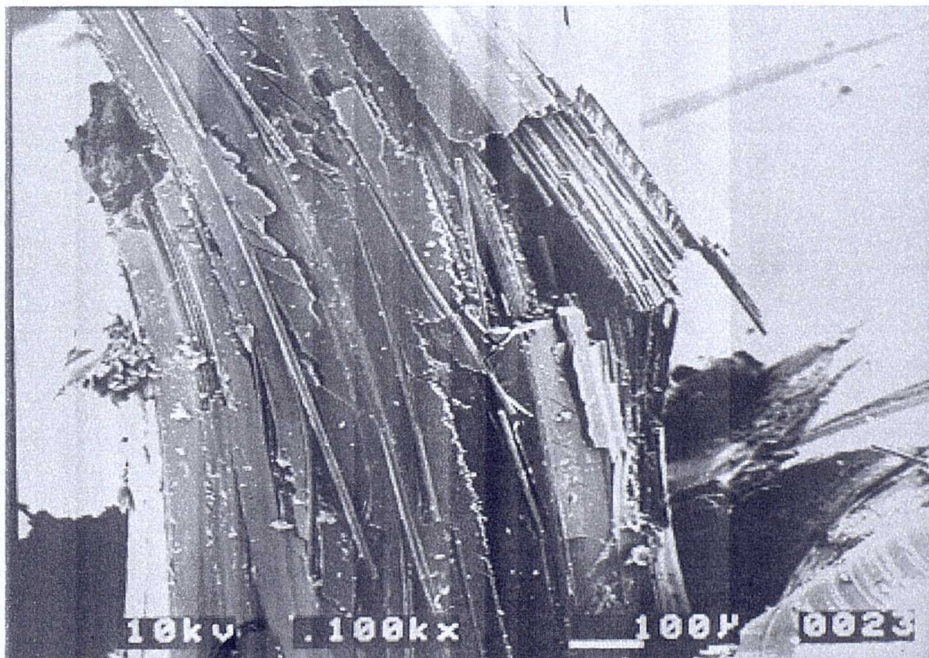


Figure 6-15: As above, higher magnification

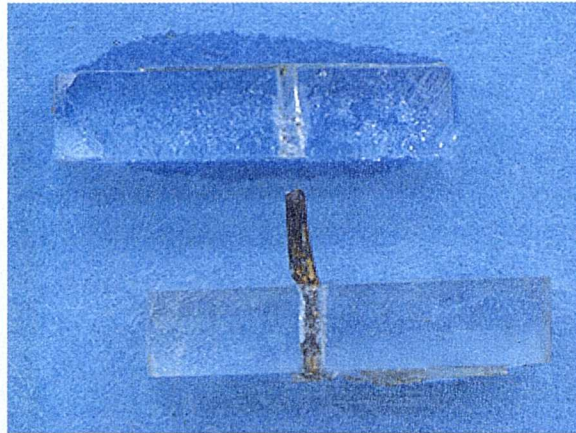


Figure 6-16: Post-mortem photograph of a polycarbonate specimen pinned by a single T300/BMI Z-pin

Figure 6-16 is a post mortem photograph of the T300/BMI-polycarbonate specimen. Damage of the Z-Fibre™ near the crack plane is visible. There is no major deformation of the hole near the pin.

6.4.2.3 Titanium Z-Fibre™ in IMS/924 laminate

Opening displacement allowed

Figure 6-17 shows the effects of the sign of the angle ϕ on the behaviour of the specimens. When the Z-Fibre™ is in the nap ($\phi > 0$), the Z-pin bends under shear displacement, opens the crack, then, pulls out of the laminate (see Figure 6-18). Due to this angle the traction action of the Z-Fibre™ has a component in the pull out direction. The pullout is then easier. When the Z-pin is against the nap ($\phi < 0$), the Z-pins bends. However, the bending angle is greater than 90° and the radius of the pin deformation is small because of the higher resistance on the carbon/epoxy laminate (see Figure 6-19). Unlike titanium in polycarbonate, due to this small bending radius and high resistance to 'ploughing' of the IMS/924 laminate, the Z-pin acts like a fishing hook, locked in a composite skin. The pull out stops and the resistance of the carbon/epoxy composite is such that the titanium Z-Fibre™ fails in tension.

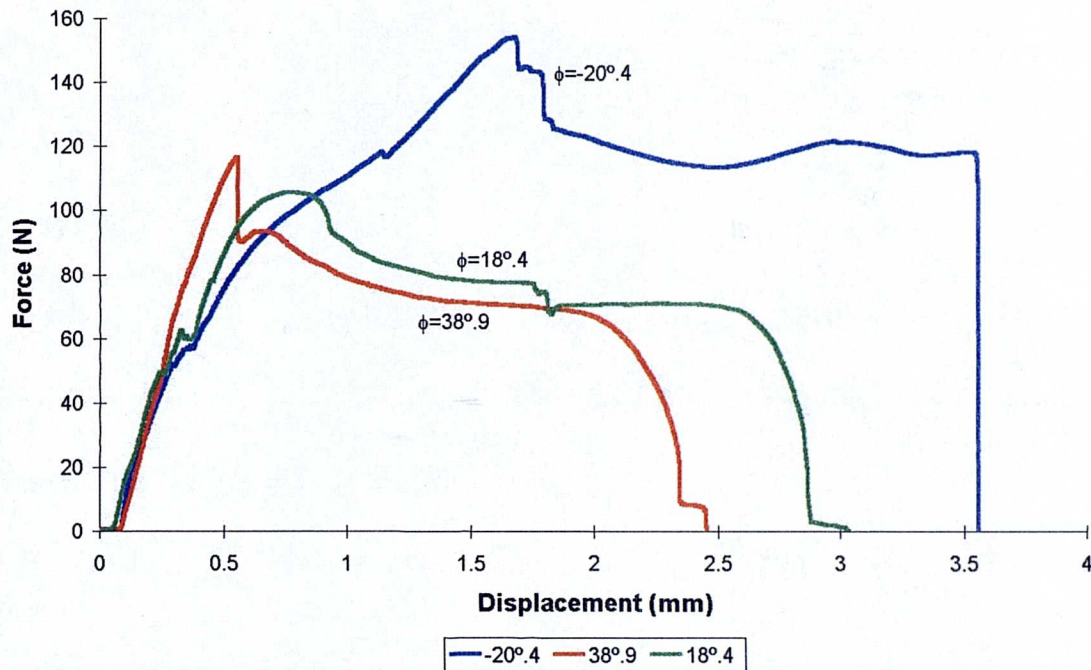


Figure 6-17: Force vs. displacement traces of shear tests of titanium Z-Fibre™ in IMS/924 laminate

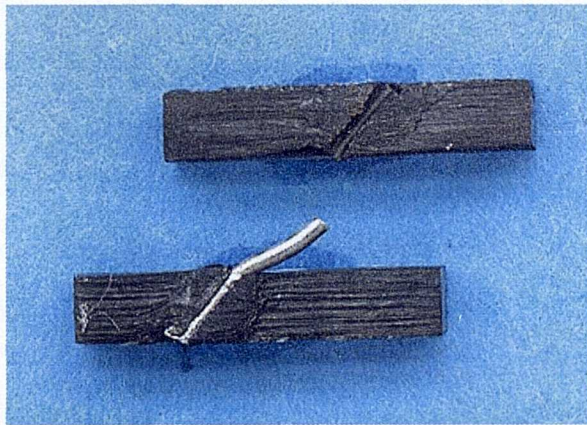


Figure 6-18: Post-mortem photo of a titanium Z-Fibre™ in shear, $\phi > 0^\circ$: pullout

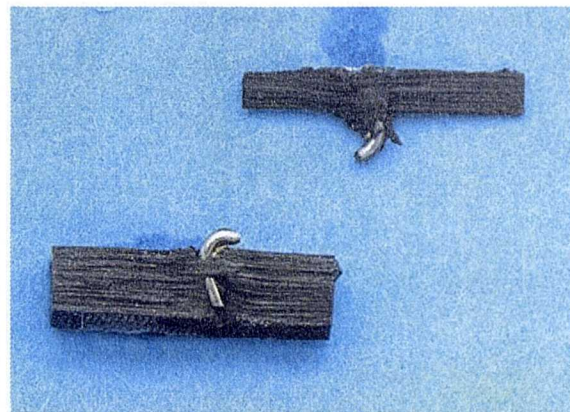


Figure 6-19: Post-mortem photo of a titanium Z-Fibre™ in shear, $\phi < 0^\circ$: tensile failure

Opening displacement constrained

Similar behaviour to that shown in Figure 6-18 is observed when ϕ is positive. The corresponding load-displacement traces are shown in Figure 6-20. After debonding, the pins pull out, the shape of the corresponding part of the load curve is then relatively flat. The constraint on the opening displacement induces an increase of the load level reached during the tests. Figure 6-21 shows that the pin bends and pulls out in a similar way as the one shown with opening displacement. The main difference is that the pin is bent closer to the surface of the laminate. On one particular case ($\phi=28^\circ$), the titanium Z-Fibre™ pulled out from both sides of the laminate (Figure 6-22), which may explain the longer pull out curve of this specimen.

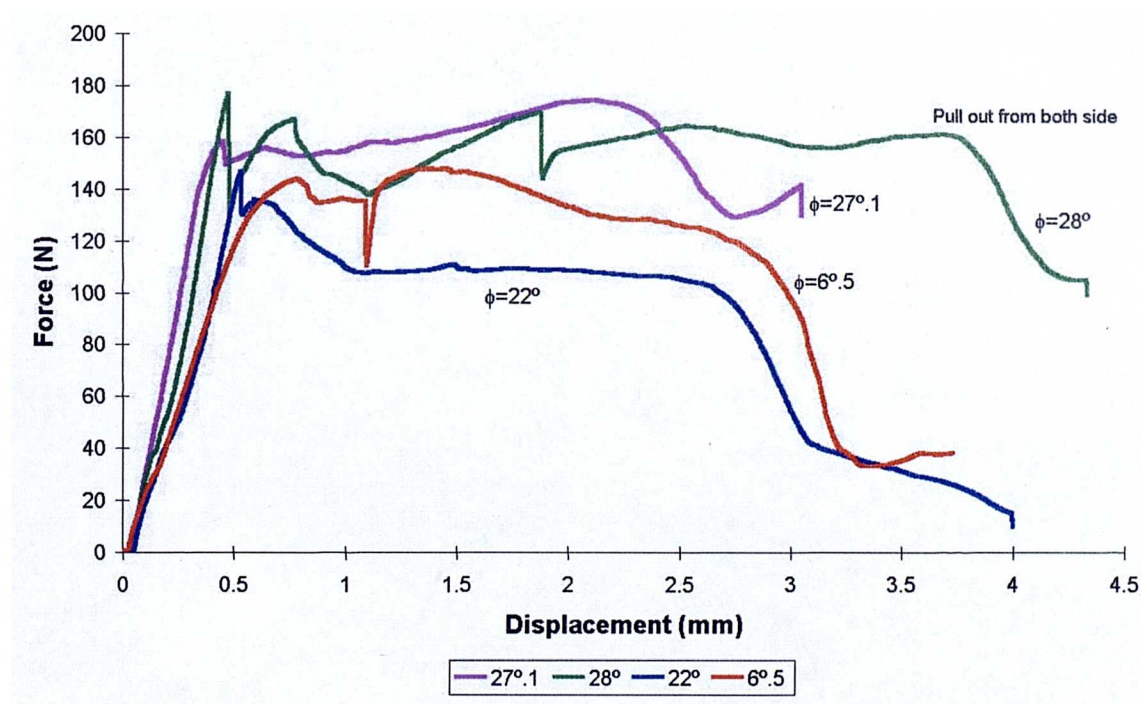


Figure 6-20: Force-displacement traces of titanium Z-Fibres™ reinforcing IMS/924 laminates (Pins in the nap)



Figure 6-21: Titanium Z-Fibre in shear in the nap (No opening displacement)

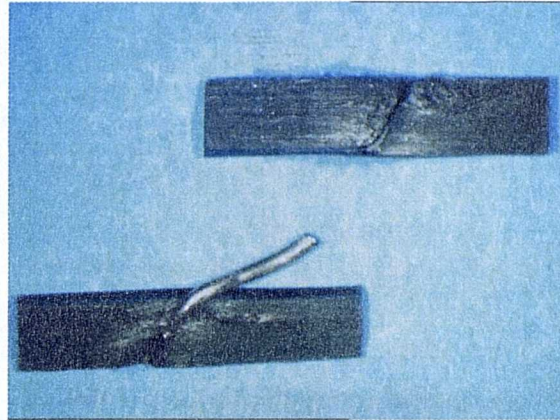


Figure 6-22: Titanium Z-Fibre™ is shear, pull out from both side of the cracked laminate

When the pins are against the nap (Figure 6-23), the 'hooking' effect of the pin in the laminate leads to catastrophic failure of the Z-Fibres™ in shear on the crack plane (Figure 6-24). The load-displacement traces show curves with two distinctly different slopes.

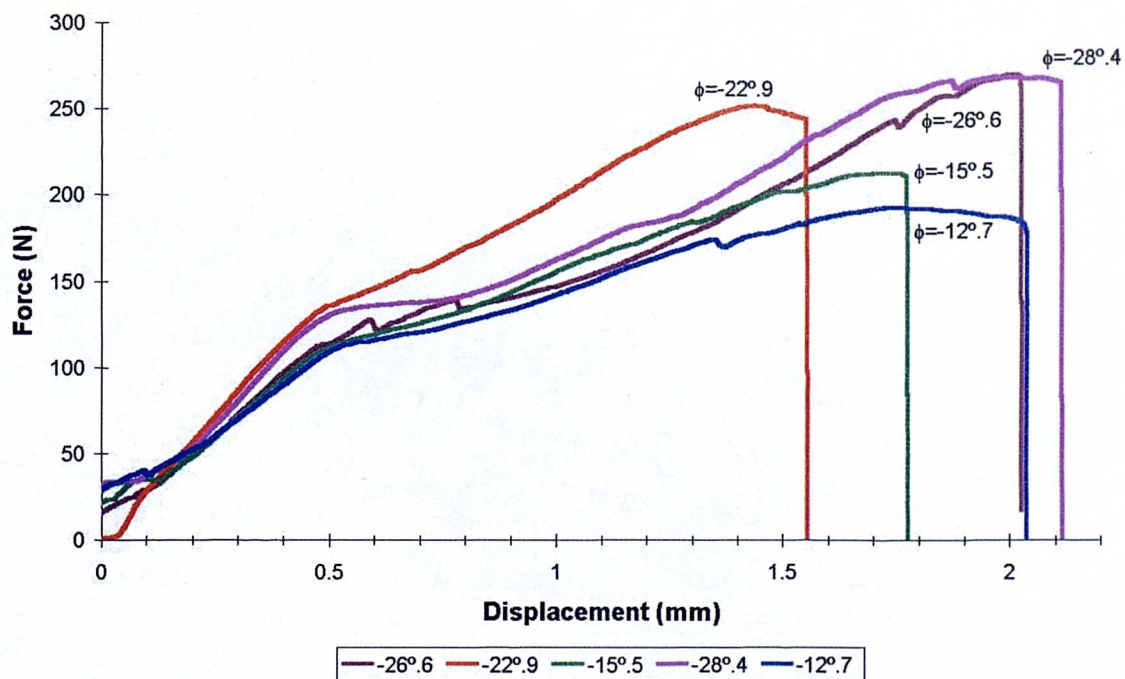


Figure 6-23: Force-displacement traces of titanium Z-Fibres™ reinforcing IMS/924 laminates (Pins against the nap)

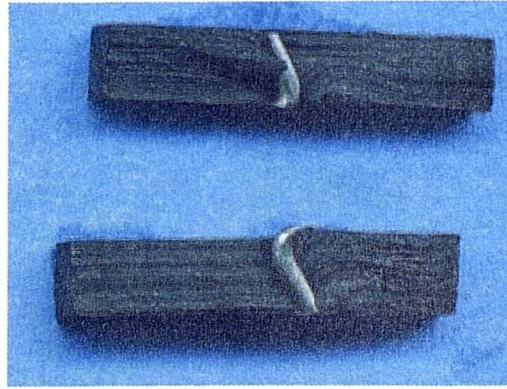


Figure 6-24: Titanium Z-Fibre™ against the nap (No opening displacement)

6.4.2.4 Carbon/BMI Z-Fibre™ in IMS/924 laminate

Opening displacement allowed

Figure 6-25 shows the loading curves of the composite Z-Fibres™ inserted in the IMS/924 laminate tested in shear. For three specimens, the loading is against the nap, for the other one the loading is with the nap, but the exact value of ϕ is not known. Like in the case of titanium pins, the sign of the angle ϕ determines the behaviour of the specimens. If ϕ is positive (pins is the nap), after loading and debonding, large mode I opening displacement occurs and the Z-Fibre™ pulls out without shear failure (see Figure 6-26).

If ϕ is negative, a greater load is reached, but this load leads to a catastrophic failure of the Z-Fibre™. The pin breaks in shear on the crack plane. No opening displacement is visible.

Figure 6-27 below shows a post mortem section through the pin plane of such a specimen. It is also noticeable that the insertion of 0.51mm diameter Z-Fibre™ introduces a waviness of the laminate fibres in the Z-X plane.

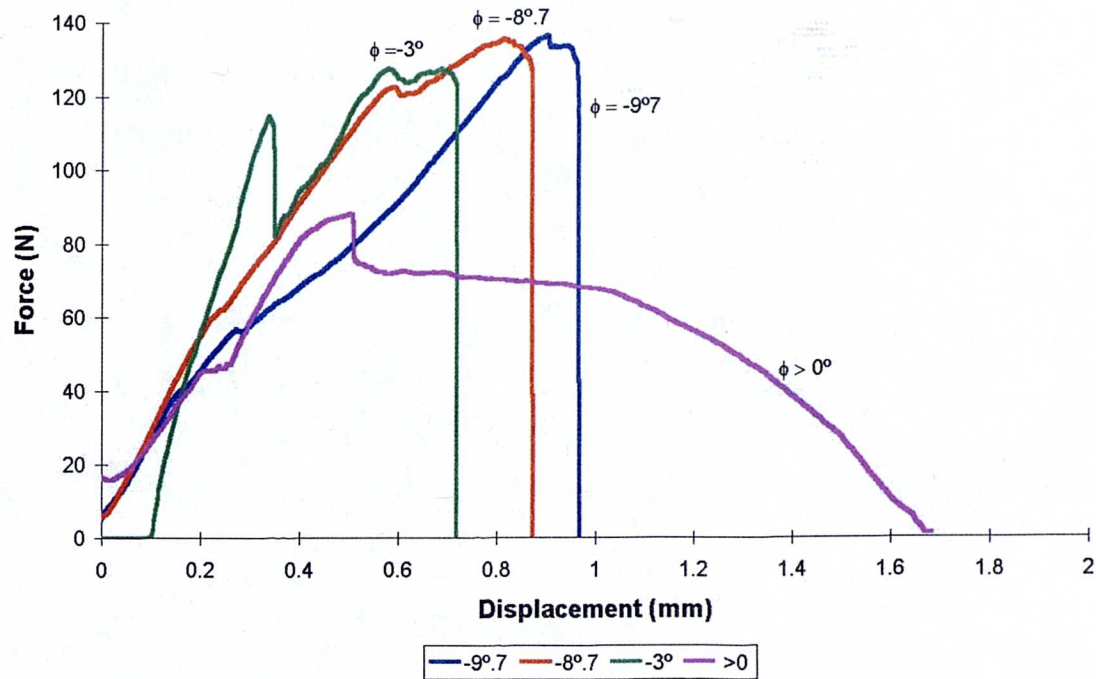


Figure 6-25: Force vs. displacement trace of shear tests of T300/BMI Z-pins in IMS/924 UD laminate

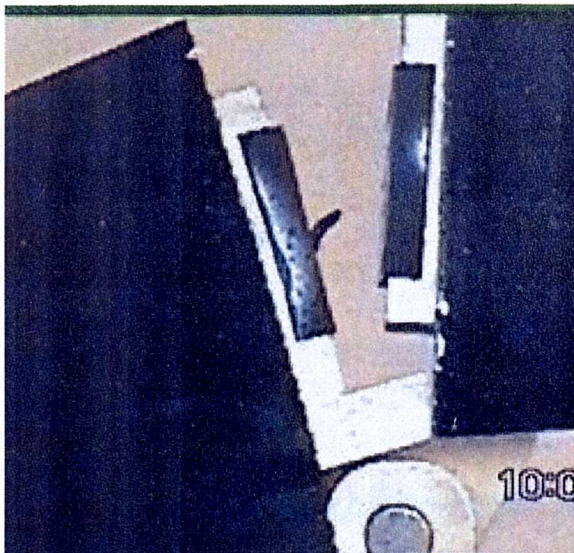


Figure 6-26: Carbon Z-Fibre™ pulled out after a shear test ($\phi > 0$)

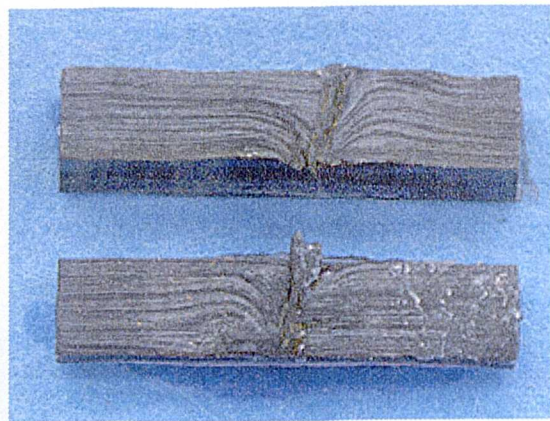


Figure 6-27: Post-mortem photo of a IMS/924 laminate reinforced with T300/BMI Z-pin ($\phi = -8^\circ$)

Opening displacement constrained

No specimen has been tested with ϕ sufficiently negative to investigate this domain of behaviour. When the pins are in the nap, as no opening displacement is possible, the pins tend to fail in shear. The loads reached are slightly greater than in the case with opening displacement. The behaviour of the specimens seems to be unstable.

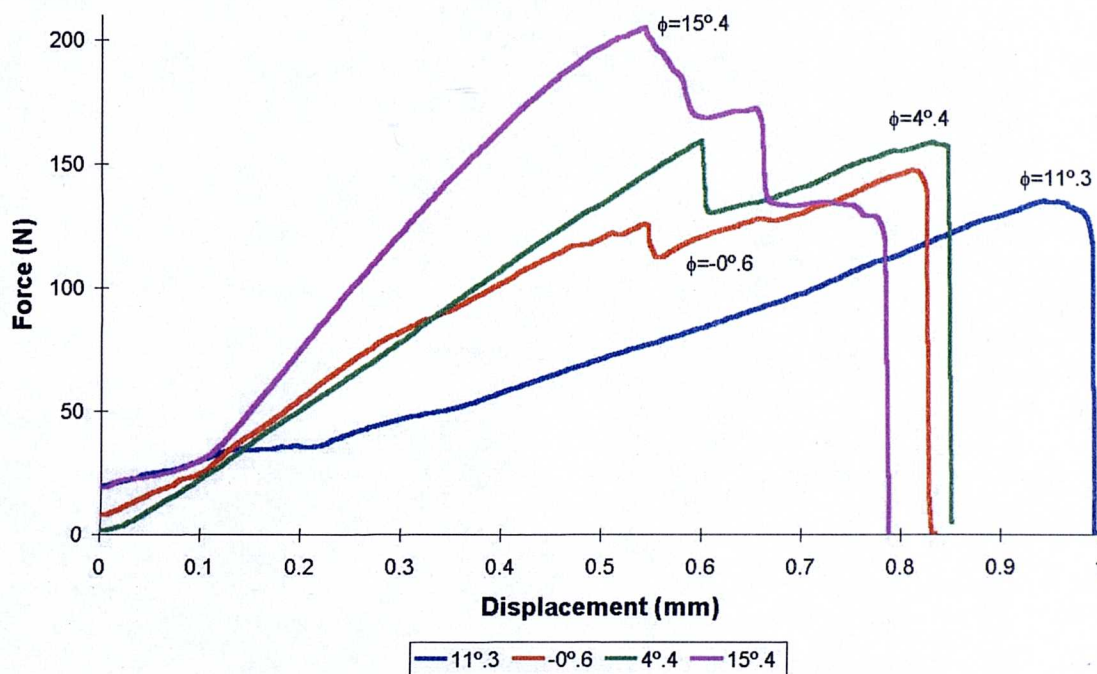


Figure 6-28: Force-displacement traces of T300/BMI Z-Fibres™ reinforcing IMS/924 laminates

Figure 6-29 and Figure 6-30 are post mortem photographs of the specimen with $\phi = 15.4^\circ$. Damage of the Z-Fibre™ is visible near the crack plane.

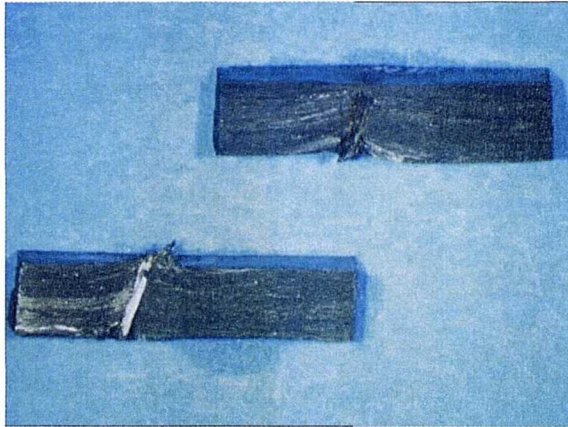


Figure 6-29: Post-mortem photo of an IMS/924 laminate reinforced with a T300/BMI Z-Fibre tested in shear without opening displacement



Figure 6-30: As Figure 6-29, higher magnification

6.5 Conclusions

Two different Z-Fibre™ materials (titanium and T300/BMI) were tested under pull-out and shear loading conditions, when a single Z-pin was bridging an already existing crack.

Pull-out testing gave consistent results. The shape of the load traces conforms with what could be expected in a pull out situation. For both materials, the adhesion shear stress is 7.3 MPa. The friction shear stress is 19 MPa for the T300/BMI Z-Fibres™ and 15 MPa for the titanium Z-Fibres™.

The angle ϕ of the Z-pin to the normal characterises the behaviour of the Z-Fibres™ under shear loading conditions. $\phi > 0$ means that the pin is 'in the nap', the loading actions have a component of the tensile axis of the Z-Fibres. If the pin material is titanium, the Z-Fibre™ pulls out with or without constraint of the opening displacement. When the pin is made from T300/BMI, it will pull out if opening displacement is allowed or break in shear if not.

An angle $\phi < 0$ of a Z-Fibre™ inserted in a composite matrix will lead to fracture of the pins. In the case of titanium Z-Fibres™, the pin will bend due to a kind of ‘hooking’ effect. The pin will fail in shear at the crack plane if the opening displacement is constrained, and in tension when completely bent otherwise. Carbon/BMI Z-Fibres™ will fail at the crack plane.

The use of polycarbonate as a ‘pseudo laminate’ allowed the visual observation of the behaviour of the pins.

Chapter 7 : Finite Element Modelling

7.1 Objectives

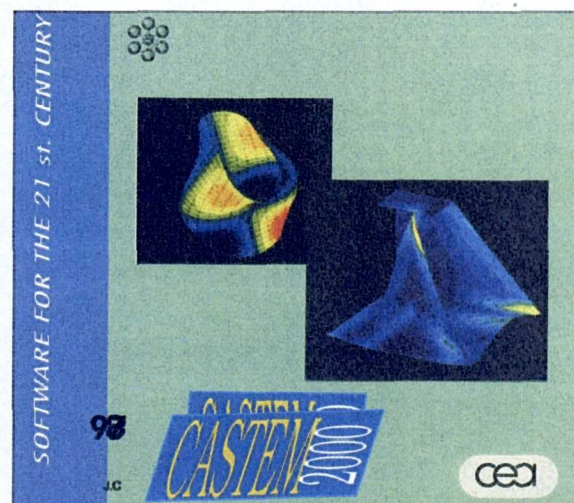
The objectives of this modelling exercise are to create a tool which can help us to understand, quantify and optimise the effects of Z-Fibre™ reinforcement on structures containing interlaminar cracks.

As a first step, simulation and analysis of the propagation of a crack in UD DCB, MMB and 3pt-ENF configurations with Z-pins is undertaken. The aim is to generate numerically R-curves similar to the R-curves shown in Chapter 5.

The focus of the study is on the actions of the pins. Therefore, experimental data from testing of single pin bridging a crack and from delamination testing of unpinned composite materials are used as starting points for the model described below. Parameters studied here are beam thickness, pin density, pin diameter, location of the pins (in relation to the crack tip) and pinning depth.

7.2 F.E. Package used

CASTEM 2000 version 98 is used in the current study. CASTEM 2000 is a finite element package developed by the CEA, French “Commissariat à l’Energie Atomique” in order to supply a high quality tool to support the design and analysis of structures either in the nuclear as other industries.



CASTEM offers several advantages, the first one of being a powerful package capable of working on any workstation, including PCs. CASTEM 2000 version 98 has been acquired for PCs working under LINUX operating system, as well as a MICROSOFT WINDOWS NT© version. It includes all the usual facilities needed to model

composites (orthotropic materials, shell element, etc...). It can work with 1, 2 or 3D models. One of the first applications of CASTEM was to predict the crack growth in pipes of nuclear power plant. Therefore, powerful fracture mechanics tools have been developed in order to compute energy release rates and stress concentration factors at the tip of a crack.

A second advantage is that the model is built using a specific programming language called 'GIBIANE'. The use of GIBIANE offers the possibility to personalise and adapt the system in order to solve a problem in the best possible way. Special subroutines and procedures can be created easily using GIBIANE. It allows the user to automate the model design and permits iterative process in a simple manner. For example, in this study, the re-meshing of the model in case of crack growth is a fairly simple procedure.

Another advantage is that the programme codes of all the computation procedure are accessible to any user and can be modified to solve new, more specific, problems.

Finally, specific behaviour laws can be implemented and used for parts of the model, allowing considerable freedom to the user.

7.3 Model

A 2D model with plane strain calculations has been chosen due to the geometry of the problem and in order to reduce computation time. The two principal directions (1-2) of the local coordinate system of the model are parallel to the directions (X – Z) of the real beam (Figure 7-1). The origin of the model coordinate system is at the crack tip. For this study, the unit system was kept consistently to millimetres (mm) for the length, Newtons (N) for the forces, Megapascals for stress and pressure (MPa) and degrees (°) for the angles.

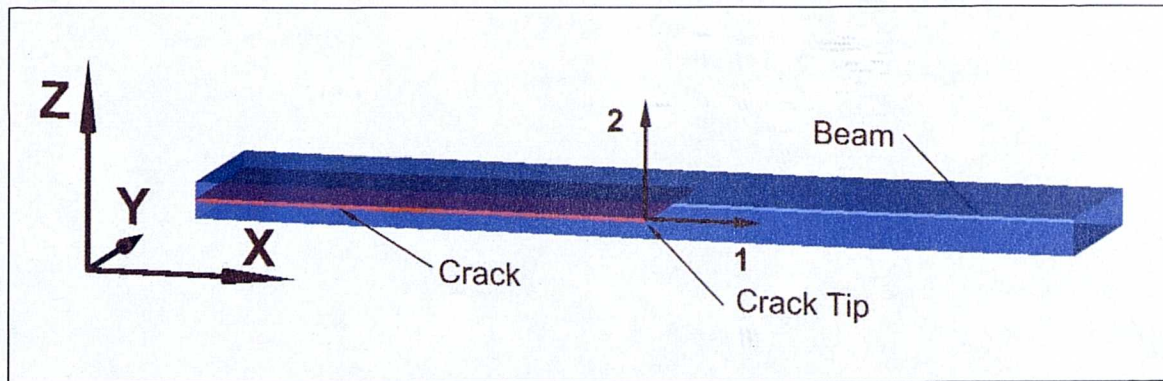


Figure 7-1: Coordinate system of the beam model

7.3.1 Model of the beam

The geometry of the beam is modelled with square elements with 8 nodes. The use of quadrilateral with 8 nodes (as opposed to 4) is necessary to be able to solve accurately flexural problems in 2D models, as it generates an order 2 interpolation polynomial. The model of the beam is built from the crack tip (See Figure 7-2). First, a radial mesh is created from the crack tip in order to improve the accuracy of the calculation of the energy release rate. The density of the crack tip mesh can be refined if needed. The origin of the global coordinate system of the mesh is located at the crack tip. Care has been taken to make sure that the orientation of each element is kept the same.

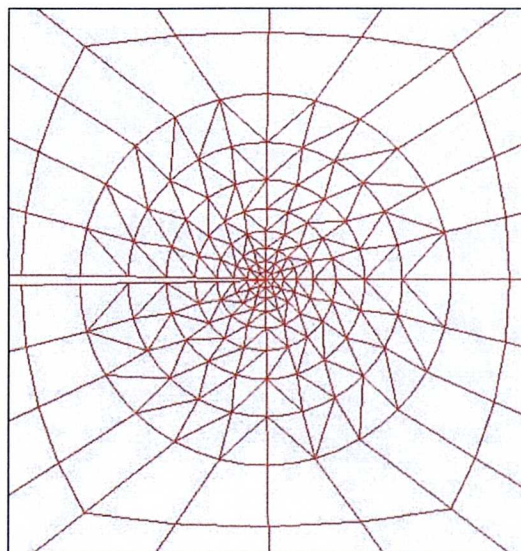


Figure 7-2: Mesh of the crack tip

The parameters defining the beam are, the half-thickness of the beam, h , its width, b , the crack length, a , and the locations of the rows of pins.

In the particular case of modelling DCB specimens, as the own weight of the specimen is not taken into account and there is no loading point on the right hand side of the crack tip, the model of the beam can be shortened to reduce the number of elements. Typically, only 15mm is modelled on the right hand side in order to avoid edge effects on the stress map.

The DCB beam model with a 50mm crack length has 6060 nodes and 1588 elements (Figure 7-3).

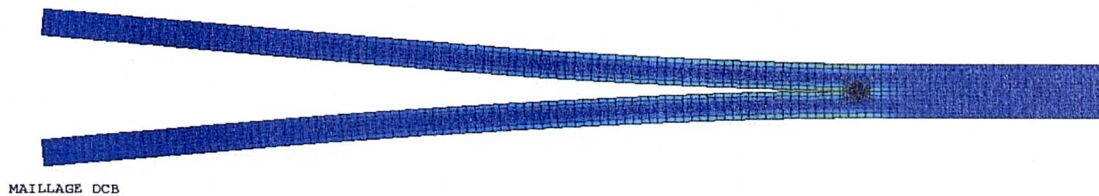


Figure 7-3: Deformed mesh of the double cantilever beam

In the case of mode II loading conditions, problems of surface penetration are avoided by defining the lower crack lip as master surface and upper crack lip as slave surface. The slave surface cannot penetrate the contact surface, but strain/stress can be transferred in the direction normal to the surface of contact.

The energy release rate is calculated at the crack tip using the G_THETA procedure specially adapted for orthotropic materials and renamed G_ORTHO . G_ORTHO computes the energy release rate using a J-integral method. The displacement of the loading points and Z-pins element nodes are recorded as well as the reaction forces at the support points. The data set of crack length, crack opening and load applied is then recorded and can be processed using the standard procedure for comparison with experimental data.

7.3.2 Model of the Z-Fibre™

The crack bridging actions of the Z-Fibres™ are represented by forces applied at the nodes of the DCB model, which are representative of the exact locations of the pins. These forces are determined as a function of the calculated displacements from the previous iteration. The force/displacement relationship is designed to follow the traction laws, determined by the single pin experimental tests described in Chapter 6. The traction law of the pins is then normalised by the width and thickness of the beam and the pin length and pin diameter and multiplied by the number of pins per row according to the pinning density.

For the case of composite Z-Fibres™ reinforcing UD laminates, the pin traction law is characterised by the maximum load a row of Z-Fibers™ can carry ($F_{\max}$), the opening displacement at the end of the elastic domain ($u_{\max}$) and the deformation when the pin exits the laminate (u_{end}). In the finite element model, the inserted length is called l_{pin} .

Figure 7-4 shows the bridging law of a single T300/BMI Z-Fiber™ pulling out of a 4mm thick IMS/924 UD laminate. The diameter of the pin is $d_{\text{exp}} = 0.51\text{mm}$. This experimental test gives the maximum force during pull out (F_{exp}), the displacement at the maximum force (u_{exp}). l_{exp} is the length of the pin pulled out during the test. The force (F_{pin}) carried by a pin of a diameter d_{pin} in the finite element model is calculated by Equation 7-1.

$$F_{\text{pin}} = \frac{l_{\text{pin}}}{l_{\text{exp}}} \frac{d_{\text{pin}}}{d_{\text{exp}}} F_{\text{exp}} \quad \text{Equation 7-1}$$

The maximum force $F_{\max}$ for the Z-pin traction law is then defined following Equation 7-2, which takes into account the number of pins per row, (nb_{pin}), and normalises the force per unit of width of the beam.

$$F_{\max} = \frac{F_{\text{pin}} \cdot nb_{\text{pin}}}{b} \quad \text{Equation 7-2}$$

where b is the specimen width.

In order to input meaningful values in the model, the experimental traction law has to be corrected for the compliance of the test apparatus. The displacement at maximum force after correction is called u_{exp_c} . The opening displacement at the maximum force, (u_{max}), of the modelled bridging law is calculated using Equation 7-3:

$$u_{\text{max}} = \frac{l_{\text{ins}}}{l_{\text{exp}}} \frac{d_{\text{pin}}}{d_{\text{exp}}} u_{\text{exp}_c} \quad \text{Equation 7-3}$$

u_{end} is determined in such a way that the traction law of the Z-fibre™ equals 0 when its opening displacement reaches the required pinning depth. This is usually the half thickness of the beam, as the pins pull out from one side of the laminate only. Figure 7-5 shows a numerical example of a traction law for 0.28mm diameter Z-Fibres™ inserted in a 3.2mm thick DCB specimen at a pinning density of 0.5%. For these conditions, $nbpin=6$, $u_{\text{end}}=1.60\text{mm}$, Equation 7-1 and Equation 7-2 give $F_{\text{max}}=5.53\text{N}$ and Equation 7-3 gives $u_{\text{max}}=0.01\text{mm}$.

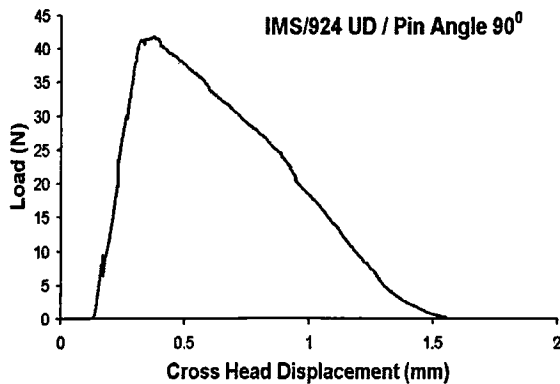


Figure 7-4: Force/Displacement trace of a pull out test

Pin diameter 0.51mm. Laminate 32 ply
IMS/924 UD.

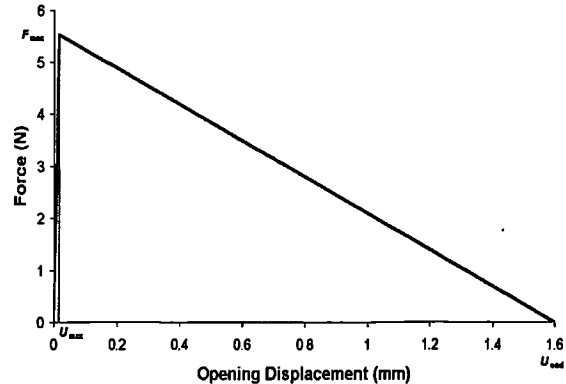
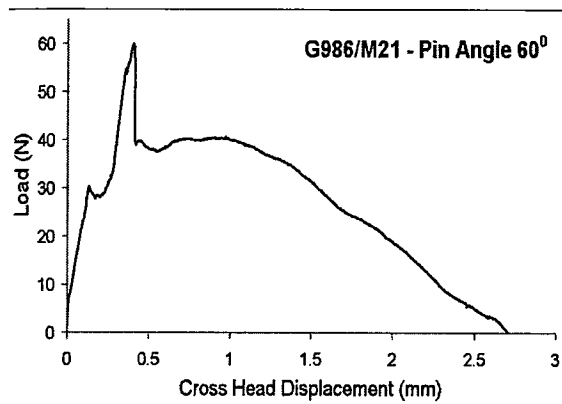


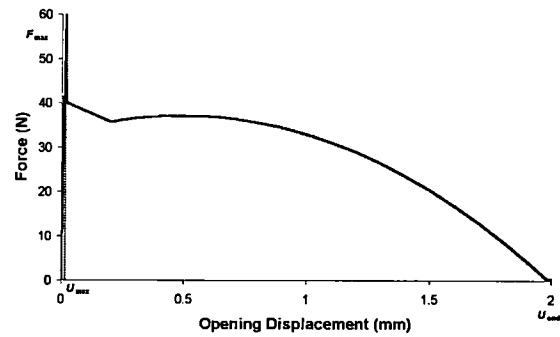
Figure 7-5: Bridging law of 0.28mm diameter pins at a density of 0.5%

Beam width 20mm.
Laminate thickness 3.2mm

Figure 7-6 shows the bridging law for a 0.51 mm diameter T300/BMI Z-Fibre™ pulling out of G986/M21 (Hexcel Composites (UK)) 4.4mm thick laminate. The pin was inserted at an angle to the vertical, which has significant effects on the subsequent pullout behaviour. The change in behaviour can be modelled by changing the shape of the traction law, using simple polynomial functions as shown in Figure 7-7.



**Figure 7-6: Pullout test of a Z-Fibre™
Laminate: G986/M21**



**Figure 7-7: Bridging law modelling an
angled pin pulling out of G986/M21**

7.3.3 Crack growth criterion

With the configurations adopted here, CASTEM2000 determines the energy release rate G at the crack tip. The crack is assumed to propagate when G calculated at the crack tip is higher than G_c determined experimentally by delamination tests of unpinned representative specimens. These values are input manually into the FE program.

Crack growth criterion:

$$\frac{G}{G_c} = 1$$

Equation 7-4

7.3.4 Algorithm

The calculations are structured following the algorithm below (Figure 7-8).

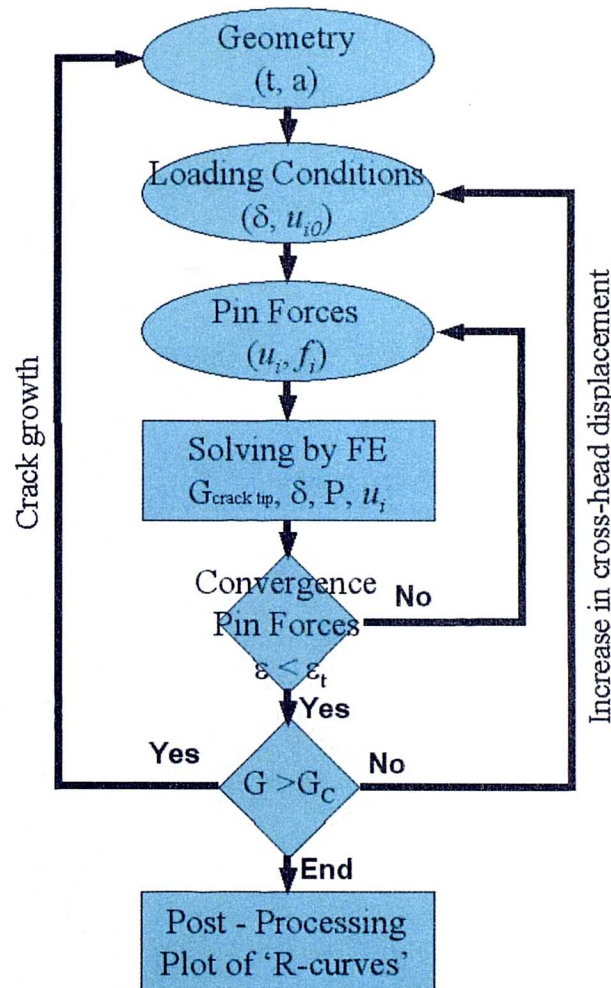


Figure 7-8: Structure of the calculations

Like the real delamination tests, the simulation is displacement controlled. From a given geometry (laminate thickness, crack length, pin density, pin length, etc...) and cross-head displacement, calculations are made to determine G at the crack tip. The cross-head displacement is increased until G at the crack tip equals G_c . When $G = G_c$, the propagation of the crack is simulated by re-meshing the beam with more elements to achieve the new crack length. The loading points and the bridging force application points are relocated relative to the crack tip. The calculation with the new geometry

starts from the opening displacement at the time of the propagation of the previous iteration of crack position. The bridging forces are also initialised from the displacements of the previous iteration.

7.4 Validation of the beam model

The aim of the validation of the beam model is to check that the material properties used in the model gives coherent Load/Displacement relationships and that the calculation of the energy release rate at the crack tip is correct. Table 7-1 summarises the properties implemented in the models.

Table 7-1: Material properties used in the FE models

Property	IMS/924
E_{11} (MPa)	138000
E_{22} (MPa)	11000
E_{33} (MPa)	100
ν_{12}	0.3434
G_{12} (MPa)	4400

Table 7-2 shows a comparison between the FE model results and results from a DCB test. The data reduction has been carried out using the ESIS TC4 spreadsheet V.5 (Tanner, 1996) for experimental DCB testing. G_{CBT} has been calculated using the corrected beam theory, using the set of data a (crack length), P (Load) and δ (opening displacement), acquired during the experimental test. G_{CBT} quoted in the FE columns has been calculated inputting a , P and δ , results of the FE calculations into the same spreadsheet. G_{FE} is the energy release rate calculated locally at the crack tip by the G_ORTHO procedure. The code of DELACAL1.DGIBI is listed in Appendix D.

Table 7-2: Comparison of experimental DCB and FE model

	IMS/924	
	Exp	F.E.
Thickness (mm)	3.21	3.2
Crack length a (mm)	49.6	49
Load P (N)	42.8	42.8
δ (mm)	4.3	4.3
G_c (J/m ²) CBT= corrected beam theory FE= calculated by CASTEM	G _{CBT} : 258±10	G _{CBT} : 261 G_{FE}: 264

7.5 Results

7.5.1 Mode I

Test case 1: 0.5% - 0.28mm

The case of the DCB specimen reinforced with 0.28mm diameter Z-Fibres™ at an areal density of 0.5% has been modelled in order to validate the concept. The pinning conditions (i.e. individual pin locations and insertion depths) of the experimental samples have been measured carefully and reproduced in the FE analysis. Figure 7-9 and Figure 7-10 show comparison of the load-displacement traces and the resistance curves for the experimental and simulated results. The good agreement between the FE analysis and the experimental results demonstrates that the bridging laws measured experimentally during pin pullout testing are representative of the actions of the Z-Fibres™ during delamination testing under mode I loading conditions.

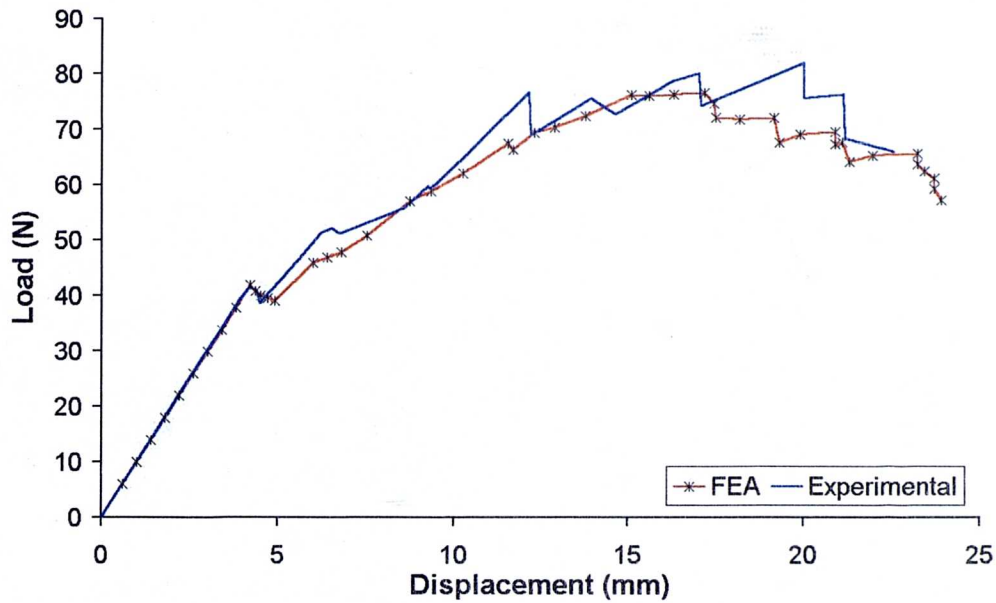


Figure 7-9: Comparison of FE output vs. Experimental load-displacement traces

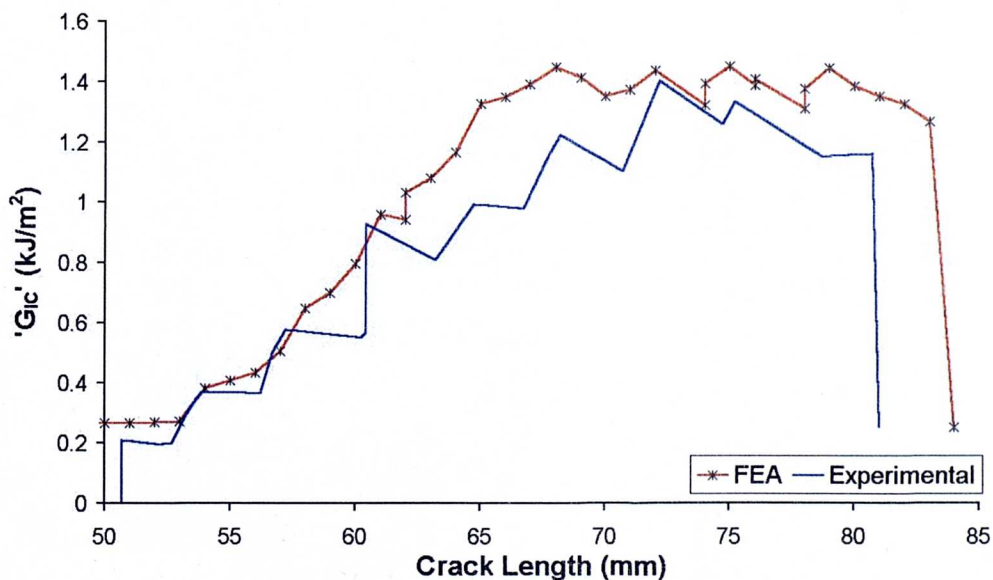


Figure 7-10: R-curves of IMS/924 DCB reinforced with 0.5%-0.28mm diameter Z-Fibres™ and the FE calculations for a similar beam

Test case 2: 2% - 0.51mm

For further investigation of the sensitivity of the model to pin depth, a particular case of 2%-0.51mm has been considered. An unexpected sudden load drop was noted in testing

of one particular specimen (see Figure 7-11). A visual inspection of the fracture surface revealed that two of the rows of pins had not been inserted through the full thickness of the specimen. Appropriate corrections of the pin forces relative to these two rows gave the line labelled 'FEA Incomplete pinning' (see Figure 7-11 and Figure 7-12). The agreement with the experimental results is very satisfactory.

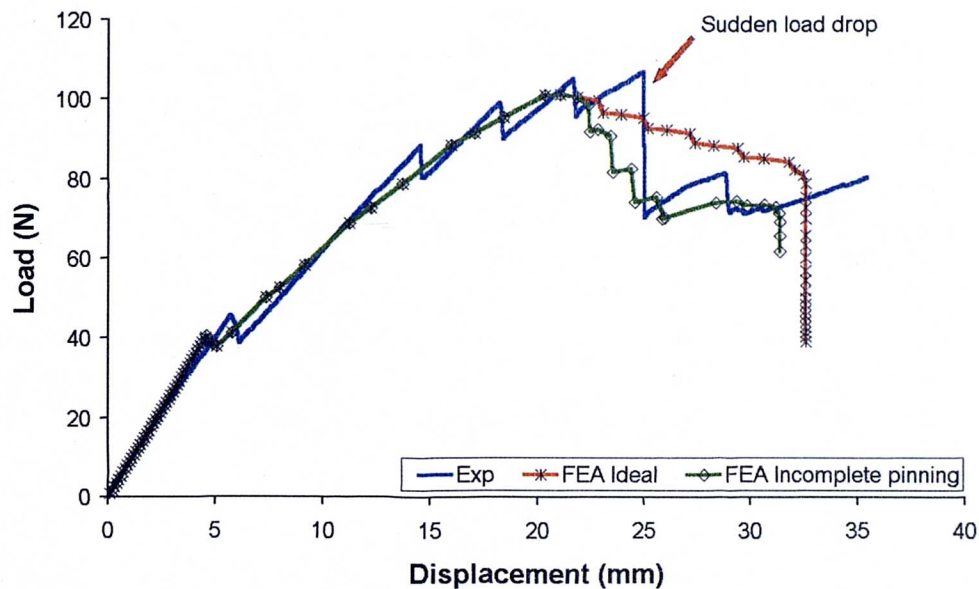


Figure 7-11: Test case with manufacturing imperfection, Z-Fibre™ density 2%, diameter 0.51mm

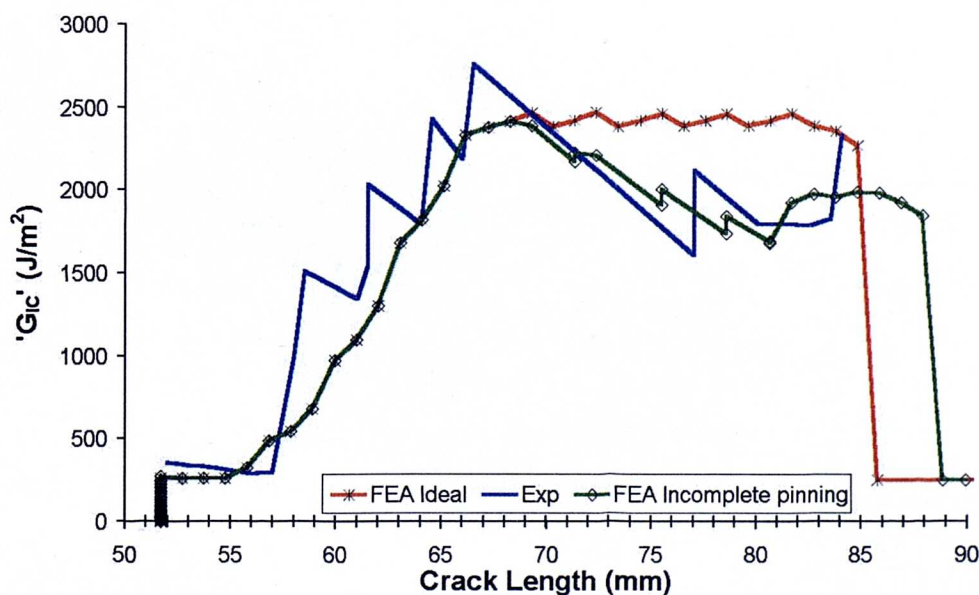


Figure 7-12: Resistance curves for the above case

Application case 1:

The first application of the model was to look at the effects of Z-fibre™ diameter on the delamination resistance of Z-pinned laminates, in order to explain the differences in apparent trends noted in studies carried out by different researchers (See Section 5.6).

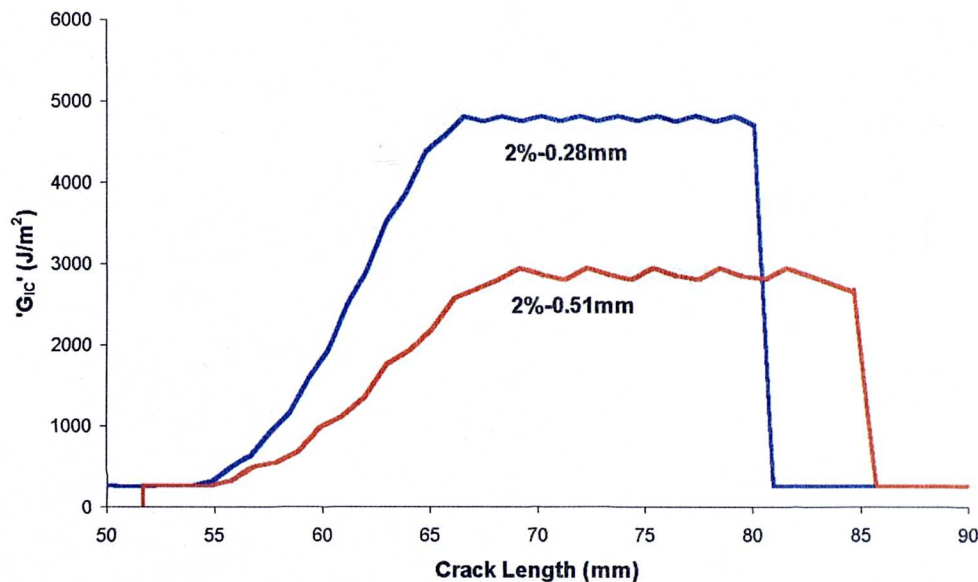


Figure 7-13: Effects of Z-Fibre diameter on the apparent toughness

Laminate thickness 3.2mm

Figure 7-13 shows the predictions of the model regarding the effects of the Z-Fibre™ diameter on the apparent toughness of a Z-pinned DCB specimen. The 0.28mm diameter pins lead to a delamination resistance higher than the 0.51mm diameter pins. These results confirm the experimental findings summarised in Section 5.5.

7.5.2 Mode II

Boundary conditions are the main problems when modelling mode II 3pt-ENF beams. Load transfer between the crack wake has to be assured. Special contact laws between the crack lips have to be applied. The upper arm lip is then defined as being the slave contact line, the lower arm lip is defined as being the master contact line. Stress can be

transferred from the slave line to the master line and the node of the slave surface cannot penetrate the master surface. To date, these contact laws have not been implemented and, consequently, it is not reasonable to present results at this stage.

7.6 Limitations of the model

It is important to state the limitations of this modelling exercise. Z-Fibres™ affect in-plane properties of the laminates. These effects are not taken into account by the current model.

Experiments presented in Section 5.4.1 have showed that under a mixed mode I/II $M_I/M_{II} = 4/1$ loading conditions, with 2%-0.28mm diameter Z-pin reinforcement, the beam breaks in flexure. Such mode of failure is not taken into account by the present model and will not be predicted.

The model of the mode I DCB specimen has been proved to be sensitive to the different pin parameters (pin length, pin diameter). However, due to the fact that the model is 2D, only average variations of the pin factors (for a given row) can be implemented. A non-uniform crack propagation, such as seen in Section 5.2.5, might not be possible to model.

The success of this exercise depends on whether or not the actions of the pins are identical in experiments involving single-pin tests and full, pinned, delamination tests. If the types of behaviour are comparable, the bridging laws determined by single pin testing are representative of the actions of the Z-Fibres™ during delamination test. If this appears not to be the case, the behaviour laws of the Z-pin/spring element will have to be determined by analytical modelling.

Chapter 8 Discussion

In this chapter, several aspects of the use of Z-Fibres™ are discussed, starting by the effects of the manufacturing conditions. The bridging laws determined by the single pin experiments are related to the shape of the R-curves of the delamination tests. The effectiveness of the reinforcement is correlated with the quality of the installation of the pins and the improvement of the compression after impact performance due to the Z-pins is compared with corresponding performance obtainable from the employment of highly toughened epoxy system as the composite matrix.

8.1 Manufacturing

The manufacture of Z-Fibre™ reinforced laminates is simple, compared to implementation of other through-the-thickness reinforcements such as stitching or tufting. The installation of the Z-Fibres™ requires only the addition of one stage during the manufacturing process, just before cure. Z-pinning can be applied to any kind of composites, whatever their manufacturing process. In the case of dry fabric, however, despite the fact that the insertion of Z-pins itself is easy, the cutting of the excess pin length is difficult because the pins are not well supported by the dry laminate preform. Alternative cutting solutions like high-speed circular sanders may be preferred, using extra precautions to avoid contamination of the laminate by the dust. In general, difficulties of removing the excess pin length from Z-Fibres™ inserted in dry fabric and difficulties in stitching of pre-pregs would indicate that Z-Fibre™ pinning and stitching are not competitive, but complementary types of through-the-thickness reinforcement.

8.1.1 Pre-cure laminate thickness

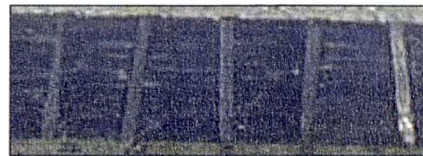
The Z-Fibres™ are inserted through the entire thickness of the **uncured** laminate. The control of the insertion depth during the installation of the pins is carried out by visual inspection of the bottom face of the laminates. The insertion is carried out until pin imprints appear on the backing paper protecting the bottom face of the laminate. The laminate thickness at each stage of the manufacturing process has to be verified. If the pre-cure laminate is much thicker than the nominal thickness, the fully inserted pins will

be effectively too long. During cure under pressure, they will either move and settle at an angle to the normal if the laminate is cured in a two-sided tool or stick out of the laminate if cured on a single sided tool.

When using unidirectional pre-preg tape, a simple debulk under vacuum is usually sufficient to minimise the final inclination angle of the Z-Fibres™. Problems arise when using fabric based pre-pregs. Such pre-pregs are bulky because of the waviness of the fibres. The bulk is increased by the fact that the fibres at the mid-plane of the tape are dry because of the manufacturing process (resin films applied on both side of the fabric). The difference in thickness of the laminate before and after cure can be several millimetres. A simple debulk period under vacuum is not sufficient to compact the laminate enough to prevent rotation of the Z-pins during cure, as illustrated by the left hand picture of Figure 8-1. Using a hot press in order to impregnate the fibres and to compact the fabric allows the subsequent insertion of the Z-Fibres™ to occur in optimum conditions. The average pin angle is close to the normal of the laminate (right hand side of Figure 8-1).



Laminate not compacted before insertion



Laminate compacted before insertion

Figure 8-1: Effect of compaction before insertion on final pin angle

The use of the gantry improves the insertion of the Z-Fibres™. The ultrasonic head position is maintained vertical and the pressure and the speed of insertion are controlled. As no force is required from the operator, the pressure is on average kept on for longer than when using a hand held unit. Thus, a greater length of pin tends to be inserted when a gantry is used. As a consequence, a greater pin inclination has been observed in panels containing Z-Fibres™ inserted with a gantry.

8.1.2 Surface finish requirement

The surface finish of the part is important from the manufacturer's point of view. The surface finish of a pinned laminate when using a polymer release film is shown in Figure 8-2. The pins are in contact with the caul plate and therefore they are flush with the surface of the laminate, but the release film tends to create creases visible on the cured panel.

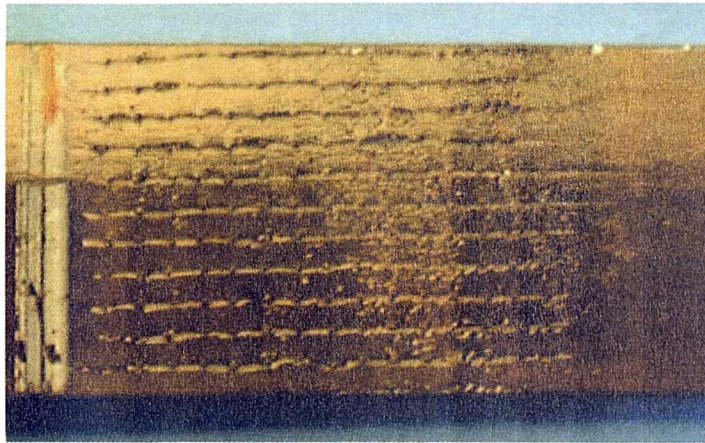


Figure 8-2: Surface finish of a pinned specimen cured with a polymeric release film on the surface

Some manufacturers use a fabric peel ply at the surface of the laminate to improve bonding properties. When a fabric peel ply is used, the fabric can be compacted locally and allows the Z-Fibres™ to protrude from the surface of the laminate. Figure 8-3 is an example of a T300/914 laminate where this kind of peel ply has been used. The 'heads' of the pins protruding from the laminate are apparent.

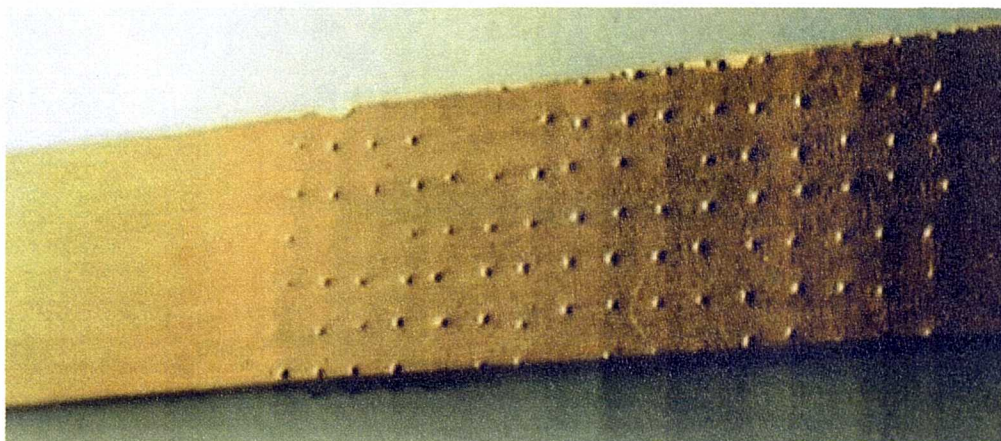


Figure 8-3: Surface finish of a pinned specimen cured with a fabric peel ply on the surface of the tools

When perfect surface finish is required, the insertion of the Z-Fibres™ can be carried out before completion of the lay-up. The Z-pins can be inserted in the laminate when the outer layers of pre-preg are not yet laid up. The addition of the outer layers after insertion of the pins masks the presence of the Z-Fibres™ and allows the surface finish to be perfect. It also prevents the pins from rotating during cure as they are not in contact with the tool.

8.2 Validity of the LEFM analysis methods

The current data analysis methods combine linear elastic fracture mechanics with beam theory. As seen in Chapter 2, the data reductions rely on using the beam theory to express the compliance of the beam as a function of the known parameters (applied load, crosshead displacement, crack length). Only the elastic deformation of the beam and the creation of a new cracked surface area are taken into consideration.

Doing the analysis with through-the-thickness reinforcement requires the implementation of the bridging actions of the Z-Fibres™ in the initial phase of the beam theory analysis in order to link the known parameters to the real stress seen by the crack tip. To date, this requires assumptions on the bridging law and iterative numerical solving procedures. Most models assume a constant bridging law, independent of crack length, which does not reflect experimental observations on Z-pinned composites.

As seen in Section 2.2.1 and Section 5.5 the presence of the Z-pins affects the correction factors Δ and n . Although the scatter in the experimental values is high, Δ is generally increased by the increased intensity of the bridging actions in the crack wake. Similarly, the compliance parameter n is decreased by increased density of pinning, particularly in the case of the 0.28mm diameter pins. However, the determination of these parameters using the procedures recommended in the test protocols might not be valid as it assumes a particular mathematical expression for the compliance of the

specimens using the global parameters applied (- load P , cross head displacement δ and crack length a).

8.3 Energy absorption mechanisms

As shown in Chapter 5, Z-Fibre™ pinning is a remarkably efficient method to improve the delamination performance of carbon fibre/epoxy composites. The presence of the Z-Fibres™ radically changes the behaviour of the samples. New energy absorption mechanisms are created. Different energy levels and noise distribution in the acoustic emission recording also confirm the presence of these new mechanisms. It is therefore important to identify and characterise these mechanisms to be able to analyse the effects of Z-Fibres™ on the delamination behaviour of laminated composites.

In situ SEM fractographs, such as Figure 5-2 and Figure 5-13, as well as visual observation of the tests allowed an identification of the mode of failure of Z-pinned laminates to be made. Under mode I loading conditions, the Z-pins debond and pull-out as the crack opening increases as illustrated by Figure 5-3. Under mode II loading conditions, the deformation of the pins in bending and shear induces traction actions which counteract the relative shear displacement of the crack lips. If opening displacement occurs, the pins may be allowed to pull-out.

Single pin experiments allowed the determination of the shape of the traction law of a single pin under pull-out and shear loading conditions to be made. The shape of the resistance curve of a mode I DCB test is related to the shape of the traction law of a single pin experiment. During pull-out of a single Z-Fibre™, the amplitude of the action of the pin increases rapidly to its maximum value (debonding). When the pin starts to pull out the bridging actions decrease with the decreasing length of the pins still embedded in the laminate.

It is apparent in the mode I DCB tests that the laminate delamination resistance increases as soon as the crack has reached the first row of Z-Fibres™, it is then that the bridging forces are maximum. The mode I R-curves show a more or less steep rise

depending on the pin areal density and pin diameters. With the crack propagating, the pins pull out completely and a steady-state regime appears with a constant number of rows of pins working, a row being completely pulled out as a new one is reached by the crack front (See Figure 8-4). It is also apparent in Figure 8-4 that some bending of the pin must occur in the wake of the crack for the pins to pull out. Shortly after the last row of pins is passed by the crack front, the delamination toughness of the laminate returns to its original value (non 3D-reinforced delamination toughness).

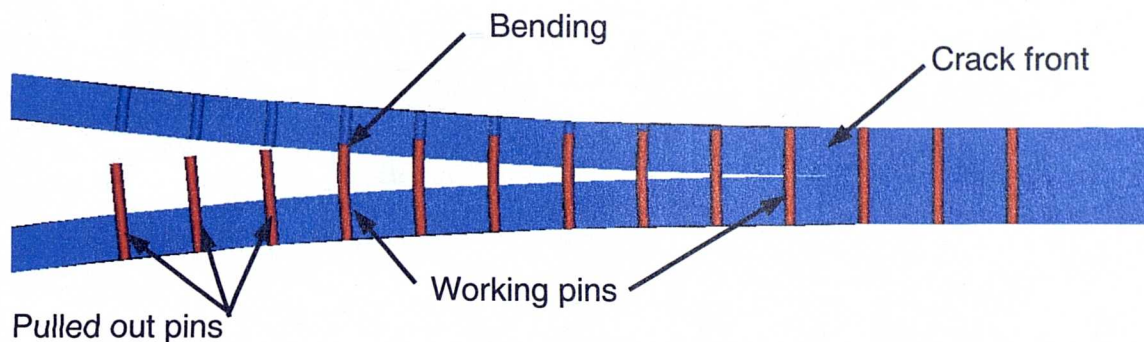


Figure 8-4: Steady-state crack propagation of Z-Fibre™ reinforced laminates

The single pin experiments under mode II loading conditions showed that the action of the pins increases with increasing shear displacement. When the opening displacement is constrained, the load increases with increasing shear displacement until catastrophic failure of the pin in shear. This shear displacement must be high for the bridging action to be significant. Shear failure of 0.51mm diameter Z-Fibres™ occurs for a shear displacement of 0.8mm. Thus, the effectiveness of the Z-pins in 3pt-ENF tests appears more gradual as the actions of the pins are not immediate. The mode II R-curves present this constantly rising shape until the limit of validity of the tests is reached, as the effects of the pins persists even after the crack front has passed completely through the pinned region. To reach a steady-state, with a plateau value similar to that in mode I, a critical shear displacement where the pins fail in shear must be reached. In mode II loading conditions, the 3-pt ENF configuration presents the determination of crack propagation lengths sufficient to reach these conditions. The ELS or 4pt-ENF configurations would allow greater crack propagation lengths to be achieved, therefore

greater shear displacement, which may be sufficient for the apparition of a steady-state in mode II.

Stability of crack propagation under mode I loading conditions

Delamination testing under dominant mode I loading conditions showed that the pin-to-pin spacing has influence on the stability of the test. If the pin-to-pin spacing is sufficiently large (relative to the crack stopping capability of each row of pins), the behaviour is unstable. This is illustrated by the 0.5%-0.28mm or the 2%-0.51mm Z-Fibre™ reinforcement results presented in Section 5.2.3 and Section 5.2.5. Each row of pins acts as a crack stopper, but with the increasing opening displacement, the bridging actions diminish and the crack will propagate rapidly to the next row. If the efficiency of each single row is sufficiently high, the crack propagates from row to row in a stable manner (like in the mode I delamination of 2%-0.28mm pinned laminate in Section 5.2.4). This level of stability/instability is decided by the pin areal density in relation to the pinning parameters such as embedded pin length (or laminate thickness) and pin angle.

Effect of pin diameter and pin density

If we assume that the principal energy absorbing mechanisms under mode I loading conditions is the pull-out (controlled by friction), then the key parameter controlling the bridging between the crack faces is the surface of contact between the Z-Fibres™ and the laminate. The surface of contact is related to the embedded length of pins in the laminate and the circumference of the pin as seen from the top. For a given pin density (surface area of pins from the top), the pins of a smaller diameter have a greater surface of contact than pins of a larger diameter, which is confirmed by the experiments presented in Section 5.2.

Under mode II loading conditions, the energy absorbing mechanisms are bending and shear. These phenomenon are functions of the moment of inertia, thus the cross section area of the pins, therefore the pin density. It is a possible explanation of why the mode II tests appear less sensitive to the pin diameter than the mode I tests.

8.4 Pinning quality

Apparent contradictions in the trends of the effects of the pin diameter between the delamination study by the present author (presented in Section 5.2 and Section 5.3) and the study carried out by Bitsianis (1999) (results presented in section 5.6) initiated further investigation of the different parameters involved during the whole process of manufacturing and testing of Z-Fibre™ reinforced laminates. The parameters which differed between these two studies were the laminate materials (IMS/924 and T300/914), the laminate thickness (3mm and 4mm) and the pinning attributes, the latter being operator dependent.

8.4.1 Effects of the pinning quality

Closer examination of all the specimens involved revealed that differences in the pin insertion depth were visible (See Section 4.1.2). Figure 8-5 shows cross-section photographs of open IMS/924 DCB specimens after testing. The pulled out pins are visible. The Z-pins length are comparable (1.5mm approximately), but the presence of the chamfered end is obvious on the 2%-0.51mm sample. This is due to the fact that the insertion was stopped as soon as the pin imprints were visible on the backing paper of the panel. The chamfer reduces the effective pin length inside of the laminate, which artificially decreases the performance of the corresponding specimens. The chamfered ends are also present in the 2%-0.28mm pinned samples, although the reduction of the pin effective length is smaller here due to the smaller pin diameter. The 2%-0.28mm pinned laminates present an effective pin length almost 10% higher than the 2%-0.51mm pinned laminates. As seen in Sections 6.3, 7.4 and 8.3, the level of bridging is dependent on the effective pin length. Thus the action of the 0.28mm diameter pins will be enhanced artificially, compared to the 0.51mm diameter ones.

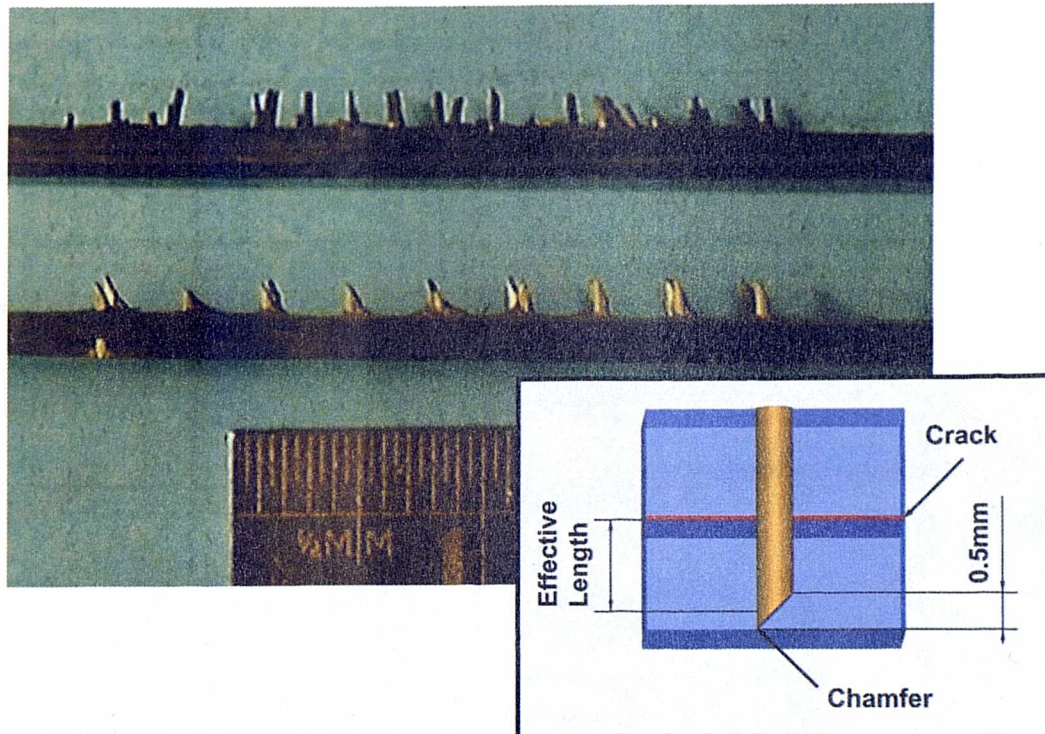


Figure 8-5: Effective insertion depth differences between 2%-0.28mm Z-Fibres™ (top) and 2%-0.51mm Z-Fibres™ (bottom) in IMS/924

Figure 8-6 shows cross-section photographs of the 4mm thick T300/914 DCB beam specimens. The chamfered ends of the 2%-0.51mm pinned samples are not present because this particular pinning process was stopped only when the end of the pins had been crushed. The pins were inserted through the whole thickness, as seen on Figure 8-7, where the pins are visible on both sides of a delaminated specimen. The effective pin length inside of the laminate was 2mm. In contrast, Figure 8-6 shows that the 2%-0.28mm pins were inserted through only 3mm of the whole thickness, which means that only 1mm of the length of the pins was effective during DCB testing. This artificially decreases the performance of the 2%-0.28mm Z-pinned samples, as presented in Section 5.6. Figure 8-8 shows that the 2%-0.28mm pins did not go through the entire thickness of the laminate.

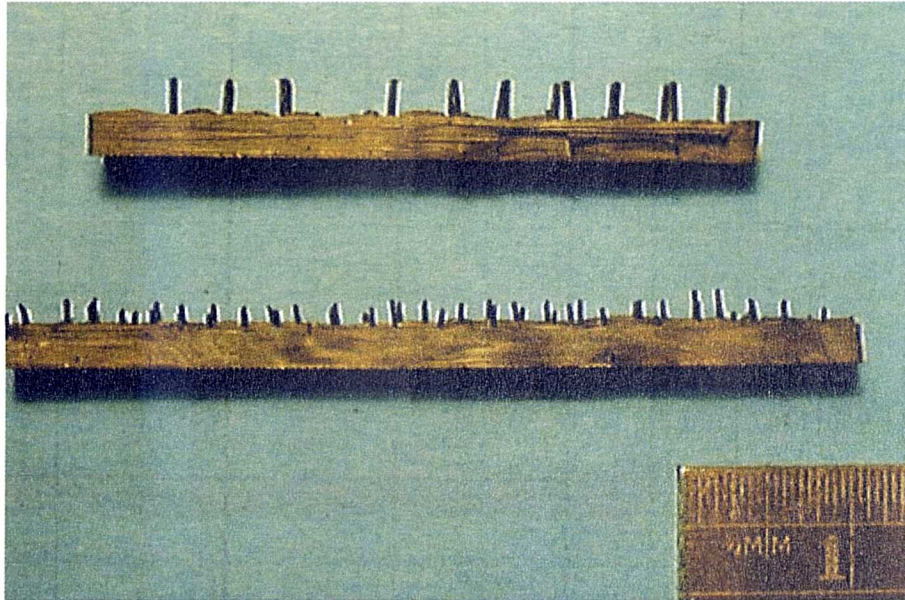


Figure 8-6: Insertion depth of 2%-0.51mm Z-Fibres™ (top) and 2%-0.28mm Z-Fibres™ (bottom) in T300/914 (Bitsianis, 1999)

In both these studies, the fact that the pins pull out from only one side of the specimens shows that the installation of the Z-Fibres™ is not symmetrical. The pulled out part of the pins shows the chamfered ends. The effective length of the pins can be measured a posteriori by measuring the pulled out length, as shown above.

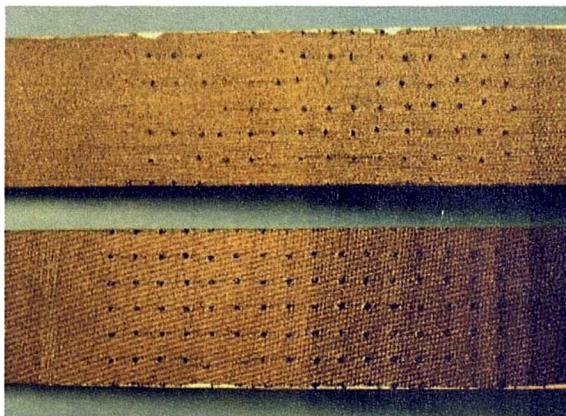


Figure 8-7: Top and bottom surface of a 2%-0.51mm Z-Fibre™ reinforced T300/914 DCB specimen (Sample by courtesy if Bitsianis, 1999)

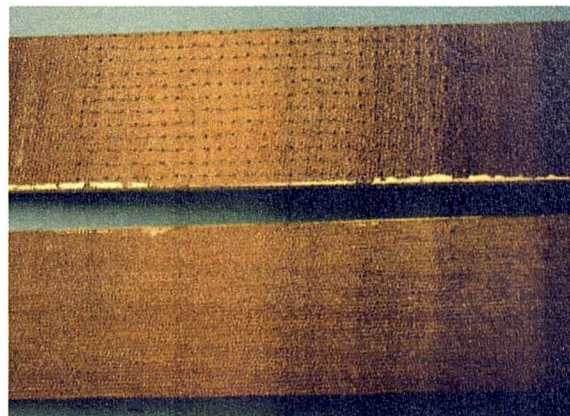


Figure 8-8: Top and bottom surface of a 2%-0.28mm Z-Fibre™ reinforced T300/914 DCB specimen (Sample by courtesy of Bitsianis, 1999)

8.4.2 Assessment of the pinning quality

A quantification of the pinning conditions or pinning quality is required in order to analyse accurately any experimental work and draw any conclusions on the effects of the different parameters involved in Z-Fibre™ pinning. There are several means of checking the manufacturing quality of Z-pinned laminates. In the first instance, all cured plates are C-scanned routinely to ensure the absence of gross defects from any test samples. Higher magnification C-scan (Figure 8-9) is capable of revealing the regularity or otherwise of the pinning pattern. The ovality of the black 'dot' representing the pins may give information on the insertion angle as a pin normal to the laminate plane is represented by a perfect circle imprint and an angled pin is represented by an oval shape.

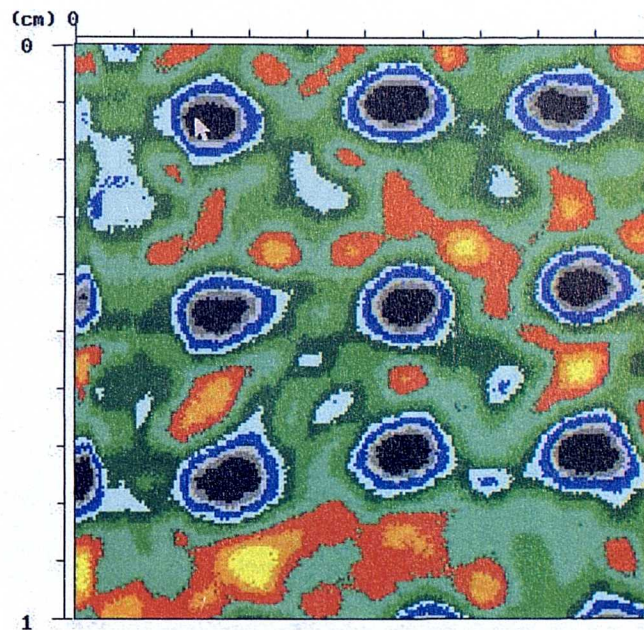


Figure 8-9: High resolution C-scan of the pinned area (After Cartié et al, 2000)

In the orthogonal plane, metallographically polished cross-sections (Figure 8-10) give information on the inserted pin angle and insertion depth.

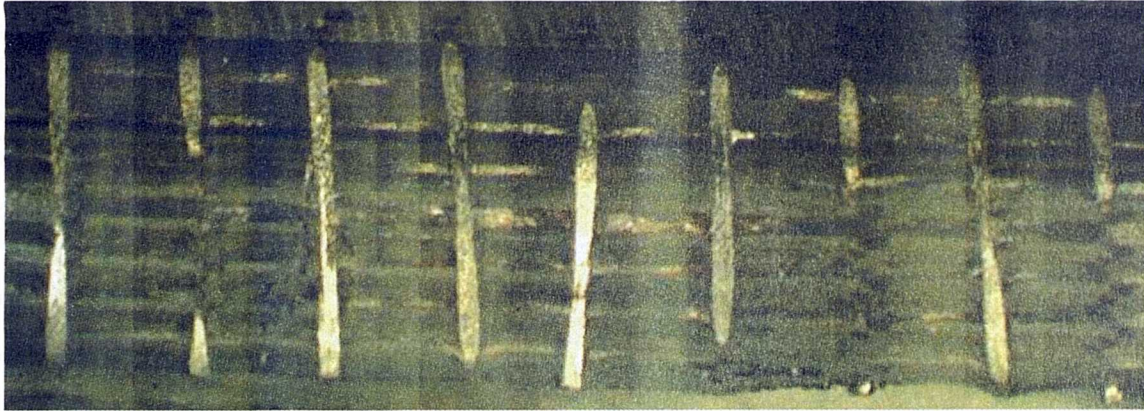


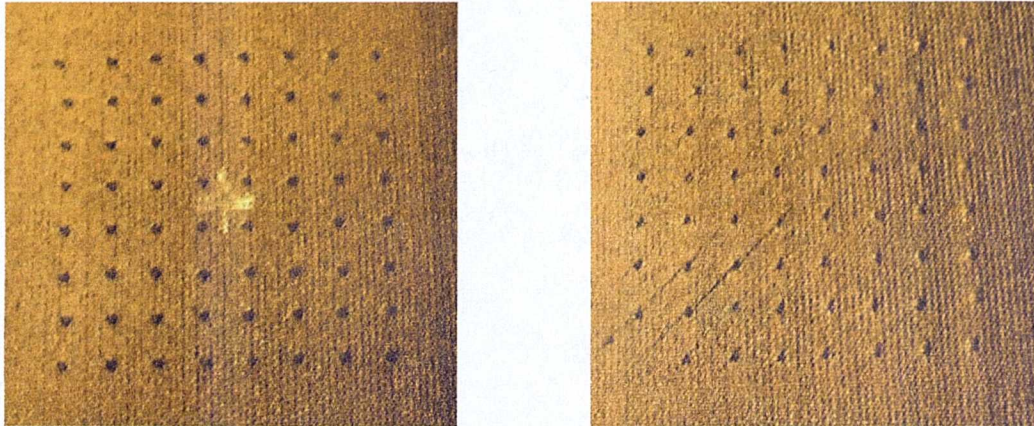
Figure 8-10: Polished cross-section of a pinned QI laminate (After Cartié et al, 2000)

8.5 Compression after impact

Figure 8-11 and Figure 8-12 show that the pinning quality of the compression after impact samples. This was comparable for samples used in the separate MSc studies. The Z-Fibres™ had been inserted through the whole thickness of the laminate in both cases and the regular pinning pattern for both, top and bottom surfaces, indicates that the pin angles are relatively small.



Figure 8-11: Top and bottom surface of a 2%-0.28mm pinned CAI specimens (Sample by courtesy of Bitsianis, 1999)



**Figure 8-12: Top and bottom surface of a 2%-0.51mm pinned CAI specimens
(Sample by courtesy of Bitsianis, 1999)**

Simple damage area assessment by C-scan reveals that a reduction of the delamination area up to 30% can be achieved by the use of the 2%-0.28mm pins accompanied by a 50% increase in the ultimate compression strength, for a given impact energy. For a given damage area, the ultimate compression strength can be up to 30% higher in Z-pinned laminates than in control samples. This shows that the Z-Fibres™ act during the impact event by reducing the damage as well as during the compression loading by delaying and/or slowing down the propagation of the impact damage.

For relatively high impact energy (20J), and more especially in the case of the 0.51mm diameter pins (Figure 8-13), the delamination damage is not contained in the pinned area. This explains the dilution effect of the action of the pins for damage area greater than 900mm² visible in Figure 5-37.

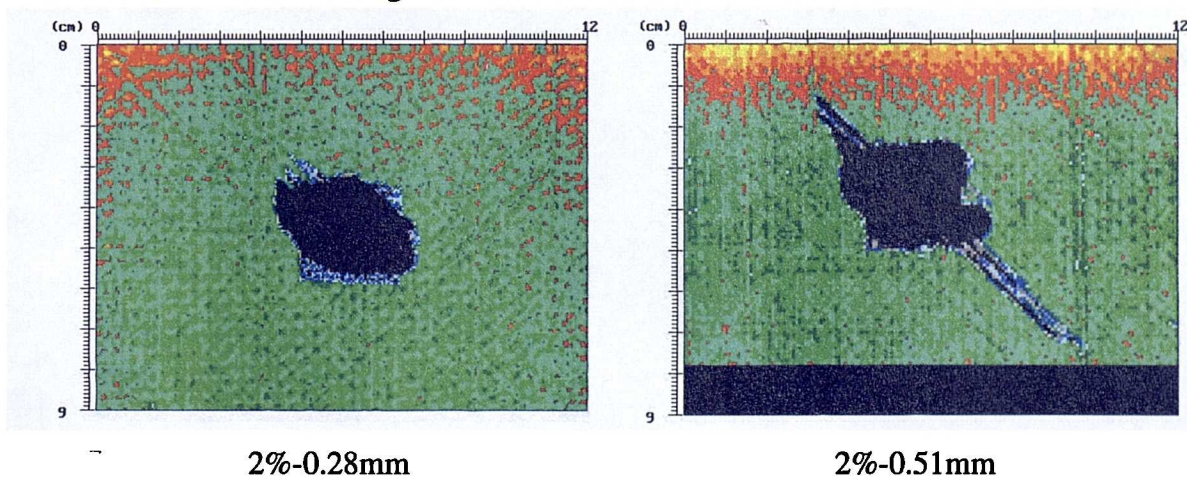


Figure 8-13: Damage of CAI samples impacted at 20J

It may be observed that Z-Fibre™ pinning improves the delamination toughness up to 20 fold. However, in impact and compression after impact, ‘only’ a 50% improvement is measurable. During an impact event, the global deflection of the typical Boeing standard sample is about 6mm. The shear strain levels reached inside such a CAI sample between the delamination crack faces in the pinned area are therefore very low compared to shear displacement seen by the Z-Fibres™ during a mode II delamination test. As seen in Section 6-3, Section 5-3 and Section 8-3, the magnitude of the actions of the Z-pins is highly dependent of the meso-scale displacement of the crack faces. This explains why there is such an apparent difference in the effectiveness of Z-Fibre™ pinning.

The threshold force for damage initiation for an impact is reduced when the impact is located on the pinned region. It is probable that the presence of the Z-Fibres™ introduces stress concentration factors, which reduce the threshold energy for crack initiation.

The comparison of Figure 1-1 and Figure 5-35 shows that Z-Fibre™ pinning enhances the compression after impact performance of IM7/8552 composites to a level comparable to composites based on highly toughened epoxy resin matrices such as 920. CAI performance of the Z-pinned T300/914 material is greater than that of any other currently available aerospace grade carbon fibre/epoxy composite and is only slightly below that of HTA/920 material.

8.6 Need for pinning quality metrics

The use of the Z-Fibres™ improves the delamination propagation resistance of the laminates. However, the effect of the pins on the initiation of the delamination in fracture testing is not known and is very difficult to study. It requires insertion of the pins on the edge of the starter film or pre-cracking up to the first row of pin. In both cases, it is difficult to control and monitor the test. Furthermore, the bridging actions of

the Z-Fibres™ will modify the behaviour of the crack growth as soon as propagation occurs.

A detailed knowledge of the pin and pin installation parameters is important for any detailed or accurate study of Z-Fibre™ reinforced laminates. The meso-mechanics of failure will be dependent on the pinning conditions. It is therefore important to create a pinning quality metrics table which would regroup all the Z-Fibre™ parameters (material, density, diameter) as well as the insertion variables (location of the reinforcement, proportion of missing pins, pin length/ depth, pin angle) and installation parameters (lab temperature, insertion pressure and speed, travel of the insertion head) in order to characterise fully the material under study.

To date, relatively little is known about the effects of the pin angle on the performance of Z-Fibre™ reinforced laminates. Experimental evidence on the effects of the pin angle is reported here in Chapter 6. As shown in Figure 8-1, when the pins are angled, the angle is similar for all the pins. Under mode II loading conditions, the single pin experiments suggest that the presence of an inclination may create a weaker loading direction depending on whether the pins are working ‘in the nap’ or ‘against the nap’.

When the different variables had been separated, more extensive studies of the effects of these parameters can then be carried out using analytical or numerical tools.

The potential advantages of the Z-Fibre™ pinning in increasing 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, as shown by Steeves and Fleck (1999).

Chapter 9 Conclusions and Suggestions for Further Work

9.1 Conclusions

1. The work reported here has achieved its objectives of reporting, illustrating and quantifying the effects of Z-pinning on the delamination behaviour of unidirectional carbon fibre reinforced epoxy matrix laminates. Extensive manufacturing skills and experience on the installation of Z-Fibre™ have been acquired. Delamination fracture testing procedures have been adapted to testing of 3D-reinforced composites.
2. Z-Fibre™ pinning proves to be an efficient method to improve delamination resistance of UD laminates. For the range of reinforcement used during this study, the load carrying capability of DCB beams under mode I loading conditions has been improved up to 5 times. In terms of delamination toughness ' G_{IC} ', the improvement can be up to 20 times.
3. The usually unstable crack growth observed in the mode II 3pt-ENF test configuration is stabilised by the presence of pins in the crack path. Compared to a sudden catastrophic load drop in the tests of laminates without pins, the load carrying capability is maintained and even increased with increasing crack length by the use of the Z-Fibre™ reinforcement. Intermediate types of behaviour have been observed in the mixed mode I/II (MMB) samples.
4. The current standard data analysis methods, based on LEFM, are not valid for the case of three dimensionally reinforced composites. At the present time, they can only be used as normalising tools for comparison purposes. Analyses are under development, based upon the concept of large scale bridging. In this work, pull-out laws for a single pin reinforcing an already existing crack have been determined experimentally. The traction law of a single pin in shear is dependent on the inclination of the pin to the normal of the laminate. These single pin traction laws have been implemented in a 2D finite element model of the delamination fracture test beam, in order to create a numerical tool for parametric studies of the different pinning parameters. In the case of mode I loading conditions the very good agreement between the simulated and

experimental R-curves demonstrates that the delamination behaviour of a DCB specimens is related to the single pin traction laws.

5. A double action of the Z-Fibres™ has been observed during compression after impact tests. Not only does the presence of the pins reduce the extent of the delamination damage by about 30% and increases the CAI strength up to 50% for a given impact energy, it also improves the CAI strength by 30% for a given damage area.

6. The delamination behaviour of Z-Fibre™ reinforced samples is highly dependent of the pinning quality. Parameters affecting the effectiveness of the Z-Fibres™ in bridging of a crack have been identified and can be grouped into two main categories to create a 'pin quality matrix'. The first category will describe parameters related to the nature of the pins themselves, namely their material, their diameter and the areal density at which they are installed in the laminate. The second group of parameters characterises the quality of the Z-Fibre™ installation, namely the effective pin length or pinning depth, pin angle after cure, number and location of missing pins and state of the chamfered end.

9.2 Suggestions for further work

The Z-Fibre™ pinning is a young technology, not yet widely accepted by designers of structures made from composite materials. From the experience gained during this study, two main topics appear to need to be addressed in the near future.

The first topic is the rigorous re-evaluation of data analysis procedures for the delamination fracture tests in order to be able to derive design-meaningful values of the delamination resistance of Z-pinned laminates. An industrial user of Z-Fibre™ is interested in a simple fracture test allowing him to determine a number of parameters on the effects of Z-pins in his structure. As a first approximation, data analysis derived from LEFM can be utilised, by making simple assumptions on the mathematical formulation of the bridging actions, using a limited number of parameters. The compliance of the beam as a function of these parameters can then be derived. A plot of

the experimental compliance as a function of the crack length will determine the bridging parameters and therefore quantify the bridging actions in a crude but simple manner.

The second main topic is the development of what might be called the pinning quality metrics, which would achieve a full structural characterisation of the laminates studied. The use of such quality metrics would ensure that only results of tests which are truly comparable end up being grouped together. Such quality control is a direct pre-requisite for the validation of new models and new data analyses.

For completion of the work presented here, specific studies of the effects of the pin angle, pin length and partial insertion are necessary for the determination of the full delamination test envelope. Single pin pull-out and shear tests with different Z-Fibres™ (material and diameter) are required for exact determination of the friction stress and behaviour laws. There are also some more detailed considerations of testing of Z-pinned laminates and structures that are deserving of attention. For example, for the mode I loading conditions, single pin testing and finite element modelling showed that the bridging actions of the pins are function not only of pin diameter and pin length, but also of the crack opening displacement. In a structure under load, the crack opening or shear displacement is related to the stiffness of the structure. Therefore, for a given pinning density, the crack bridging effects of the different pin parameters (pin diameter, pin length, pin angle) will be affected by any change of structure stiffness. Extensive parametric studies on the effects of all the different parameters need to be carried out, either experimentally or by modelling.

The finite element model tool presented here has proved to be very successful in the DCB case. However, it needs finalisation in the case of ENF and MMB specimens. This approach, combined with analytical modelling of single pin traction laws, such as developed by Cox, will create a modelling package in which the experimental aspect will be reduced to minimum. Implementation of cohesive bridging laws (bridging laws defined by a continuous mathematical expressions applied on a finite portion of the crack wake as opposed to local forces at the location points of the pins) can be carried

out in order to check the validity of current analytical model such as the ones developed by Massabò et al and Mai et al.

All the delamination tests presented here have been performed at one particular cross-head speed. The influence of strain rate on the mechanisms of failure is not known and could be significant. Similarly, the implementation of another testing configuration for delamination fracture under mode II loading conditions, such as the 4pt-ENF, would allow the investigation of the existence of a steady-state crack propagation under shear loading to be carried out. Finally, investigations of the effects of Z-Fibres™ on in-plane and fatigue properties of laminates are certain to be required for the implementation of design rules for the use of Z-Fibres™ in composite structures.

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S. Tanner

Excel work sheet for the data analysis of DCB test

©EMPA, CH-8600, Dübendorf, Switzerland.

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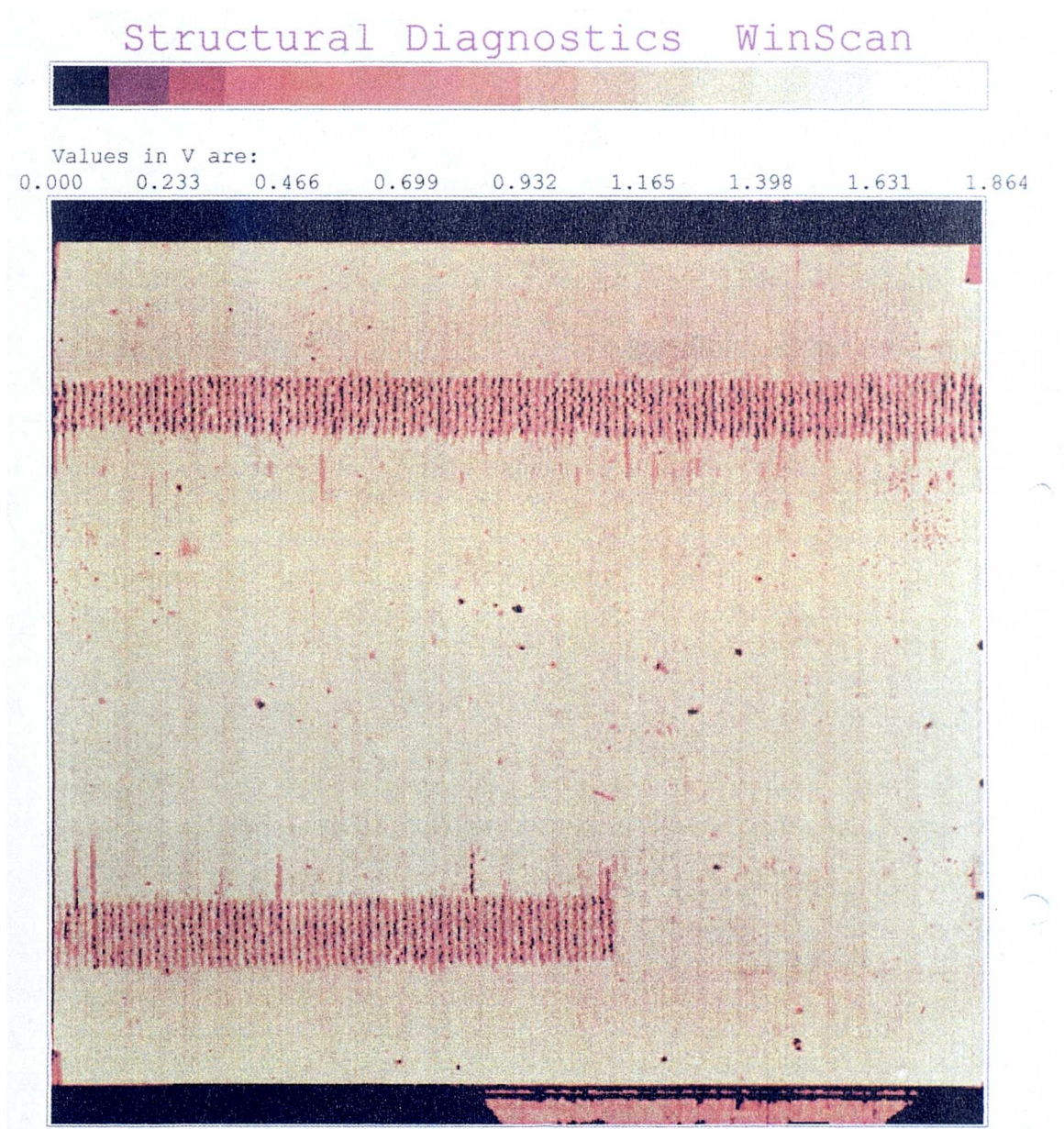
Zhang, 1998

X. Zhang

Impact damage in composite aircraft structures- experimental testing and numerical simulation

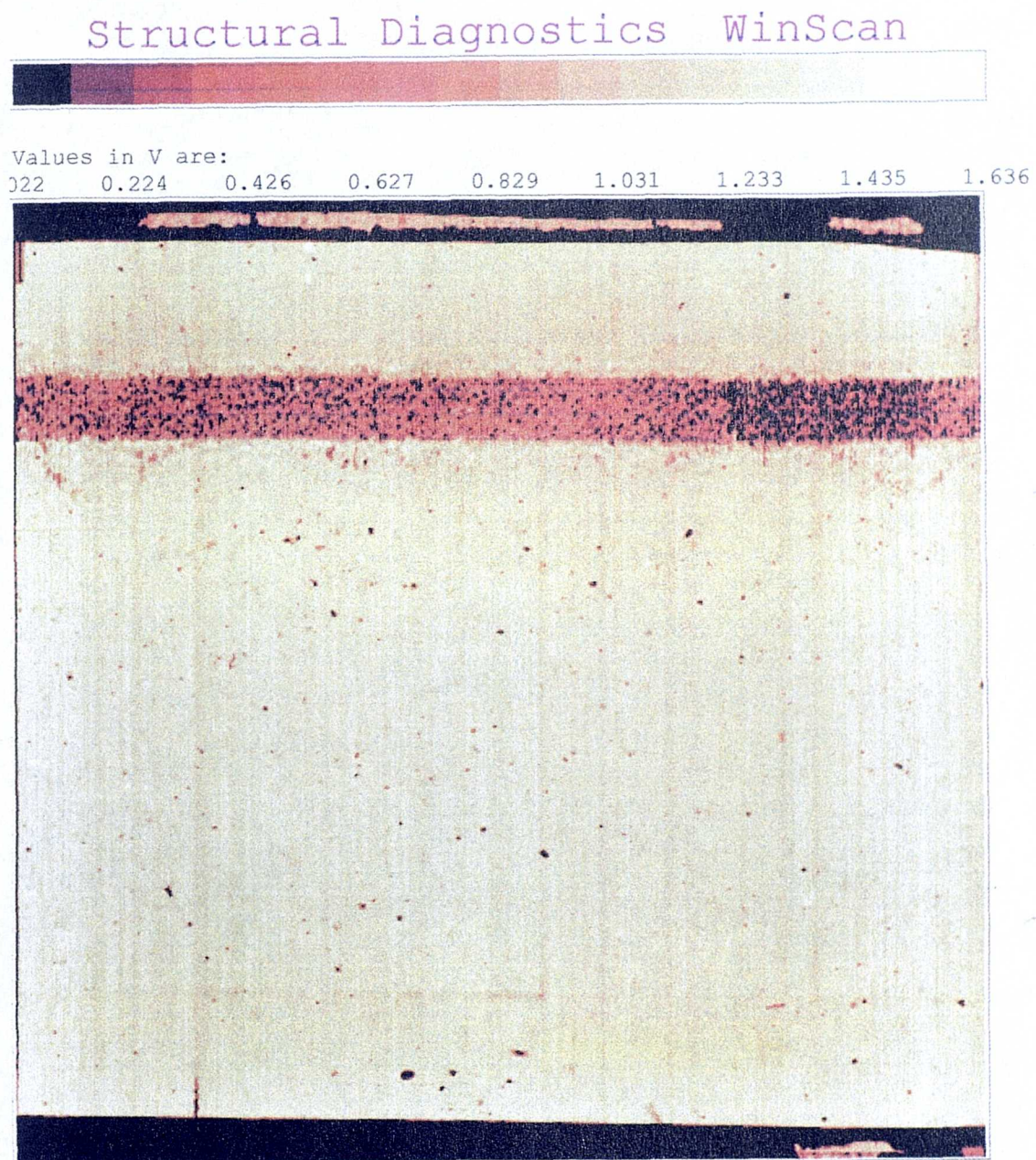
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Appendix A: C-scans



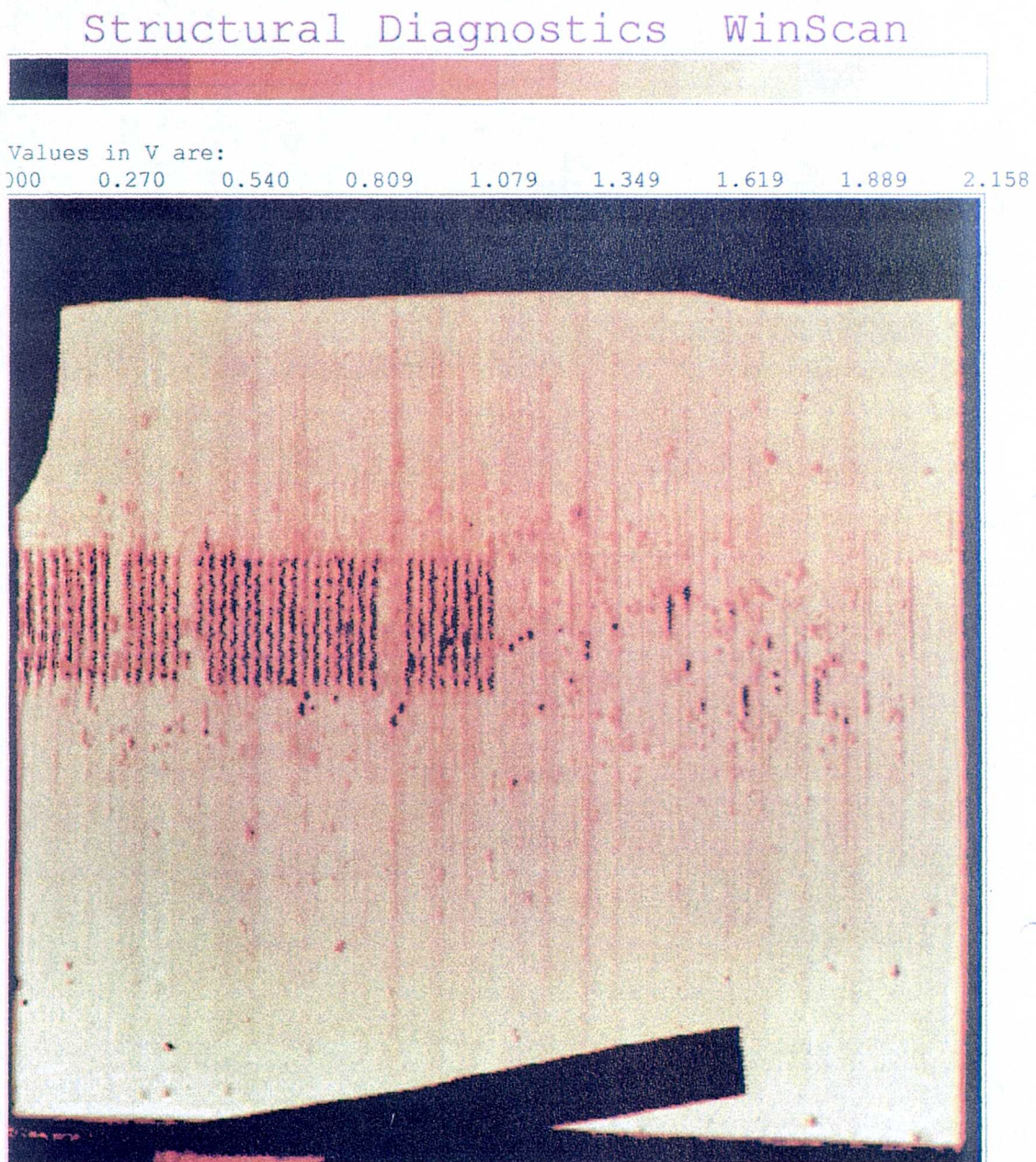
IMS/924

24 ply panel 3.5mm pins



IMS/924

24 ply UD 1.75mm pins



IMS/924

24 ply UD interleaved

Appendix B: Delamination Test Data

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4/18/01 4:51 PM

DCB Mode I from Insert

V2.0 Beta

ge8ana_id3

Points for	x	y	z	y	x	y
Point 1	50.30	0.47	1.70	-0.99	0.46	15.08
Point 2	100.30	0.90	2.00	-0.15	0.90	30.73

Regr. value	Δ	σ	A1
$Y=aX+b$	$Y=aX+b$	$Y=aX+b$	
$a=0.0066$	$a=2.5166$	$a=35.4359$	
$b=0.0347$	$b=5.7857$	$b=1.1974$	
$r=0.9984$	$r=0.9974$	$r=0.9984$	

Test	min.	E-Modulus average	max.	$\sigma/2\theta$
Mat.	134.2	143.0	151.9	15.3354
Prop.	134.2	143.0	151.9	15.3354
Prop.	134.2	143.0	151.9	15.4878
Prop.	134.2	143.0	151.9	15.6402
Prop.	134.2	143.0	151.9	15.9451
Prop.	134.2	143.0	151.9	16.2500
Prop.	134.2	143.0	151.9	16.5549
Prop.	134.2	143.0	151.9	16.8598
Prop.	134.2	143.0	151.9	17.1646
Prop.	134.2	143.0	151.9	17.4695
Prop.	134.2	143.0	151.9	17.7744
Prop.	134.2	143.0	151.9	18.0793
Prop.	134.2	143.0	151.9	18.3841
Prop.	134.2	143.0	151.9	18.6890
Prop.	134.2	143.0	151.9	18.9939
Prop.	134.2	143.0	151.9	19.2988
Prop.	134.2	143.0	151.9	19.6037
Prop.	134.2	143.0	151.9	19.9085
Prop.	134.2	143.0	151.9	20.2134
Prop.	134.2	143.0	151.9	20.5183
Prop.	134.2	143.0	151.9	20.8232
Prop.	134.2	143.0	151.9	21.1280
Prop.	134.2	143.0	151.9	21.4329
Prop.	134.2	143.0	151.9	22.6524
Prop.	134.2	143.0	151.9	22.9573
Prop.	134.2	143.0	151.9	23.2622
Prop.	134.2	143.0	151.9	23.5671
Prop.	134.2	143.0	151.9	23.8720
Prop.	134.2	143.0	151.9	24.1768
Prop.	134.2	143.0	151.9	24.4817
Prop.	134.2	143.0	151.9	25.0001
Prop.	134.2	143.0	151.9	27.5305
Prop.	134.2	143.0	151.9	29.4451
Prop.	134.2	143.0	151.9	29.0549
Prop.	134.2	143.0	151.9	30.5793

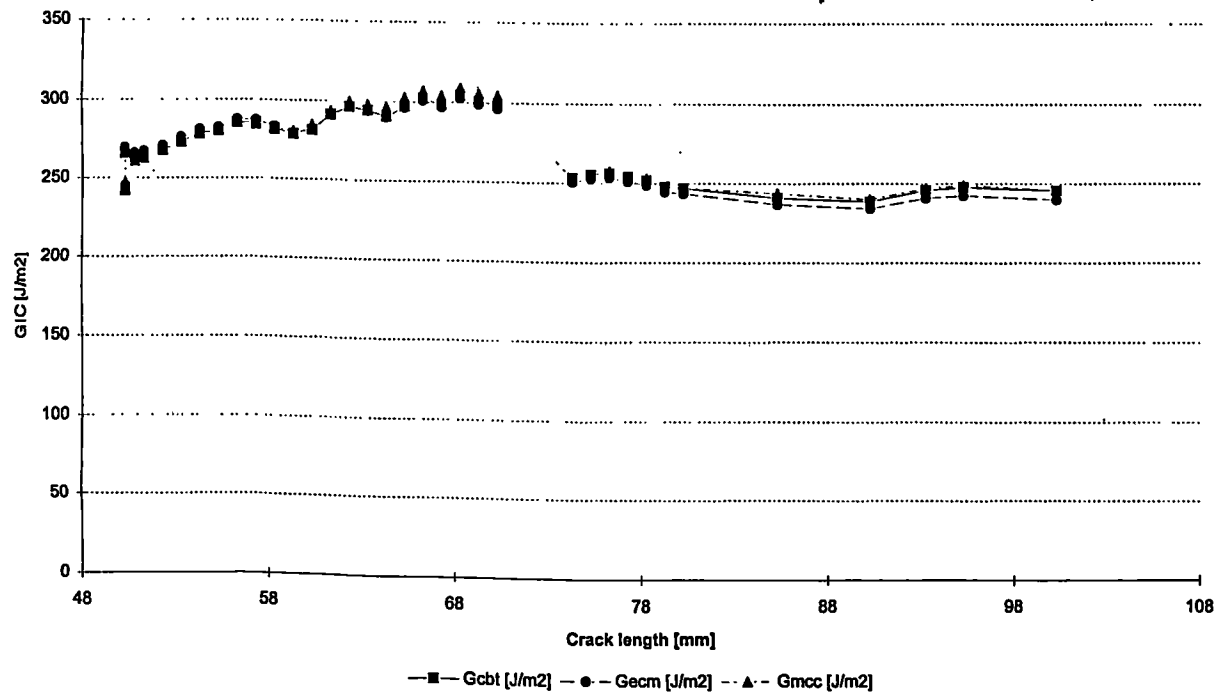
[illegible]

DCB Mode I from Insert

V2.0 Beta

ge6ana.xls

IMS/924 Control



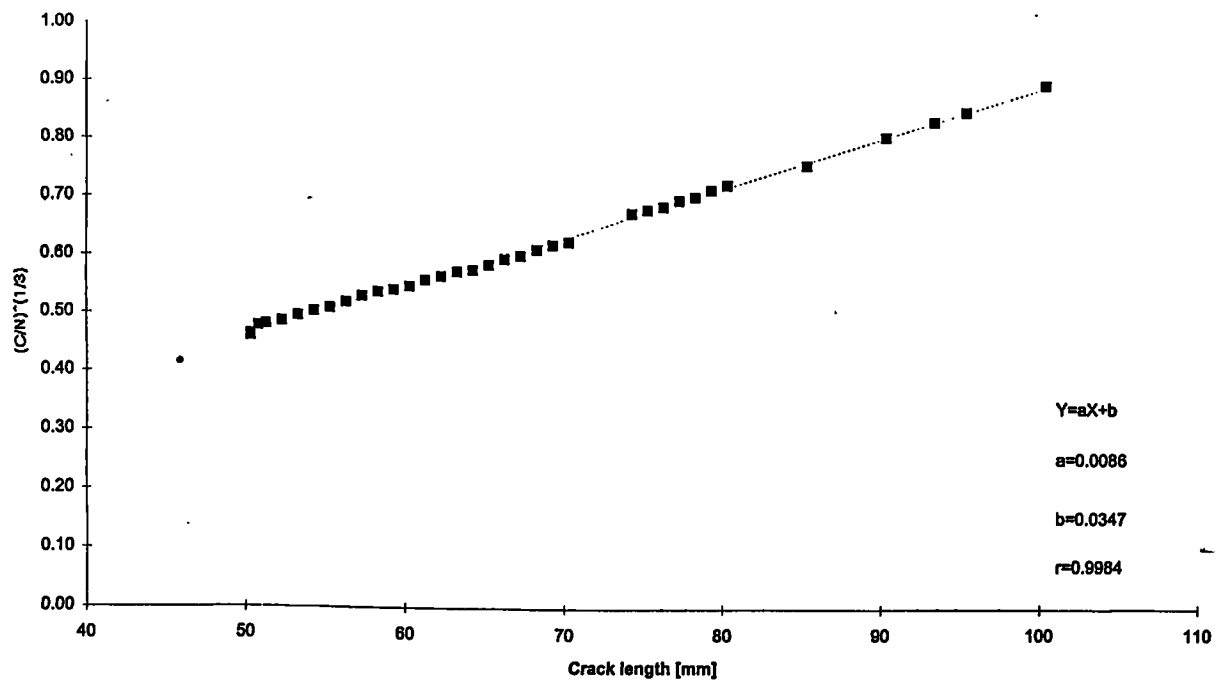
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DCB Mode I from Insert

V2.0 Beta

ge6ana.xls

IMS/924 Control



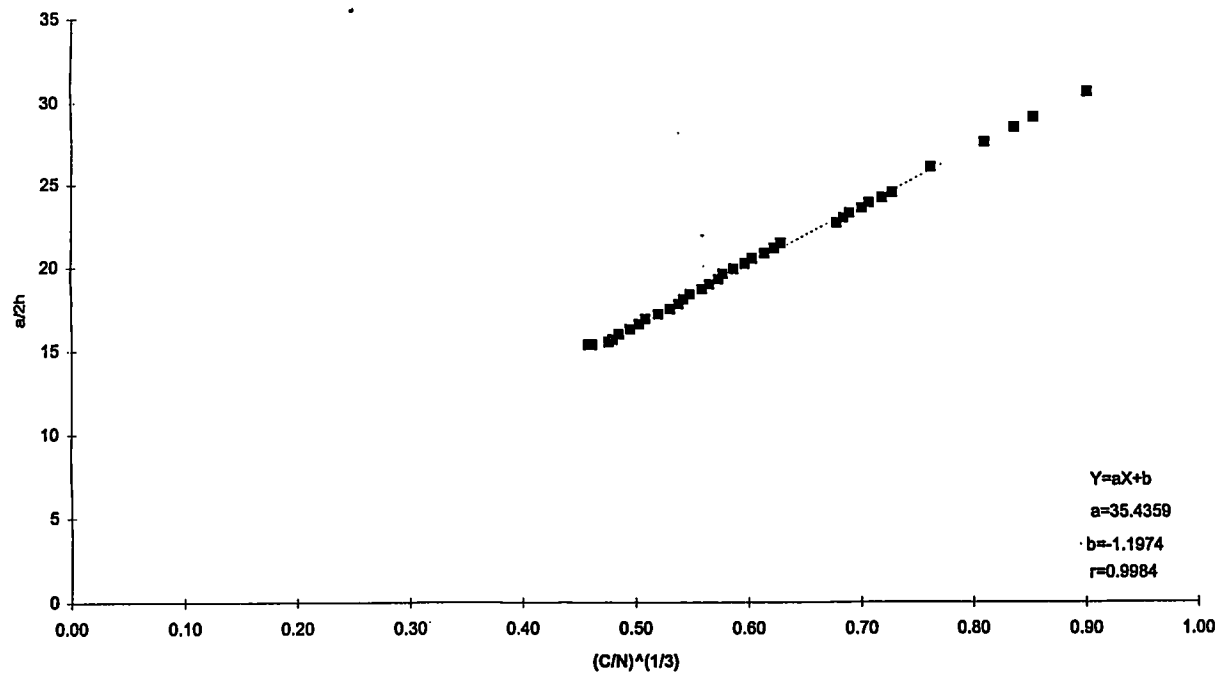
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DCB Mode I from Insert

V2.0 Beta

ge6ana.xls

IMS/924 Control



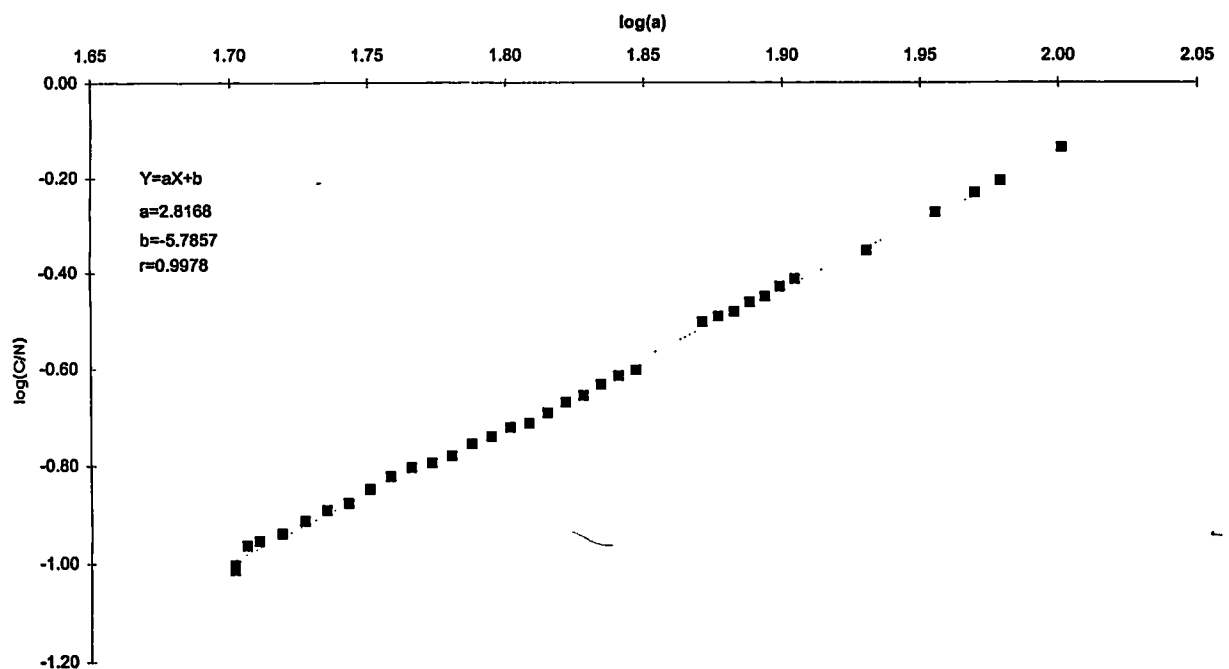
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DCB Mode I from Insert

V2.0 Beta

ge6ana.xls

IMS/924 Control



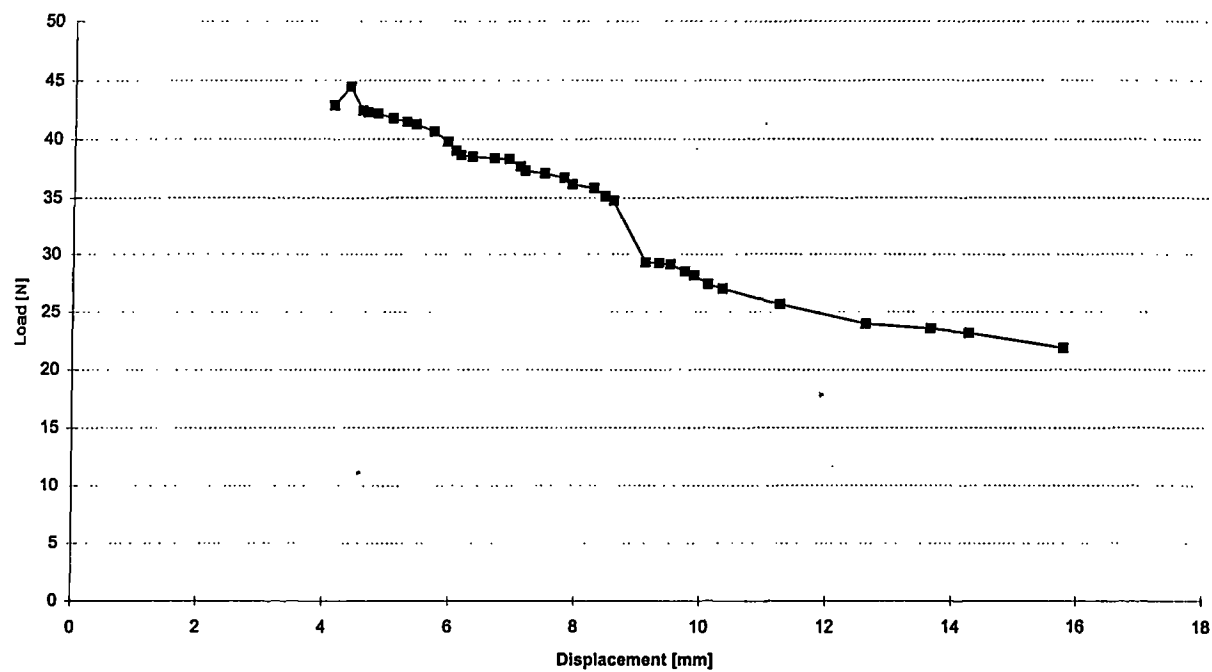
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DCB Mode I from Insert

V2.0 Beta

ge6ana.xls

IMS/924 Control



4/18/01 4:51 PM

DCB Mode I from Insert

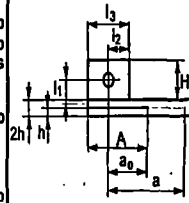
V2.0 Beta

Specimen GRE3: Mode I, 0.5%-0.28mm

gre3ana.xls

Lab/Personnel: Cranfield/D.D.C.	Fiber/Matrix: IMS/924-0.5%-0.28mm	Test Date: 27/08/98	Lab/Personnel: Cranfield
# of Specimens: GRE3	Manufacturer(s): D.C.	Stacking: UD	# of Specimens: GRE3

Specimen length	L [mm]	190.00	Surf. prep/adhesive	[-] MISSING
Free length	L [mm]	MISSING	Block thickness / length	H / l ₃ [mm]
Specimen thickness	2h [mm]	3.23	Max. cure / drying temp.	T _{mc} / T _d [°C]
Max. thickness variation	[mm]	0.05	Cure / drying duration	t _c / t _d [h]
Specimen width	B [mm]	20.00	Test temperature	T [°C]
Starter foil material	[-] Polyimide		Relative humidity	r.h. [%]
Starter foil thickness	[μm]	12.50	Loading/unloading rate	[mm/min]
Starter foil length	A [mm]	61.70	Load introduction	[-] Load blocks
Pre-crack length	a ₀ [mm]	50.70	Max. clamp displacement	d _{max} [mm]
% Change Compliance	Max / 5 [%]	max	(Fiber volume fraction)	(V _f [Vol%])
			Distances l ₁ /l ₂	[mm]



Regression

Method	Gcbt
Value	slope 0.0073405 Y-axis 0.1055528
Correction	Δ = -14.3796
Correl. coef	0.990753

Text	a [mm]	Measure Load [N]	δ [mm]
NL	50.70	39.60	3.94
Max	50.70	41.40	4.19
Prop.	50.70	40.96	4.40
Prop.	52.20	38.63	4.48
Prop.	52.70	39.19	4.55
Prop.	53.20	46.42	5.57
Prop.	53.70	51.24	6.23
Prop.	53.90	52.07	6.52
Prop.	56.20	51.04	6.76
Prop.	56.70	55.65	8.58
Prop.	57.20	59.72	9.28
Prop.	60.20	59.20	9.31
Prop.	60.40	59.95	9.49
Prop.	60.40	76.62	12.15
Prop.	63.20	68.86	12.20
Prop.	64.70	75.62	13.95
Prop.	66.70	72.73	14.64
Prop.	67.70	78.62	16.23
Prop.	68.20	79.96	17.01
Prop.	70.70	74.06	17.07
Prop.	72.20	81.91	19.99
Prop.	74.70	75.61	20.00
Prop.	75.20	76.22	21.11
Prop.	78.70	68.25	21.16
Prop.	80.70	65.90	22.56

Plate Manufacturer:

Specimen and Insert
Location on Plate

Results	Gcbt [J/m ²]	Gecm [J/m ²]	E-Mod. [GPa]	Gmcc [J/m ²]
	179.3	186.8	260.5	186.6
	199.3	207.6	255.9	206.3
	207.1	215.6	241.0	210.0
	194.4	201.1	239.1	196.6
	198.8	205.3	244.3	202.5
	285.9	294.6	241.0	290.2
	350.2	360.2	242.8	356.6
	371.3	381.6	237.7	375.5
	365.1	372.0	248.3	374.6
	501.1	509.6	216.8	492.1
	577.2	586.0	219.3	569.4
	551.3	554.1	245.6	564.3
	567.5	570.0	245.9	581.2
	926.7	930.8	243.5	948.5
	806.6	803.2	243.9	825.4
	992.7	984.3	247.1	1021.7
	977.2	963.7	244.1	1001.7
	1155.8	1136.6	246.0	1189.3
	1224.0	1202.4	242.6	1254.5
	1104.9	1078.7	245.5	1136.0
	1404.0	1365.9	242.8	1441.1
	1261.1	1220.1	244.4	1296.6
	1333.5	1288.7	236.7	1357.8
	1152.9	1106.3	238.1	1174.8
	1161.5	1110.2	229.4	1169.6

Average
Max. Variation241.7
Check

4/18/01 4:49 PM

DCB Mode I from Insert

V2.0 Beta

gre3ana.xls

D.D.C.	IMS/924-0.5%-0.28mm	Test Date: 27/08/98	Lab/Personnel: Cranfield/D.D.C.	IMS/924
Manufacturer(s): D.C.		Stacking: UD	# of Specimens: GRE3	Manufacturer(s):

Comments and Observations

Gecm	Gmcc
slope 2.4338517	Y-axis -5.114417
n= 2.4339	Y-axis -4.230192
0.989368	0.990753

Variation 18.08

Points for
Point 1
Point 2
Regr. value
a=
b=

F/N [-]	C/N [mm/N]	(C/N)*1/3 [mm/N]	log(C/N) [mm/N]	log(a) [mm]	δ/a (< 0.4 ?)	Check ok ? (yes or no)
0.9974	0.1005	0.4849	-0.9980	1.7050	0.0777	yes
0.9972	0.1023	0.4676	-0.9902	1.7050	0.0826	yes
0.9970	0.1086	0.4771	-0.9641	1.7050	0.0868	yes
0.9971	0.1172	0.4894	-0.9310	1.7177	0.0858	yes
0.9971	0.1173	0.4896	-0.9305	1.7218	0.0863	yes
0.9964	0.1216	0.4954	-0.9151	1.7259	0.1047	yes
0.9959	0.1234	0.4979	-0.9087	1.7300	0.1160	yes
0.9957	0.1272	0.5029	-0.8956	1.7316	0.1210	yes
0.9959	0.1344	0.5123	-0.8714	1.7497	0.1203	yes
0.9945	0.1573	0.5398	-0.8033	1.7536	0.1513	yes
0.9941	0.1588	0.5415	-0.7991	1.7574	0.1622	yes
0.9946	0.1604	0.5433	-0.7948	1.7796	0.1547	yes
0.9945	0.1615	0.5446	-0.7918	1.7810	0.1571	yes
0.9925	0.1631	0.5463	-0.7876	1.7810	0.2012	yes
0.9931	0.1818	0.5685	-0.7404	1.8007	0.1930	yes
0.9922	0.1900	0.5749	-0.7212	1.8109	0.2156	yes
0.9922	0.2074	0.5919	-0.6832	1.8241	0.2195	yes
0.9913	0.2135	0.5977	-0.6706	1.8306	0.2397	yes
0.9909	0.2204	0.6041	-0.6568	1.8338	0.2494	yes
0.9915	0.2363	0.6199	-0.6230	1.8494	0.2414	yes
0.9898	0.2541	0.6334	-0.5950	1.8585	0.2769	yes
0.9905	0.2746	0.6500	-0.5612	1.8733	0.2677	yes
0.9899	0.2883	0.6606	-0.5401	1.8762	0.2807	yes
0.9908	0.3217	0.6852	-0.4926	1.8960	0.2689	yes
0.9904	0.3558	0.7086	-0.4488	1.9069	0.2796	yes

Text	min.	E-Modulus average	max.	a/2h
NL	223.8	241.7	259.8	15.6996
Max	223.8	241.7	259.8	15.6966
Prop.	223.8	241.7	259.8	15.6966
Prop.	223.8	241.7	259.8	16.1610
Prop.	223.8	241.7	259.8	16.3158
Prop.	223.8	241.7	259.8	16.4706
Prop.	223.8	241.7	259.8	16.6254
Prop.	223.8	241.7	259.8	16.6873
Prop.	223.8	241.7	259.8	17.3994
Prop.	223.8	241.7	259.8	17.5542
Prop.	223.8	241.7	259.8	17.7090
Prop.	223.8	241.7	259.8	18.6376
Prop.	223.8	241.7	259.8	18.6997
Prop.	223.8	241.7	259.8	18.6997
Prop.	223.8	241.7	259.8	19.5666
Prop.	223.8	241.7	259.8	20.0310
Prop.	223.8	241.7	259.8	20.6502
Prop.	223.8	241.7	259.8	20.9598
Prop.	223.8	241.7	259.8	21.1146
Prop.	223.8	241.7	259.8	21.8885
Prop.	223.8	241.7	259.8	22.3529
Prop.	223.8	241.7	259.8	23.1268
Prop.	223.8	241.7	259.8	23.2817
Prop.	223.8	241.7	259.8	24.3653
Prop.	223.8	241.7	259.8	24.9645

Missing

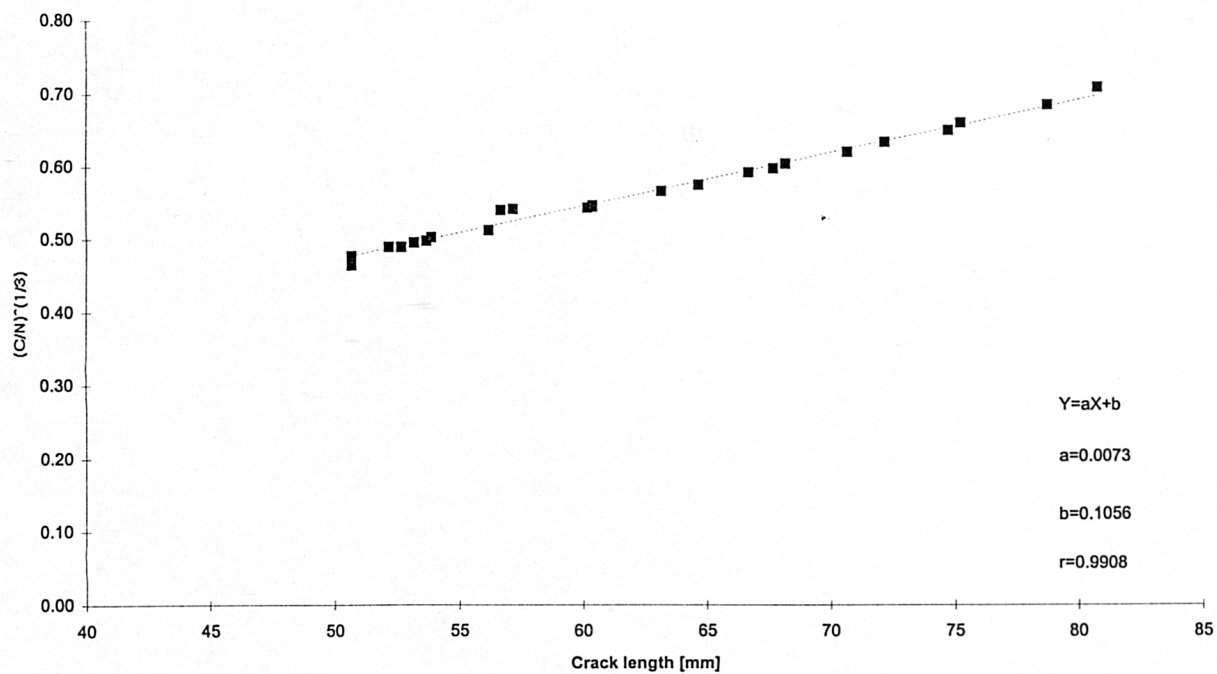
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DCB Mode I from Insert

V2.0 Beta

gre3ana.xls

IMS/924-0.5%-0.28mm



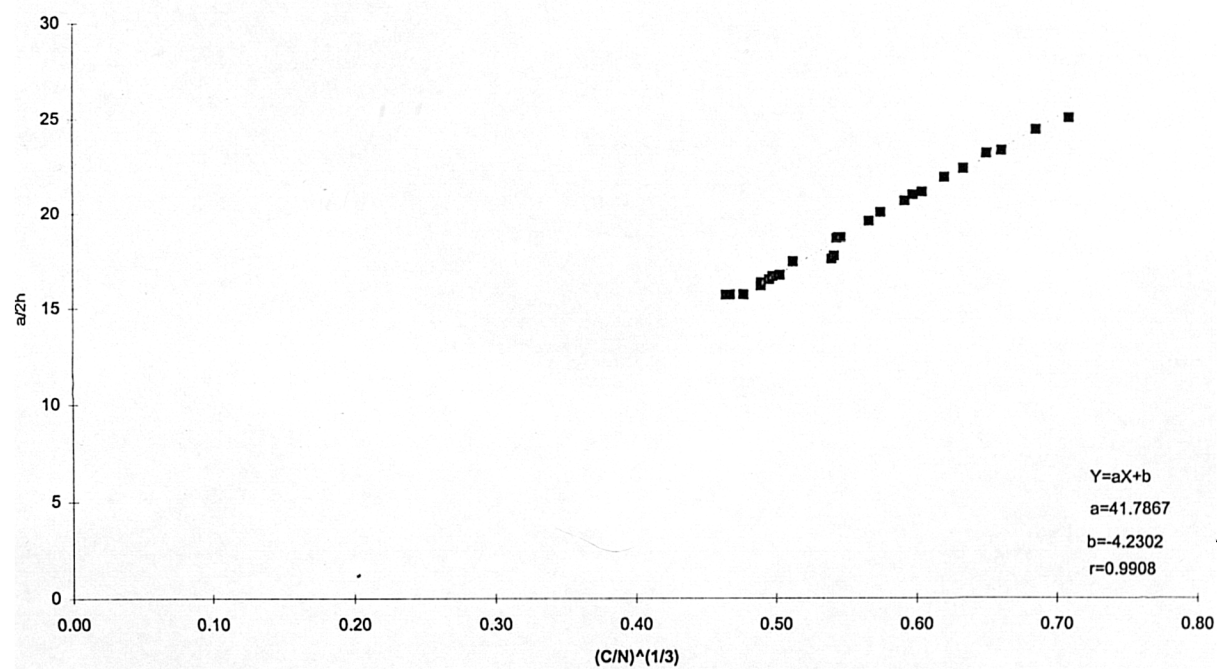
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V2.0 Beta

gre3ana.xls

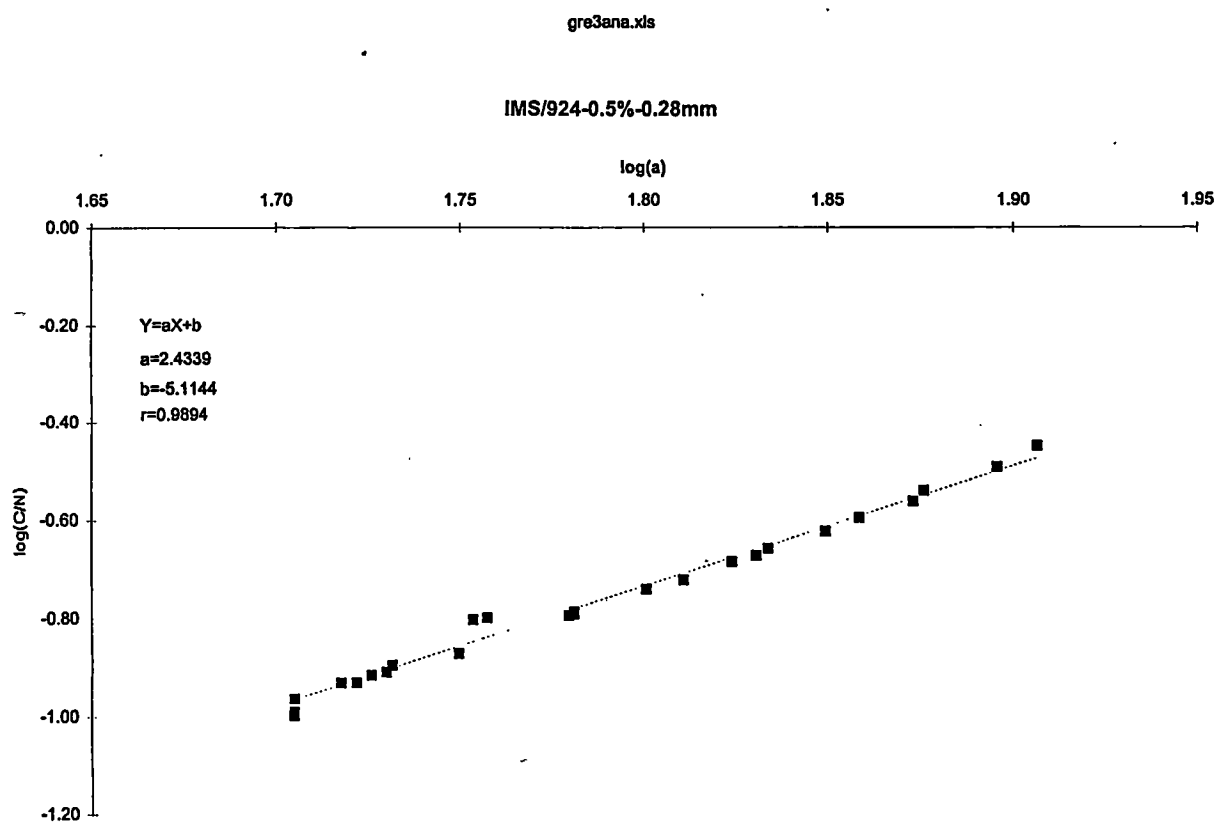
IMS/924-0.5%-0.28mm



4/18/01 4:49 PM

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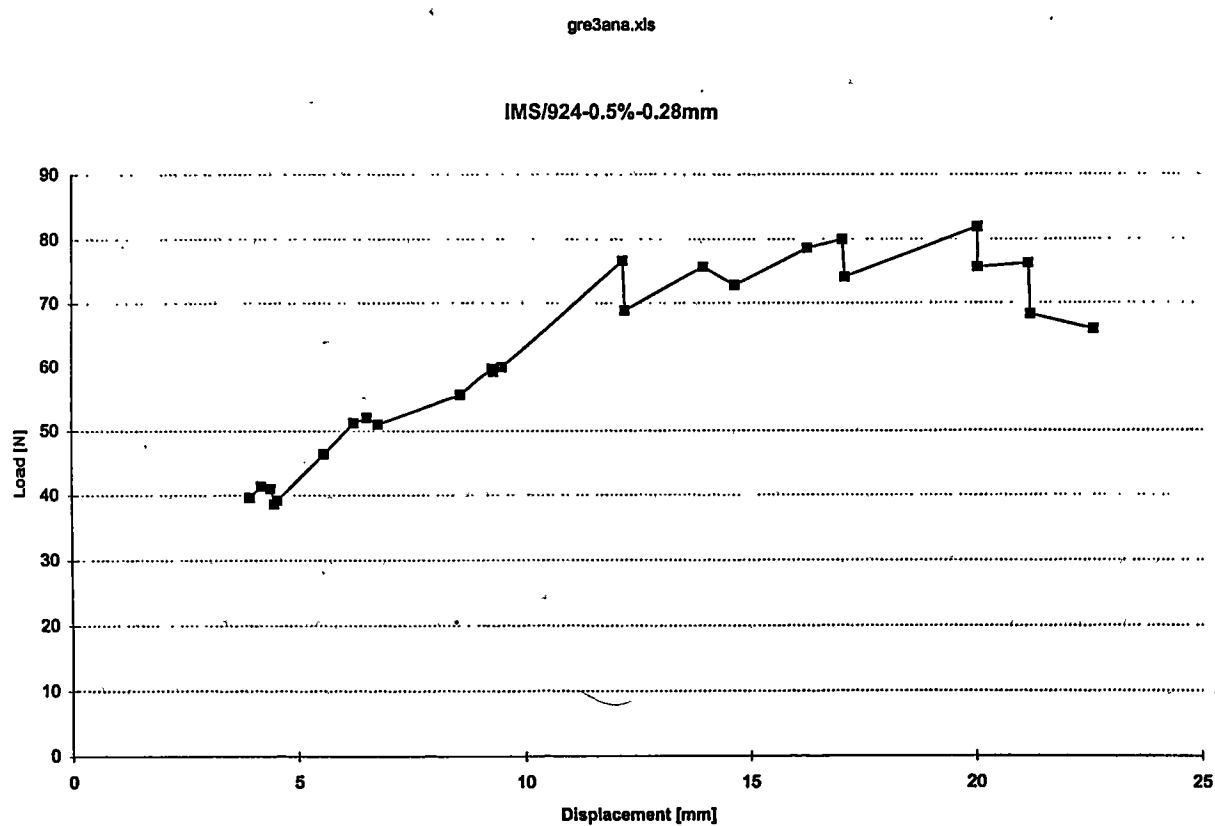
V2.0 Beta



4/18/01 4:49 PM

DCB Mode I from Insert

V2.0 Beta



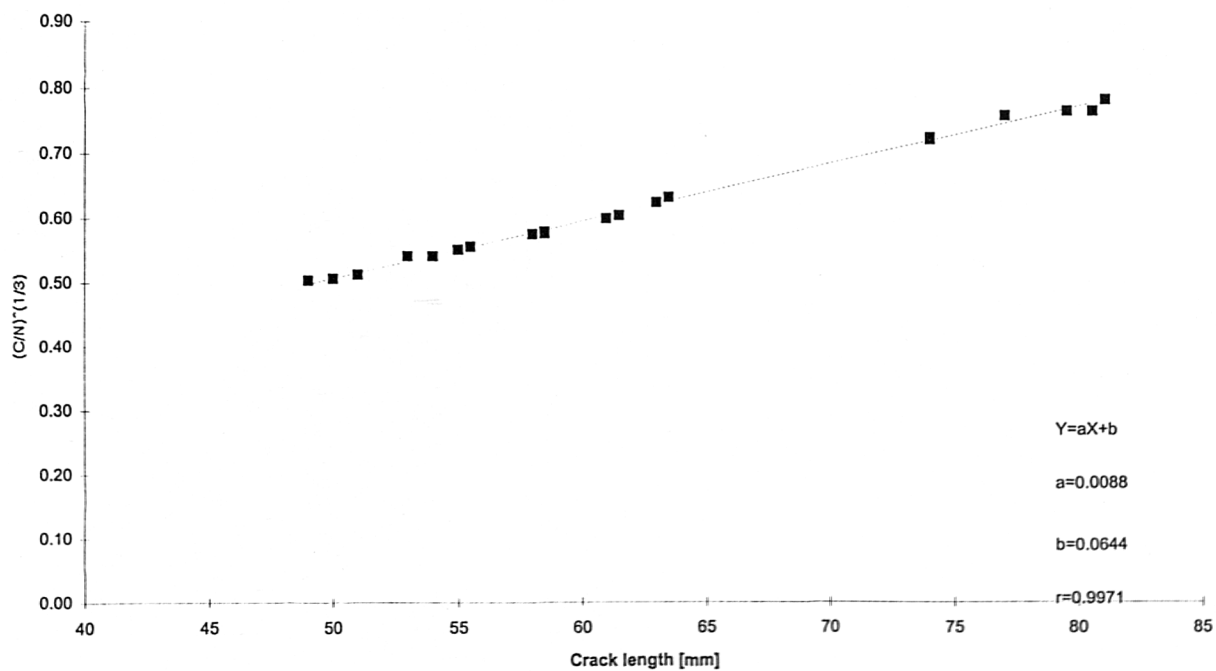
4/18/01 4:49 PM

DCB Mode I from Insert

V2.0 Beta

GTE1.xls

IMS/924-2%-0.51mm



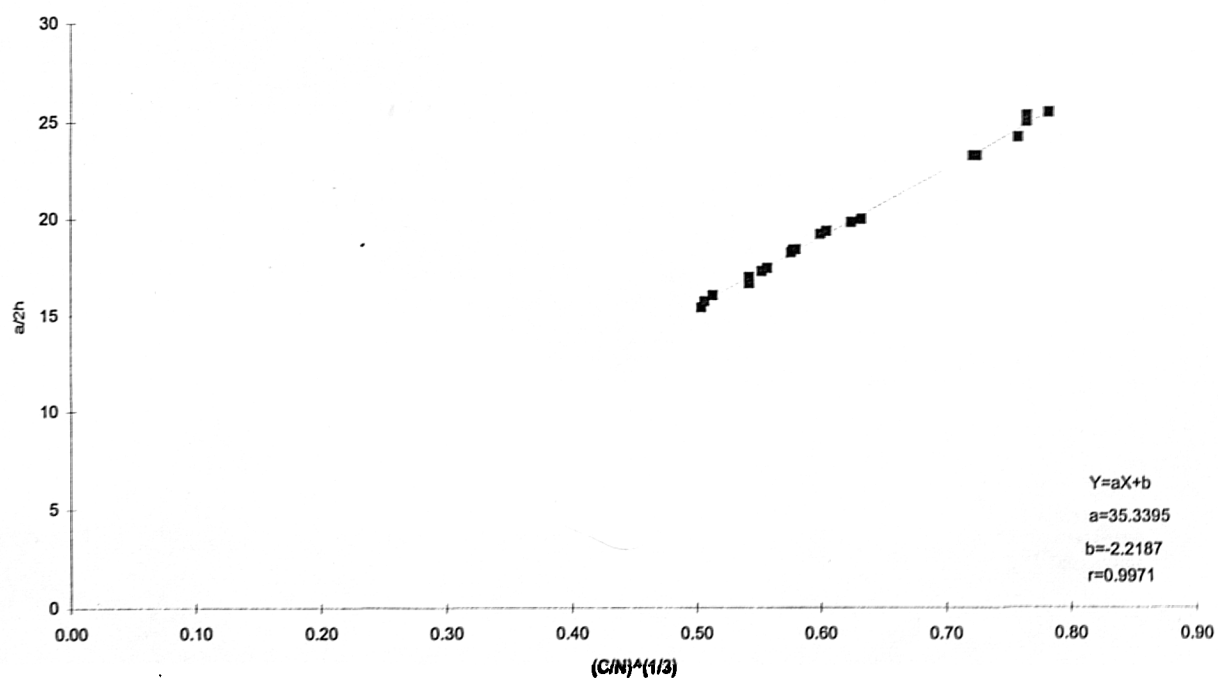
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DCB Mode I from Insert

V2.0 Beta

GTE1.xls

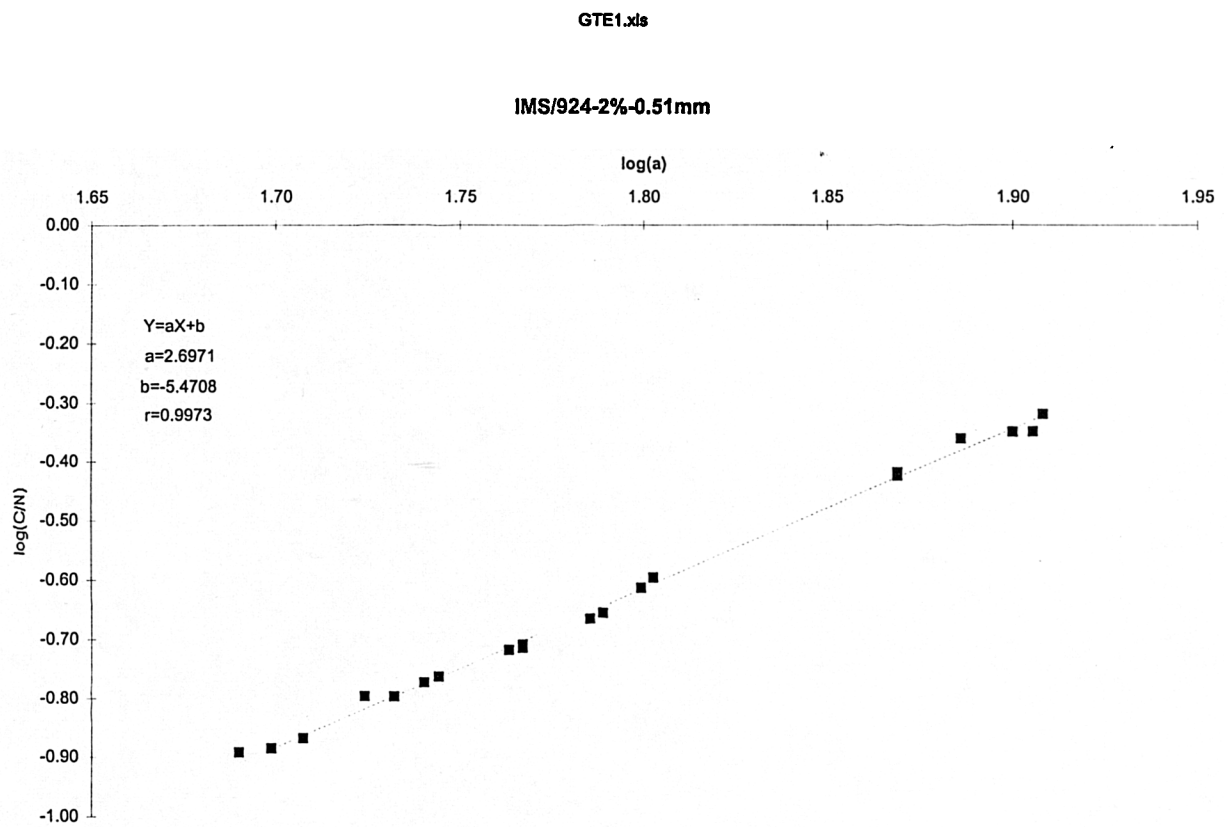
IMS/924-2%-0.51mm



4/18/01 4:48 PM

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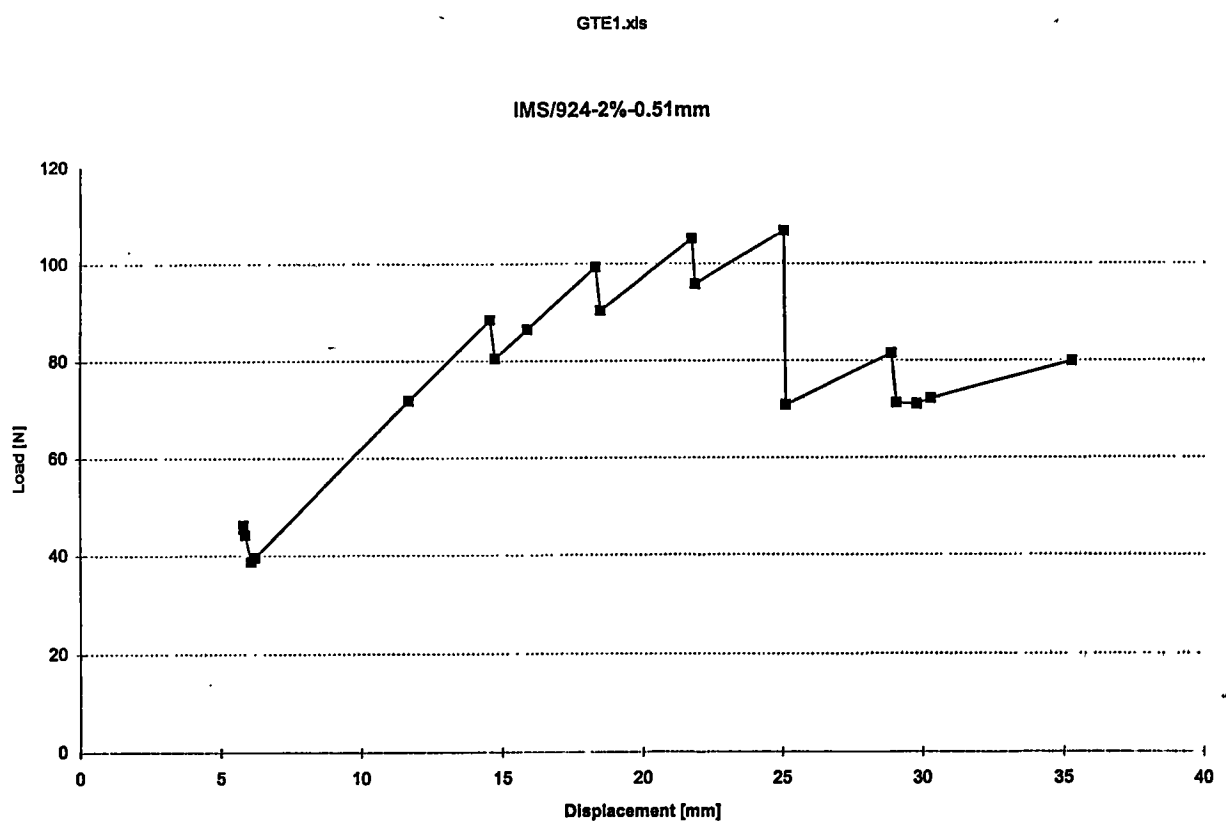
V2.0 Beta



4/18/01 4:48 PM

DCB Mode I from Insert

V2.0 Beta



4/18/01 4:48 PM

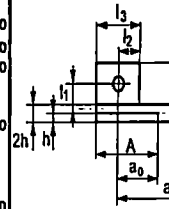
DCB Mode I from Insert

V2.0 Beta

Specimen GSE7: Mode I, 2%-0.28mm

gse7ana.xls

Lab/Personnel:	Cranfield / D.C.	Fiber/Matrix:	IMS/924 2%-0.28mm	Test Date:	04/11/98	Lab/Personnel:	
# of Specimens:	GSE7	Manufacturer(s):	D.C.	Stacking:	UD	# of Specimens:	
Specimen length	l [mm]	180.00	Surf. prep/adhesive	[-] Sand paper			
Free length	L [mm]	190.00	Block thickness / length	H / l ₃ [mm]	7.50 /	15.00	
Specimen thickness	2h [mm]	3.26	Max. cure / drying temp.	T _{mc} / T _d [°C]	180.00 /	70.00	
Max. thickness variation	[mm]	0.10	Cure / drying duration	t _c / t _d [h]	2.00 /	76.00	
Specimen width	B [mm]	20.05	Test temperature	T [°C]	23.00		
Starter foil material	[-] Polyimide		Relative humidity	r.h. [%]	MISSING		
Starter foil thickness	μm	13.00	Loading/unloading rate	[mm/min]	1.00 /	1.00	
Starter foil length	A [mm]	61.00	Load introduction	[-] Load blocks			
Pracrack length	a ₀ [mm]	50.20	Max. clamp displacement	dmax [mm]	45.00		
% Change Compliance	Max / 5% [%]	3.00	(Fiber volume fraction)	(Vf [Vol%])	MISSING		
			Distances l ₁ /l ₂	[mm]	4.57 /	3.50	



Regression

Method	Gc
Value	slope
	0.007968
Correction	Δ=
Correl. coef	0.993645

Text	a [mm]	Measure Load [N]	δ [mm]	Plate Manufacturer: Specimen and Insert Location on Plate	Results				Comments	Text	F [-] (≥ 0.9 ?)
					Gc _{bt} [J/m ²]	Gc _{cm} [J/m ²]	E-Mod. [GPa]	Gm _{cc} [J/m ²]			
NL	50.20	44.69	4.16		240.8	244.8	187.0	245.4		NL	0.9866
Max	50.20	46.60	4.41		266.2	270.6	183.8	269.7		Max	0.9857
Prop.	51.00	47.58	4.78		290.5	294.7	180.4	292.5		Prop.	0.9848
Prop.	51.80	88.19	9.26		1024.8	1037.6	177.2	1031.0		Prop.	0.9688
Prop.	52.00	95.86	10.09		1208.7	1223.2	178.0	1219.1		Prop.	0.9632
Prop.	52.50	101.44	10.81		1358.1	1372.8	179.9	1375.7		Prop.	0.9604
Prop.	53.00	104.03	11.18		1428.2	1442.0	182.7	1454.7		Prop.	0.9594
Prop.	54.00	118.77	13.68		1958.2	1972.6	177.5	1981.2		Prop.	0.9486
Prop.	55.00	126.42	14.71		2203.8	2215.2	183.9	2258.4		Prop.	0.9452
Prop.	56.00	146.04	17.69		3004.6	3013.6	183.1	3086.7		Prop.	0.9314
Prop.	58.50	176.60	22.35		4398.0	4389.3	193.4	4628.2		Prop.	0.9115
Prop.	58.50	185.00	25.27		5188.9	5178.6	176.3	5323.3		Prop.	0.8935
Prop.	62.00	173.93	25.42		4671.7	4632.9	194.3	4934.8		Prop.	0.9043
Prop.	63.20	167.86	27.48		4783.2	4733.9	181.3	4949.2		Prop.	0.8962
Prop.	64.00	178.37	29.95		5463.5	5400.2	180.9	5669.2		Prop.	0.8842
Prop.	65.00	177.72	30.22		5419.5	5348.1	186.5	5678.3		Prop.	0.8862
Prop.	66.50	176.95	31.87		5570.2	5484.2	186.5	5844.1		Prop.	0.8817
Prop.	67.20	169.26	32.01		5303.5	5216.1	183.0	5526.2		Prop.	0.8834
Prop.	68.00	168.11	32.67		5318.1	5224.4	183.7	5550.3		Prop.	0.8824
Prop.	73.00	137.07	34.06		4248.4	4145.5	175.5	4356.1		Prop.	0.8909
Prop.	74.00	139.15	34.74		4344.7	4234.2	181.2	4503.1		Prop.	0.8904
Prop.	74.50	150.10	38.19		5102.8	4970.0	178.4	5287.9		Prop.	0.8741
Average					182.5						
Max. Variation					Check						

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DCB Mode I from Insert

V2.0 Beta

gse7ana.xls

Cranfield / D.C.	IMS/924 2%-0.28mm	Test Date:	04/11/98	Lab/Personnel:	Cranfield / D.C.
GSE7	Manufacturer(s): D.C.	Stacking:	UD	# of Specimens:	GSE7

Comments and Observations

bt		Gc _{cm}		Gm _{cc}	
Y-axis	slope	Y-axis	slope	Y-axis	slope
0.05886	2.6583593	-5.536151	38.252852	-2.132671	
-7.3870	n=	2.6584	A1=	38.2529	
	0.992967		0.993645		

Variation 10.32

N	F/N	C/N	(C/N) ^{1/3}	log(C/N)	log(a)	δ/a	Check ok ?
[-]	[-]	[mm/VN]	[mm/VN]	[mm/VN]	[mm]	(< 0.4 ?)	(yes or no)
0.9895	0.9971	0.0941	0.4548	-1.0265	1.7007	0.0829	yes
0.9887	0.9969	0.0957	0.4574	-1.0190	1.7007	0.0878	yes
0.9880	0.9967	0.1017	0.4667	-0.9928	1.7076	0.0937	yes
0.9738	0.9928	0.1078	0.4760	-0.9673	1.7143	0.1788	yes
0.9709	0.9920	0.1084	0.4768	-0.9649	1.7160	0.1940	yes
0.9687	0.9914	0.1100	0.4791	-0.9586	1.7202	0.2059	yes
0.9679	0.9912	0.1110	0.4806	-0.9546	1.7243	0.2109	yes
0.9592	0.9889	0.1201	0.4933	-0.9205	1.7324	0.2533	yes
0.9565	0.9883	0.1217	0.4955	-0.9149	1.7404	0.2675	yes
0.9452	0.9854	0.1281	0.5042	-0.8923	1.7482	0.3159	yes
0.9288	0.9813	0.1363	0.5146	-0.8657	1.7672	0.3821	yes
0.9140	0.9775	0.1494	0.5307	-0.8255	1.7672	0.4320	yes
0.9227	0.9800	0.1584	0.5411	-0.8003	1.7924	0.4100	yes
0.9160	0.9784	0.1787	0.5633	-0.7478	1.8007	0.4348	yes
0.9061	0.9759	0.1853	0.5701	-0.7321	1.8062	0.4680	yes
0.9076	0.9764	0.1873	0.5722	-0.7274	1.8129	0.4649	yes
0.9039	0.9755	0.1993	0.5841	-0.7006	1.8228	0.4782	yes
0.9052	0.9759	0.2089	0.5934	-0.6800	1.8274	0.4763	yes
0.9043	0.9757	0.2149	0.5990	-0.6678	1.8325	0.4804	yes
0.9112	0.9778	0.2727	0.6485	-0.5643	1.8633	0.4666	yes
0.9107	0.9777	0.2741	0.6496	-0.5620	1.8692	0.4695	yes
0.8971	0.9743	0.2836	0.6570	-0.5473	1.8722	0.5126	yes

Text	min.	E-Modulus average	max.	a/2h
NL	172.2	182.5	192.8	15.3988
Max	172.2	182.5	192.8	15.3988
Prop.	172.2	182.5	192.8	15.6442
Prop.	172.2	182.5	192.8	15.8696
Prop.	172.2	182.5	192.8	15.9509
Prop.	172.2	182.5	192.8	16.1043
Prop.	172.2	182.5	192.8	16.2577
Prop.	172.2	182.5	192.8	16.5644
Prop.	172.2	182.5	192.8	16.8712
Prop.	172.2	182.5	192.8	17.1779
Prop.	172.2	182.5	192.8	17.9448
Prop.	172.2	182.5	192.8	17.9448
Prop.	172.2	182.5	192.8	19.0184
Prop.	172.2	182.5	192.8	19.3865
Prop.	172.2	182.5	192.8	19.6319
Prop.	172.2	182.5	192.8	19.9387
Prop.	172.2	182.5	192.8	20.3988
Prop.	172.2	182.5	192.8	20.6135
Prop.	172.2	182.5	192.8	20.8589
Prop.	172.2	182.5	192.8	22.3926
Prop.	172.2	182.5	192.8	22.6994
Prop.	172.2	182.5	192.8	22.8528

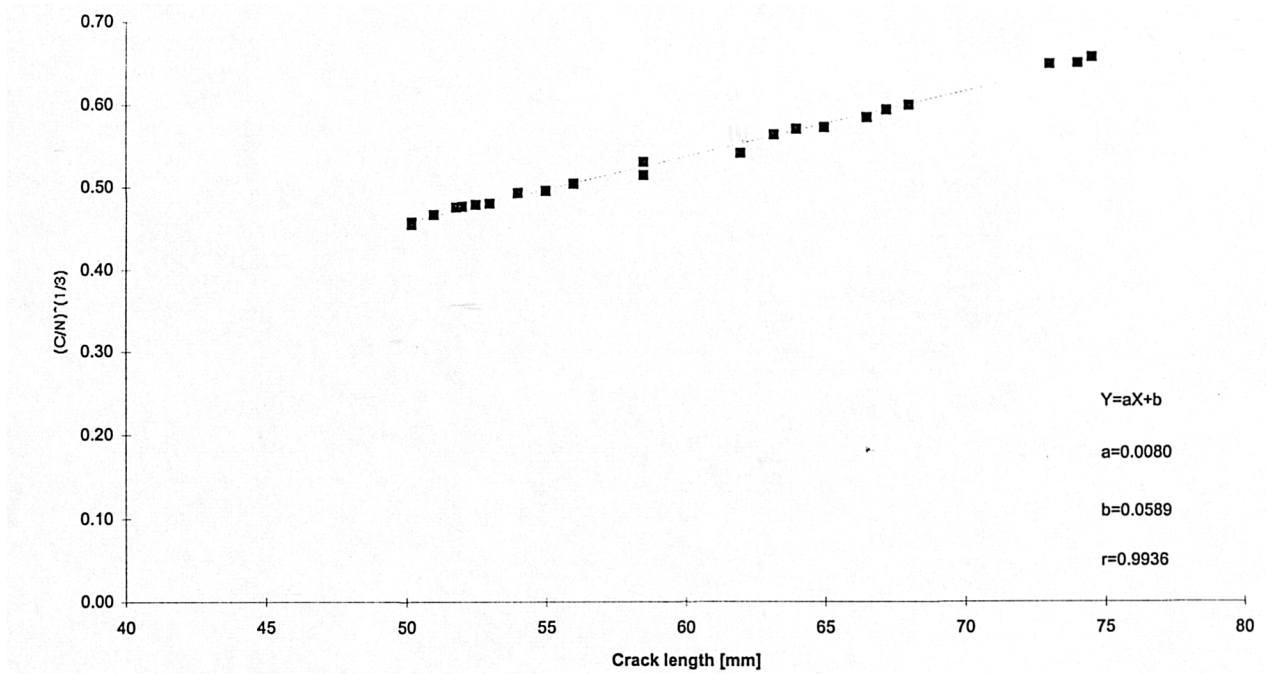
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DCB Mode I from Insert

V2.0 Beta

gse7ana.xls

IMS/924 2%-0.28mm



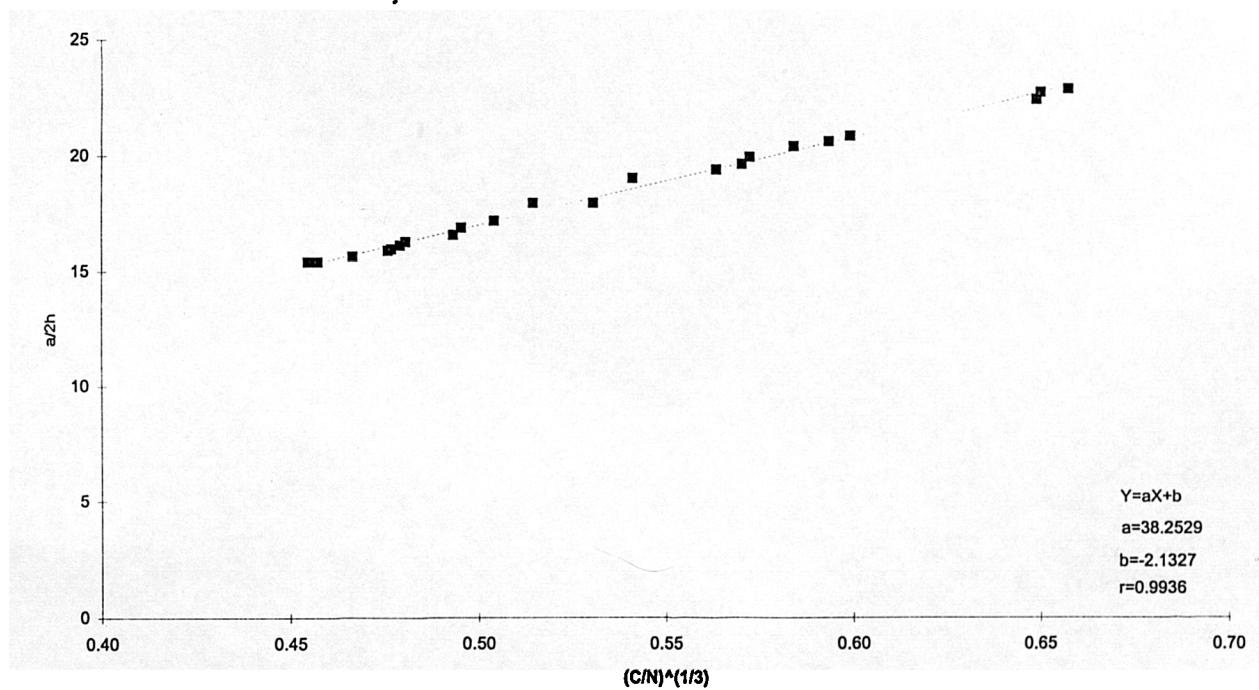
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DCB Mode I from Insert

V2.0 Beta

gse7ana.xls

IMS/924 2%-0.28mm



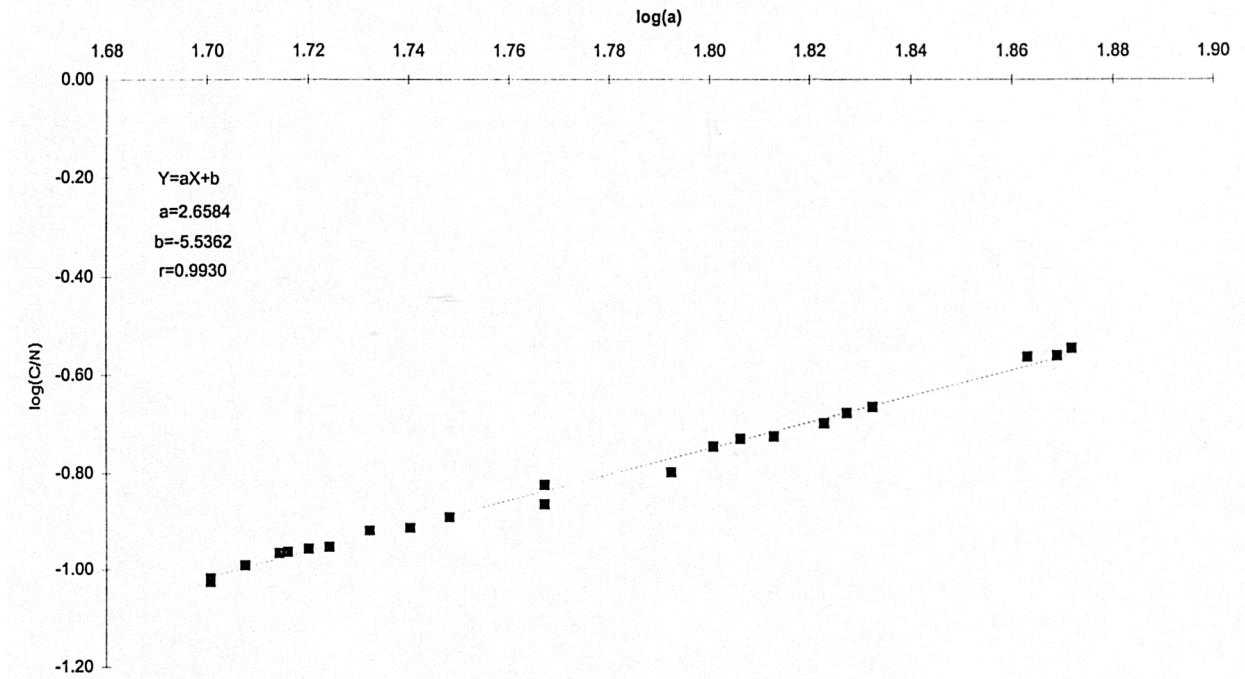
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DCB Mode I from Insert

V2.0 Beta

gse7ana.xls

IMS/924 2%-0.28mm



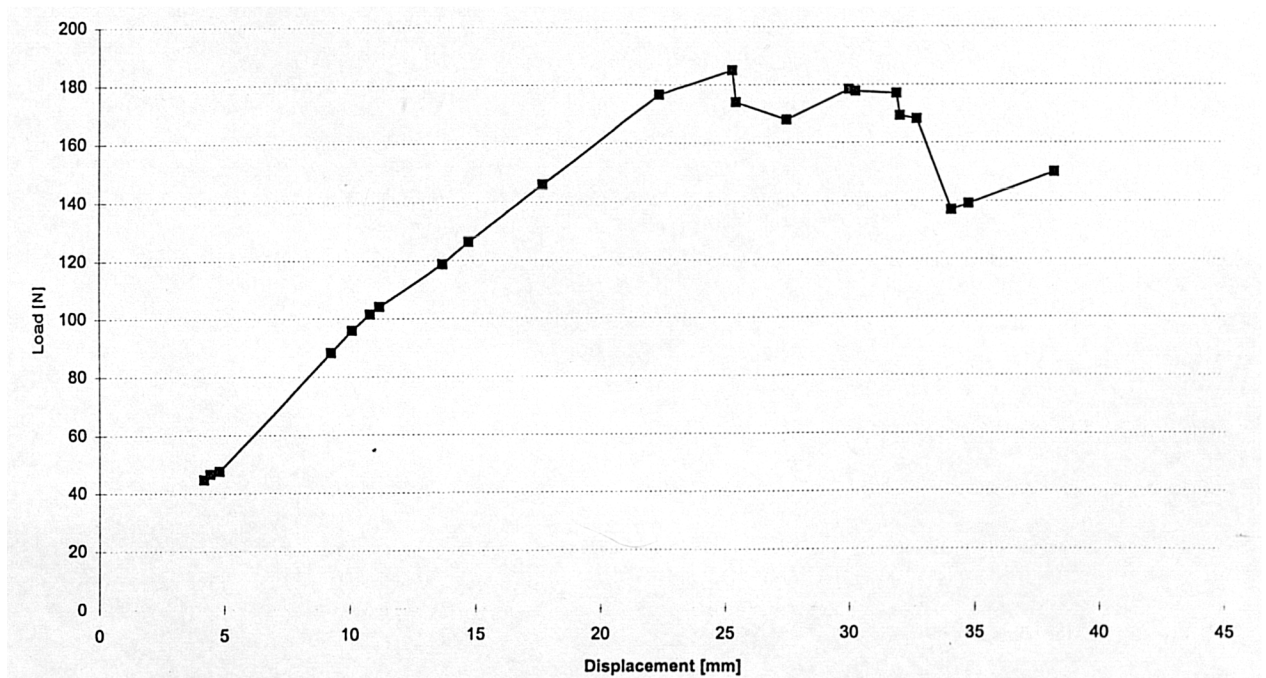
4/18/01 4:46 PM

DCB Mode I from Insert

V2.0 Beta

gse7ana.xls

IMS/924 2%-0.28mm



4/18/01 4:46 PM

DCB Mode I from Insert

V2.0 Beta

Specimen GE11: Mode II Control

MODE II ENF REPORTING FORM

MODE II		Test Laboratory: Cranfield				Material: IMS/924 control		Specimen: GE11	
		Date: 20/08/98						Number:	
Ave. Thickness		Ave. Width		Loading Rate		Temperature 23 °C		Defect Type:	
2h 3.08 mm		B 20.16 mm		0.5 mm/min		R. Humidity %		Insert: 12.5 µm	
Vf: %		2L= 100 mm							
δ (mm)	P (N)	δ/L	$a_{\text{meas.}}$ (mm)	G_{IIC} (J/m ²)					
				Exp. Calib.	BT Direct	BT _E	F/N	BT+LD	S
2.2	526	0.044	27.5	NL	554	625	670	0.998401	
		0		VISUAL	0	0	0	1	
2.45	572	0.049	27.5	5%	655	757	792	0.998018	
2.5	562	0.05	27.5	MAX	632	759	765	0.997936	
Comments: 1. Degree of non-linearity from NL to max load (Cmax-C0)/C0 % 2. Permanent deformation after unloading (mm) Tickness measurements: Width measurements: Crack length measurements (after breaking open specimen): Mode I precrack a=a0+2mm									

Compliance Calibration Mode II

MODE II		Test Laboratory: Cranfield		Material:		Specimen: GE11	
		Date:				Number:	
a_{nominal} (mm)	P (N)	δ (mm)	a_{measured} (mm)	Compliance (mm/N)			
(0)	150	0.538	2	0.003586667		Ef= 118333.1198	
(15)	150	0.539	17	0.003593333			
(20)	150	0.576	20	0.00384			
(25)	526	2.2	27.5	0.00418251			
(30)	150	0.691	32	0.004606667			
(35)	150	0.79	37	0.005266667			
(40)	150	0.928	42	0.006186667			
m=				35.577			
Comments:							

Specimen GRE8: Mode II, 0.5%-0.28mm**MODE II ENF REPORTING FORM**

MODE II		Test Laboratory: Cranfield				Material: IMS/924 Pins 3.5mm		Specimen: GRE8 Number:				
Date: 20/08/96												
Ave. Thickness 2h 3.25 mm		Ave. Width B 20.06 mm		Loading Rate 0.5 mm/min		Temperature 23 °C R. Humidity %		Defect Type: Insert: 12.5 µm		Vf: % 2L= 100 mm		
δ (mm)	P (N)	δ/L	a_{meas.} (mm)	G_{IIc} (J/m²)								
					Exp. Calib.	BT_{Direct}	BT_E	F/N	BT+LD	S	BT+SH	CSD
1.71	456.5	0.0342	25	NL	362	369	317	0.998847				
2.02	525	0.0404	25	VISUAL	478	501	419	0.998391				
2.35	593.5	0.047	25	5%	611	659	536	0.997822				
2.61	616.3	0.0522	25	MAX	659	760	578	0.997314				
		0										
Comments: 1. Degree of non-linearity from NL to max load (C _{max} -C ₀)/C ₀ % 2. Permanent deformation after unloading (mm) Thickness measurements: Width measurements: Crack length measurements (after breaking open specimen):												

Compliance Calibration Mode II

MODE II		Test Laboratory:		Material:		Specimen: GRE8	
Date: 20/08/96						Number:	
a_{nominal} (mm)	P (N)	δ (mm)	a_{measured} (mm)	Compliance (mm/N)			
(0)	150	0.407	0	0.002713333		Ef= 133799.9179	
(15)	150	0.436	15	0.002906667			
(20)	150	0.47	20	0.003133333			
(25)	456.5	1.71	25	0.003745893			
(30)	150	0.578	30	0.003853333			
(35)	150	0.667	35	0.004446667			
(40)	150	0.775	40	0.005166667			
m= 37.136							
Comments:							

Specimen GTE2: Mode II, 2%-0.51mm

MODE II ENF REPORTING FORM

MODE II		Test Laboratory: Cranfield				Material: IMS/924 Pin dia .5		Specimen: GTE2 Number:				
Date: 17/08/99		Ave. Thickness		Ave. Width	Loading Rate	Temperature 23 °C	Defect Type:		Vf: %			
2h 3 mm		B 20 mm		0.5 mm/min		R. Humidity %	Insert: µm		2L= 100 mm			
δ (mm)	P (N)	δ/L	a _{meas.} (mm)	G _{IIc} (J/m ²)								
				Exp. Calib.	BT _{Direct}	BT _E	F/N	BT+LD	S	BT+SH	CSD	
2.297	548	0.04594	27.5	NL	630	686	721	0.997801				
2.66	612.1	0.0532	28.5		844	931	966	0.997801				
3.03	650	0.0606	32.5		1237	1326	1416	0.997801				
3.42	685	0.0684	33.5		1460	1631	1671	0.997801				
3.48	692	0.0696	35.5		1673	1777	1915	0.997801				
3.62	712	0.0724	36.5		1872	1952	2144	0.997801				
3.95	719	0.079	37.5		2015	2201	2307	0.997801				
4.2	735	0.084	39.5		2337	2492	2675	0.997801				
4.25	733	0.085	40.5		2443	2559	2797	0.997801				
4.31	733	0.0862	41.5		2565	2636	2937	0.997801				
4.46	723	0.0892	43.5		2742	2763	3140	0.997801				
4.56	728	0.0912	44.5		2909	2876	3331	0.997801				
4.76	732	0.0952	47.5		3351	3095	3837	0.997801				
5.37	774	0.1074	50.5		4235	3748	4849	0.997801				
5.68	792	0.1136	51.5		4612	4069	5280	0.997801				
6.05	824	0.121	52.5		5188	4519	5940	0.997801				
Comments:				1. Degree of non-linearity from NL to max load (C _{max} -C ₀)/C ₀				% (mm)				
				2. Permanent deformation after unloading								
Thickness measurements:												
Width measurements:												
Crack length measurements (after breaking open specimen):												
Mode I precrack a=a ₀ +2mm												

Compliance Calibration Mode II

MODE II		Test Laboratory: Cranfield		Material: IMS/924		Specimen: GTE2 Number:	
Date: 36389							
a _{nominal} (mm)	P (N)	δ (mm)	a _{measured} (mm)	Compliance (mm/N)			
(0)	300	1.058	2.5	0.003526667		Ef= 131274.9422	
(15)	300	1.069	17.5	0.003563333			
(20)	300	1.147	22.5	0.003823333			
(25)	548	2.297	27.5	0.004191606			
(30)	300	1.448	32.5	0.004826667			
(35)	300	1.659	37.5	0.00553			
(40)	300	1.937	42.5	0.006456667			
m=				36.963			
Comments:							

Specimen GSE3: Mode II, 2%-0.28mm

MODE II ENF REPORTING FORM

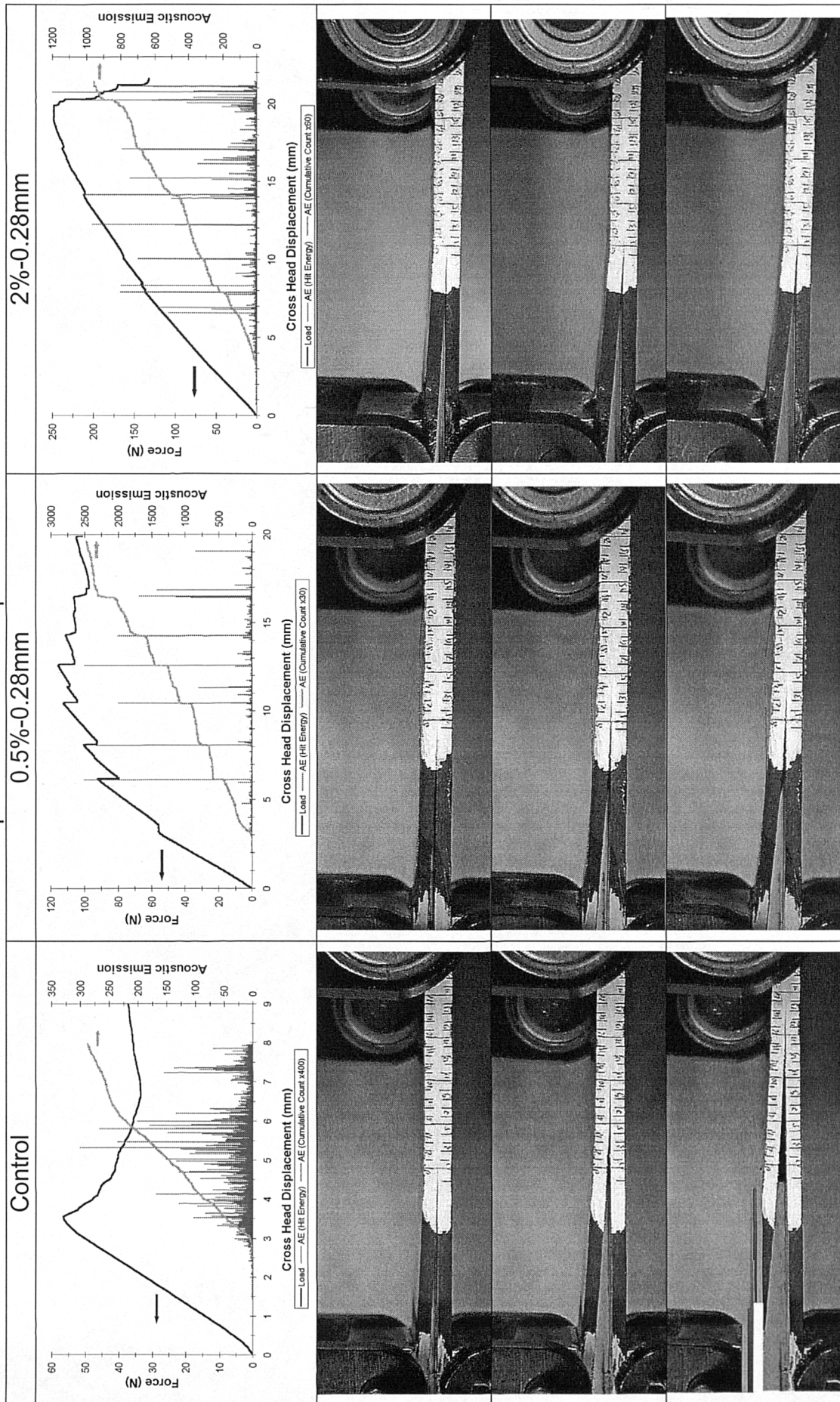
MODE II		Test Laboratory: Cranfield				Material: IMS/924 High pin density		Specimen: gse3 Number:	
Date: 9/7/98									
Ave. Thickness	Ave. Width	Loading Rate	Temperature	23 °C	Defect Type:	Vf:	%		
2h 3.24 mm	B 20.04 mm	0.5 mm/min	R. Humidity	%	Insert:	µm	2L=	100 mm	
δ (mm)	P (N)	δ/L	a _{meas.} (mm)	G _{IIc} (J/m ²)					
				Exp. Calib.	BT _{Direct}	BT _E	F/N	BT+LD	S
2.58	797	0.0516	25	NL	998	972	996	0.997376	
2.66	820	0.0532	25	Max	1056	1031	1054	0.997376	
2.792	823	0.05584	28		1335	1281	1332	0.997376	
3	870	0.06	29		1600	1525	1597	0.997376	
3.26	922	0.0652	30		1923	1835	1920	0.997376	
3.83	1017	0.0766	35		3185	2830	3179	0.997376	
4.14	1067	0.0828	36		3709	3297	3702	0.997376	
4.21	1078	0.0842	37		3999	3471	3992	0.997376	
4.62	1128	0.0924	41		5376	4307	5366	0.997376	
4.84	1150	0.0968	42		5864	4668	5853	0.997376	
5.11	1167	0.1022	45		6932	5181	6919	0.997376	
5.53	1182	0.1106	46.5		7594	5753	7579	0.997376	
5.99	1228	0.1198	48		8734	6541	8717	0.997376	
Comments: 1. Degree of non-linearity from NL to max load (C _{max} -C ₀)/C ₀ % 2. Permanent deformation after unloading (mm)									
Thickness measurements: Width measurements: Crack length measurements (after breaking open specimen): Mode I precrack a=a ₀ +2mm									

Compliance Calibration Mode II

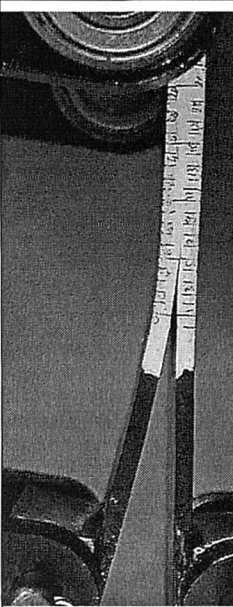
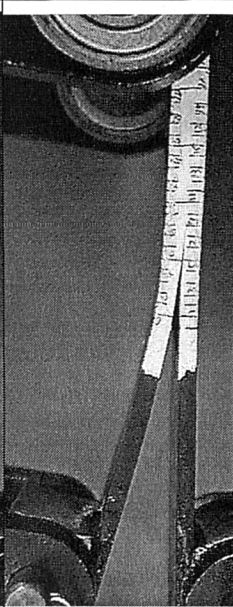
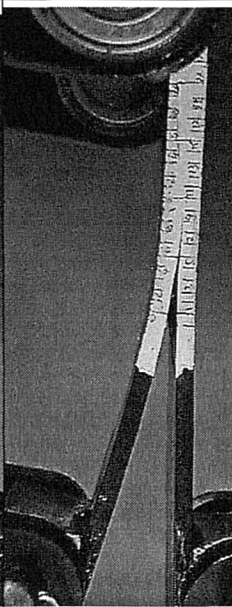
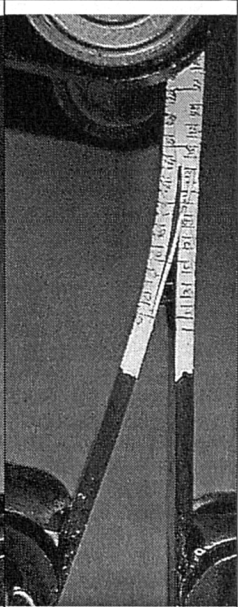
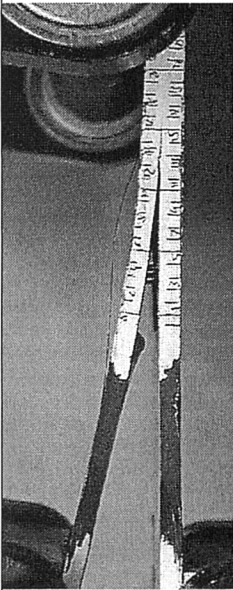
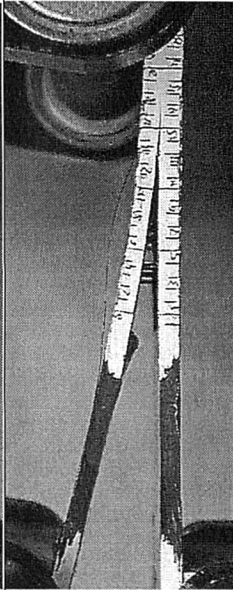
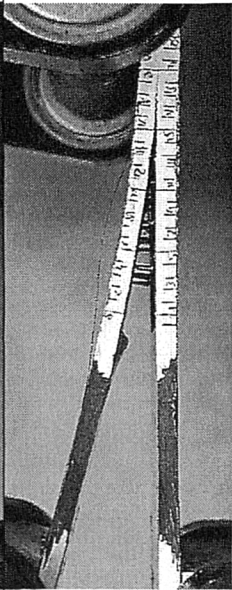
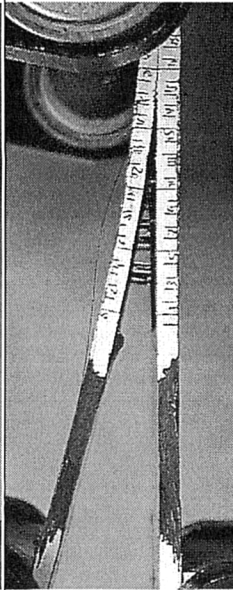
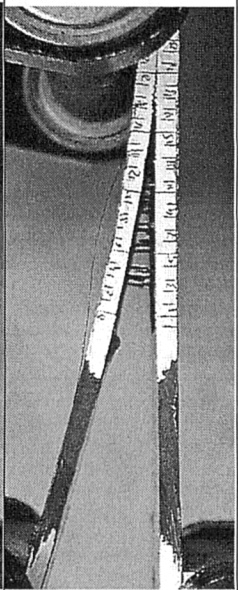
MODE II		Test Laboratory: Cranfield		Material: IMS/924		Specimen: gse3 Number:	
Date: 36045							
a _{nominal} (mm)	P (N)	δ (mm)	a _{measured} (mm)	Compliance (mm/N)			
(0)	150	0.419	0	0.002793333		Ef= 131305.9774	
(15)	150	0.438	15	0.00292			
(20)	150	0.457	20	0.003046667			
(25)	797	2.58	25	0.003237139			
(30)	150	0.554	30	0.003693333			
(35)	150	0.64	35	0.004266667			
(40)	150	0.737	40	0.004913333			
m= 33.583							
Comments:							

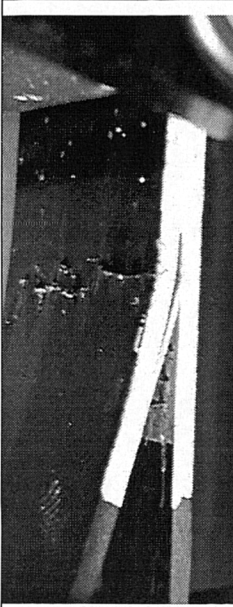
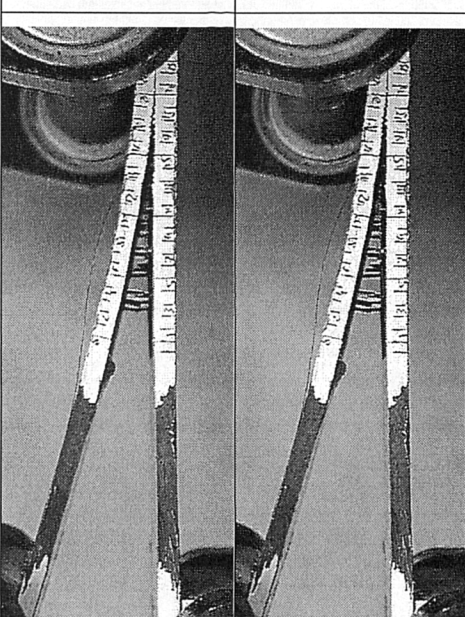
Crack Propagation Imaging of MMB $M_I/M_{II}=4/1$

Cross-head displacement between pictures 0.75mm



			Test finished	

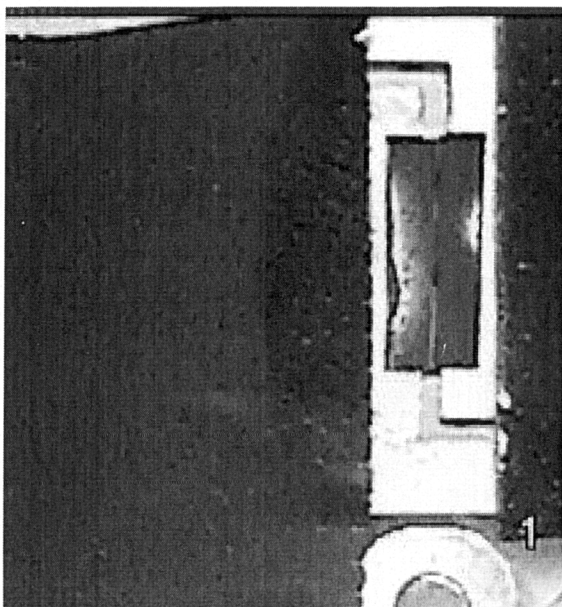
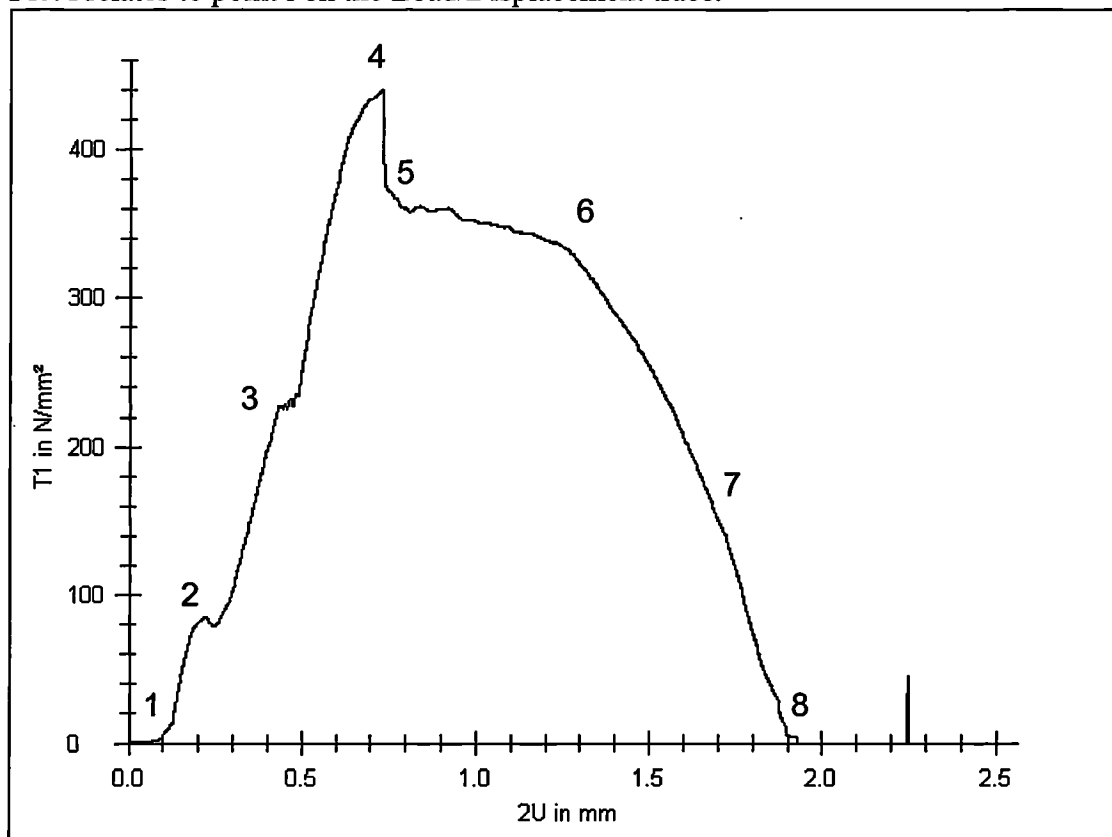
				
				

	Flexural failure of the top beam
	

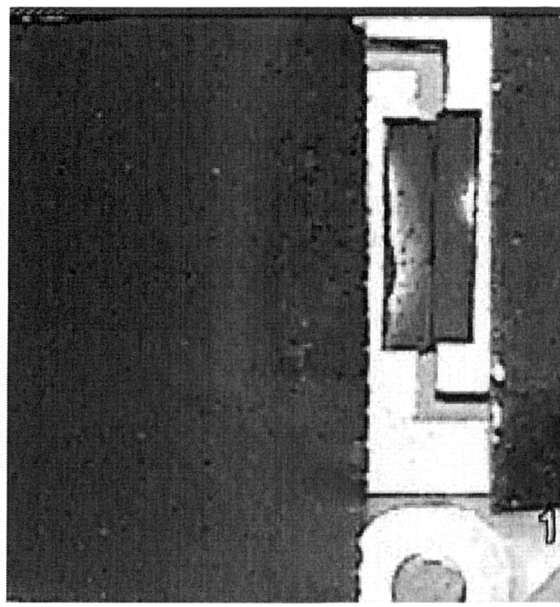
Appendix C: Single Pin Testing Imaging

Appendix C_1: Composite Z-Fibre™ in composite laminate

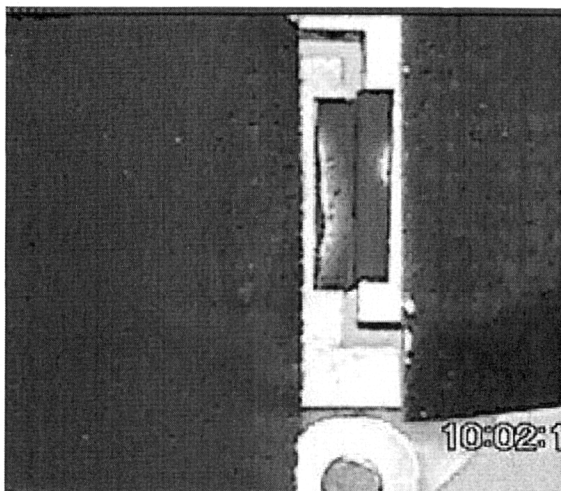
Pict i relates to point i on the Load/Displacement trace.



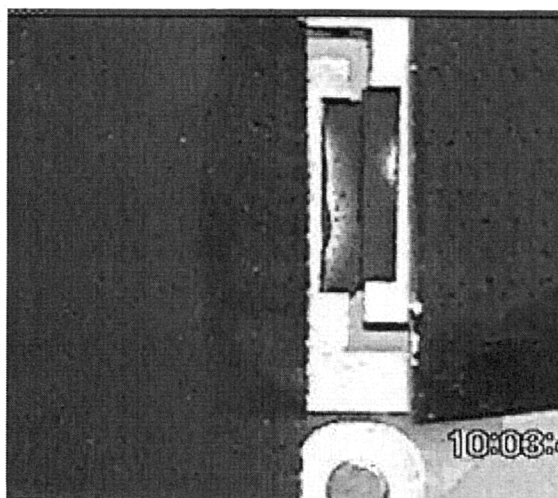
Pict 1



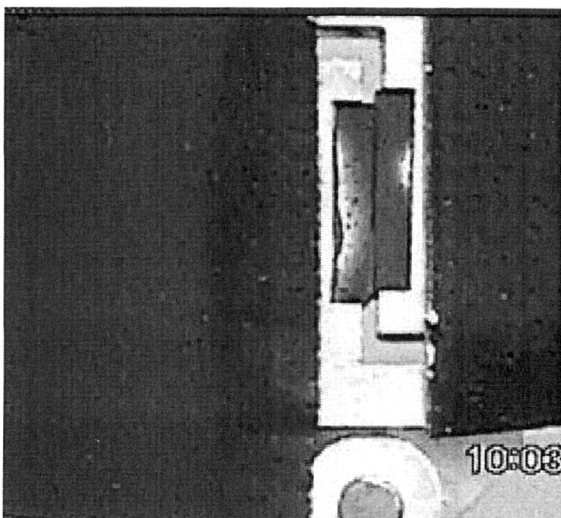
Pict 2



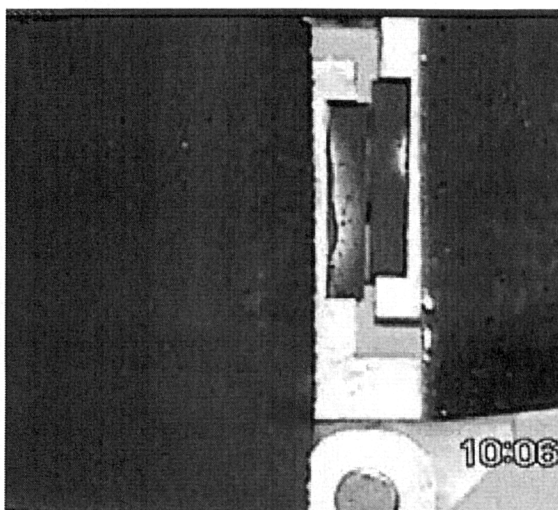
Pict 3



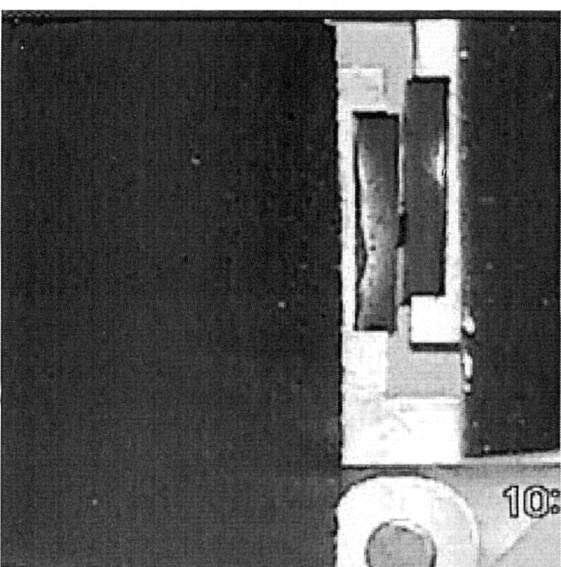
Pict 4



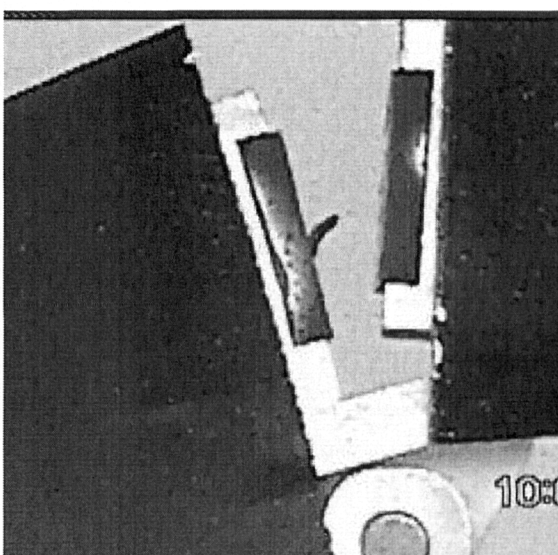
Pict 5



Pict 6



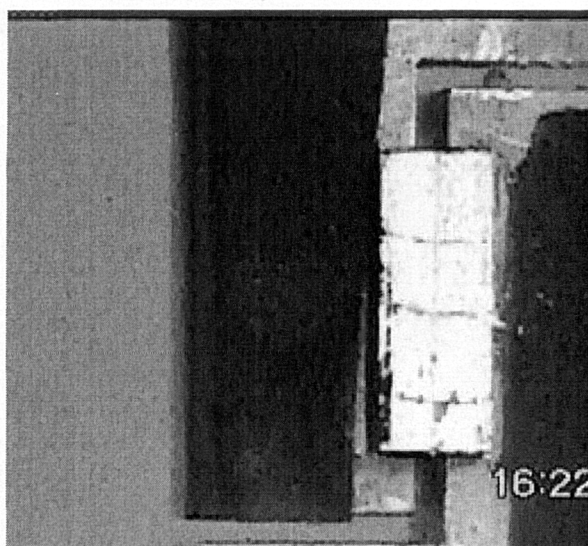
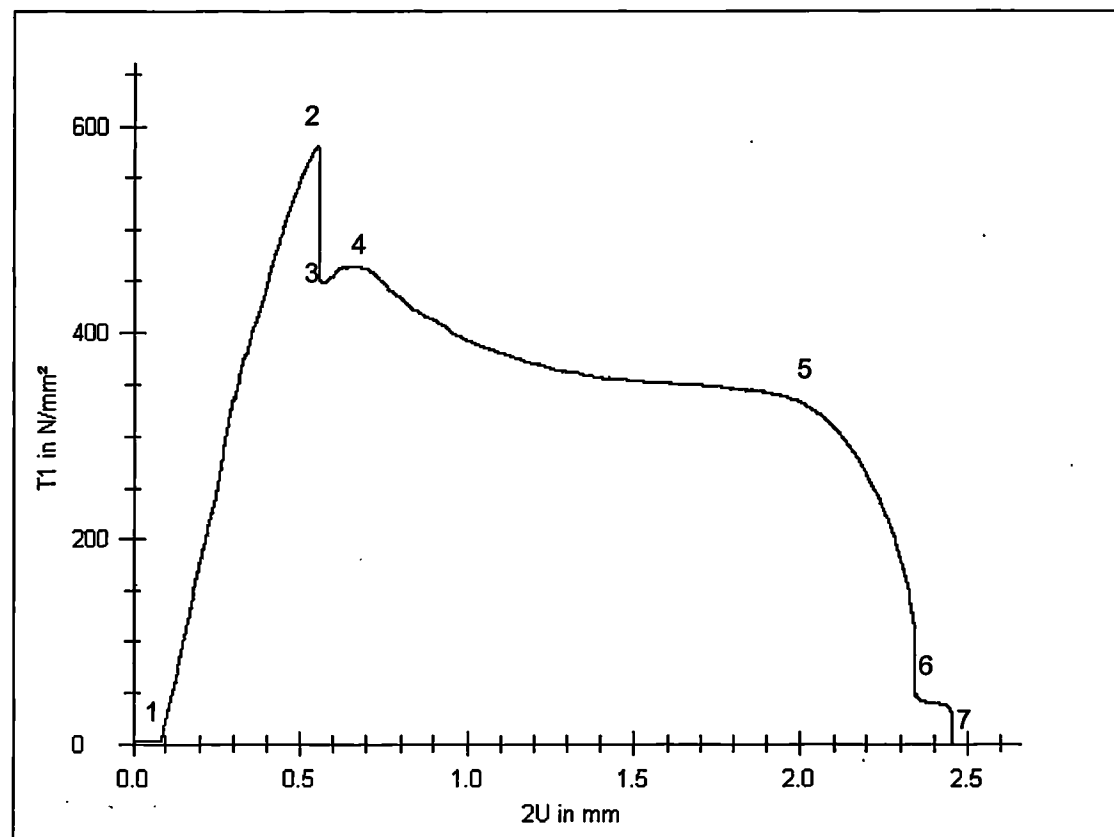
Pict 7



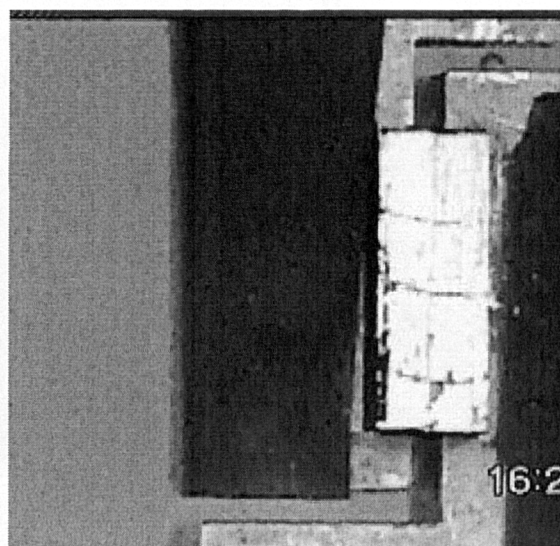
Pict 8

Appendix C_2: Titanium Z-Fibre™ in composite laminate

Angle of the pin $\phi = 38^\circ.9$



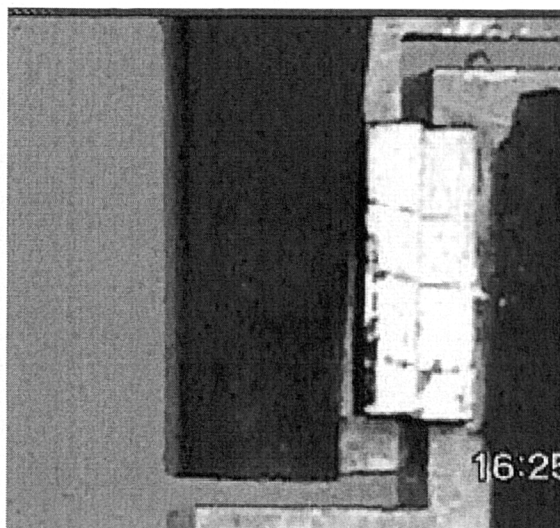
Pict 1



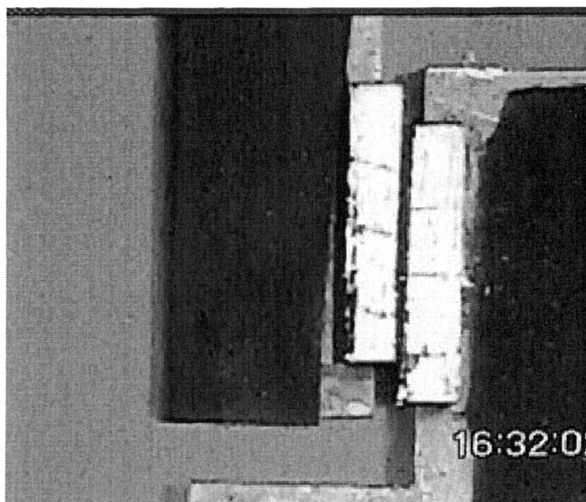
Pict 2



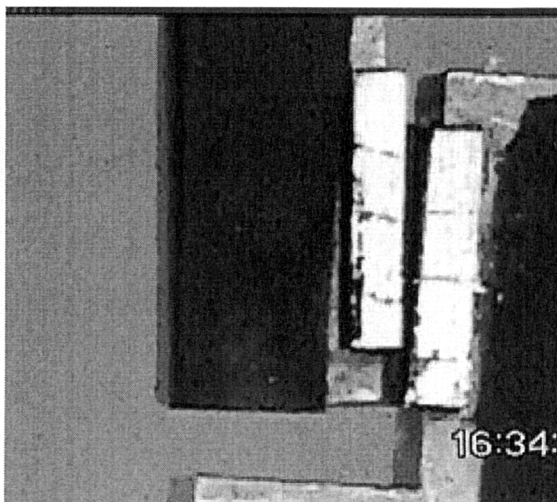
Pict 3



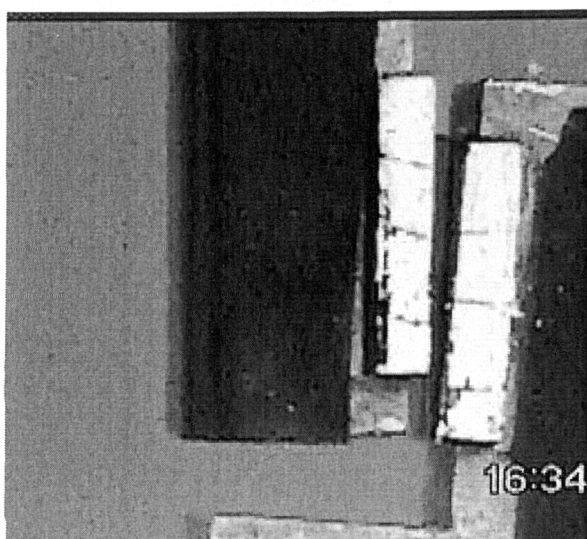
Pict4



Pict 5



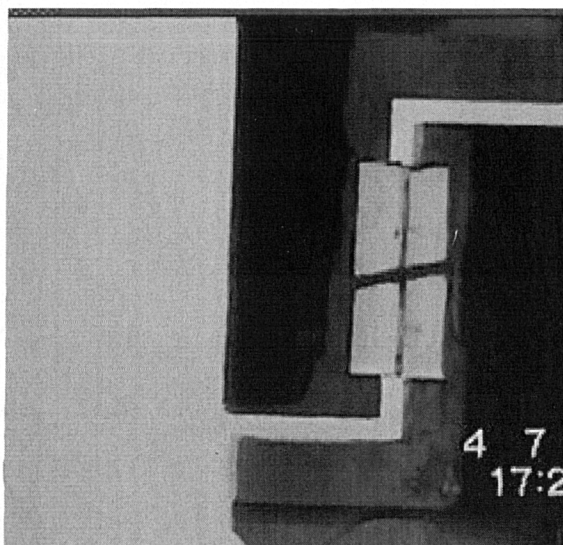
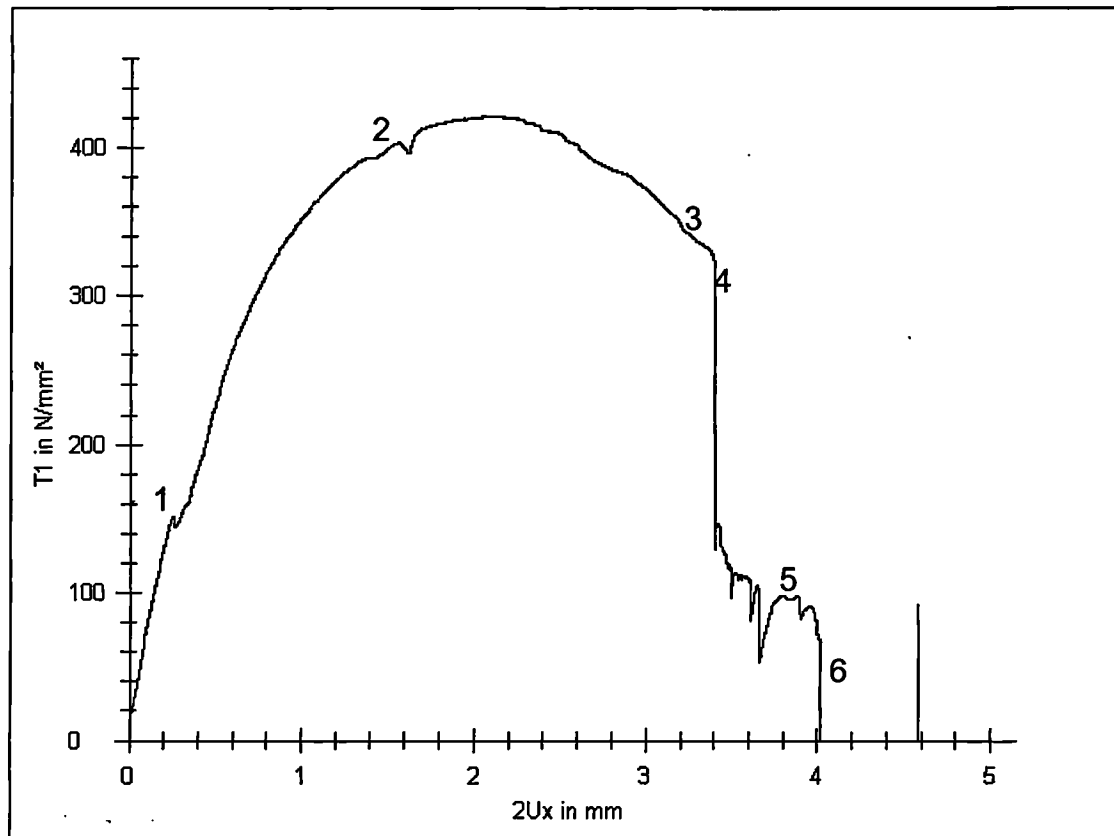
Pict6



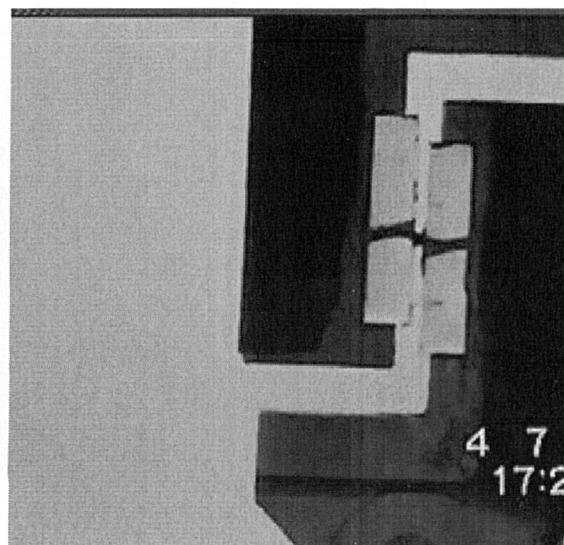
Pict 7

Appendix C_3: Titanium Z-Fibre™ in polycarbonate

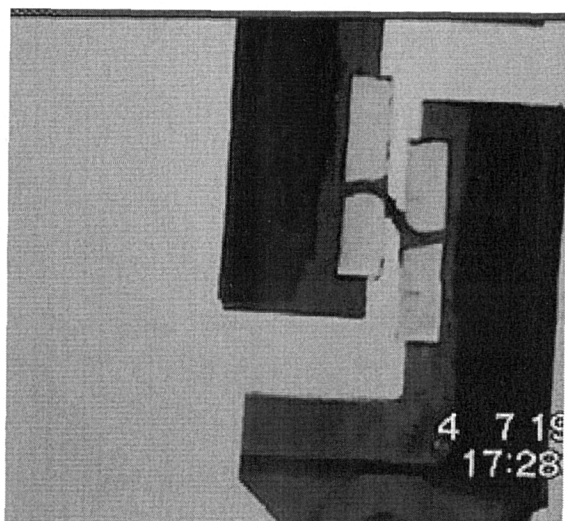
Angle of the pin $\phi = -12^\circ$



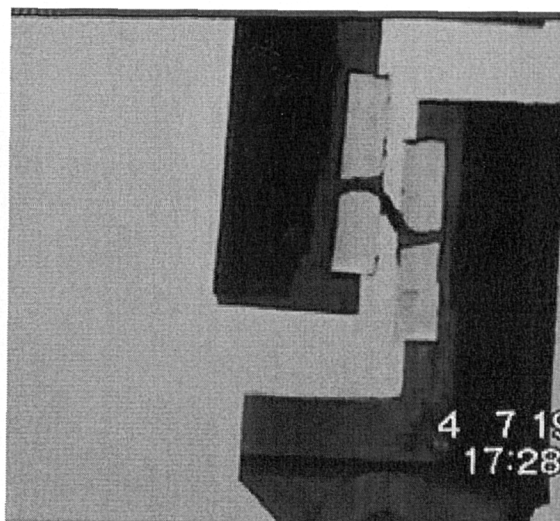
Pict 1



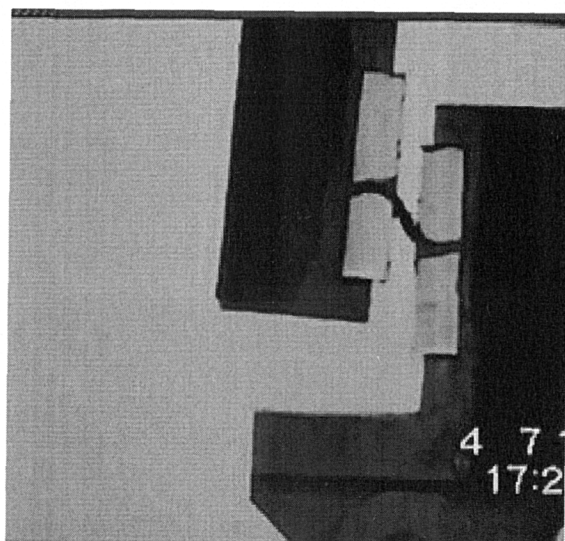
Pict 2



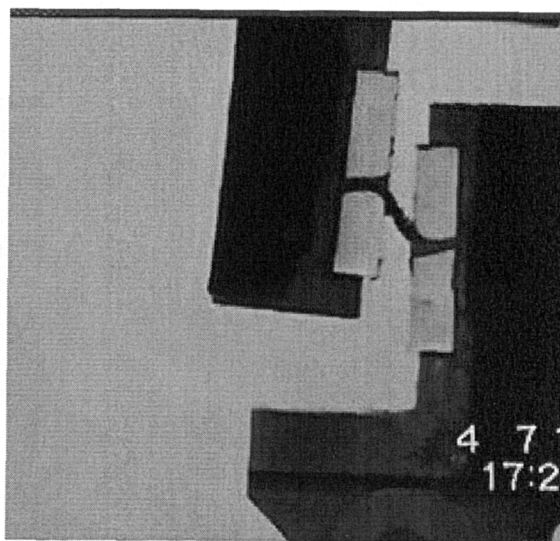
Pict 3



Pict 4



Pict 5

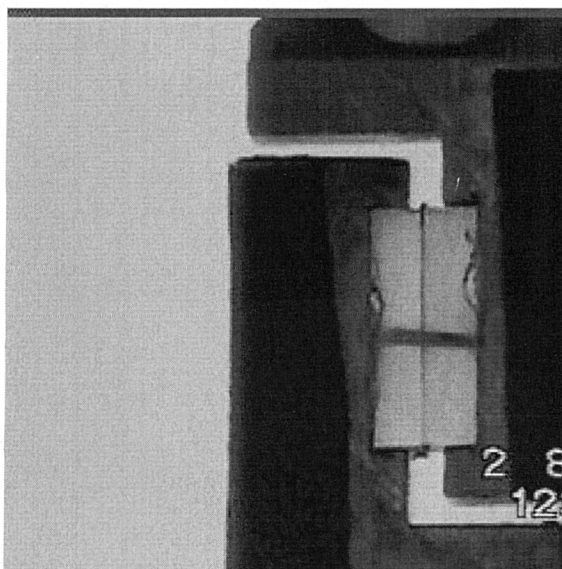
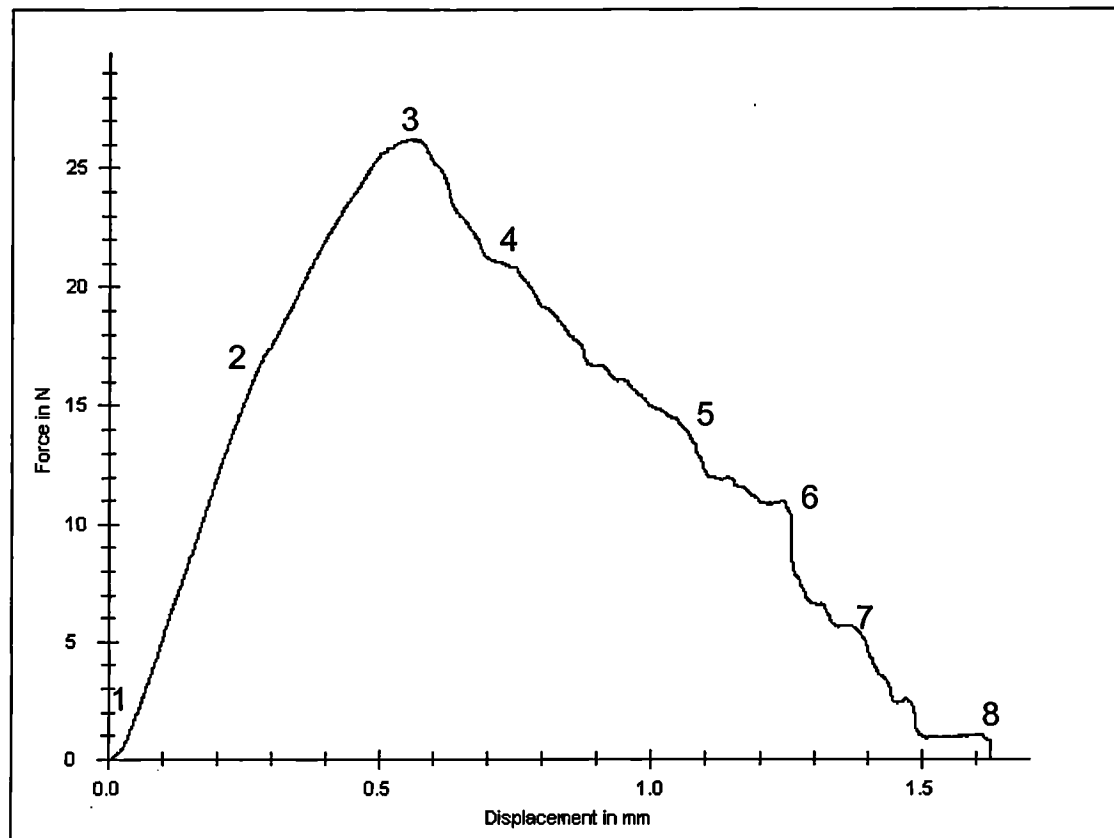


Pict 6

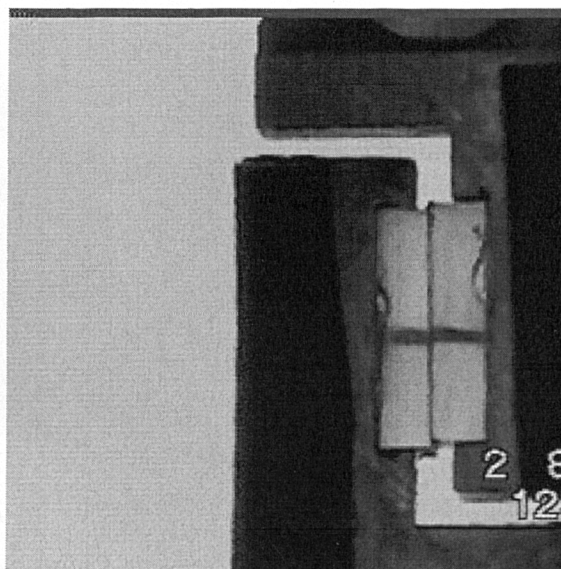
Appendix C_4: Composite Z-Fibre™ in polycarbonate

Angle of the pin $\phi = -1^\circ.7$

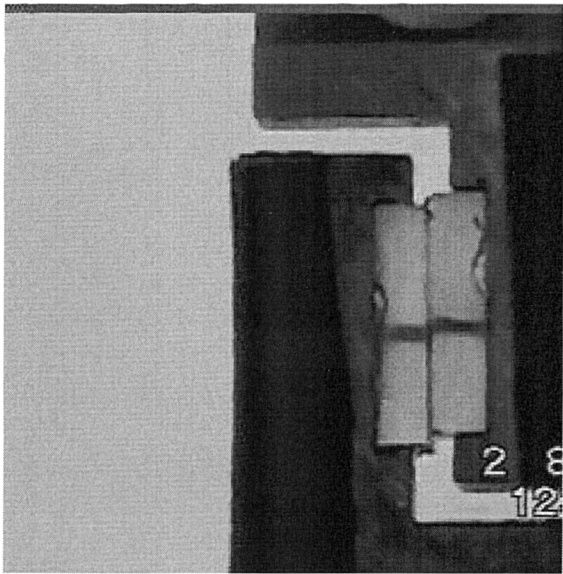
No Friction.



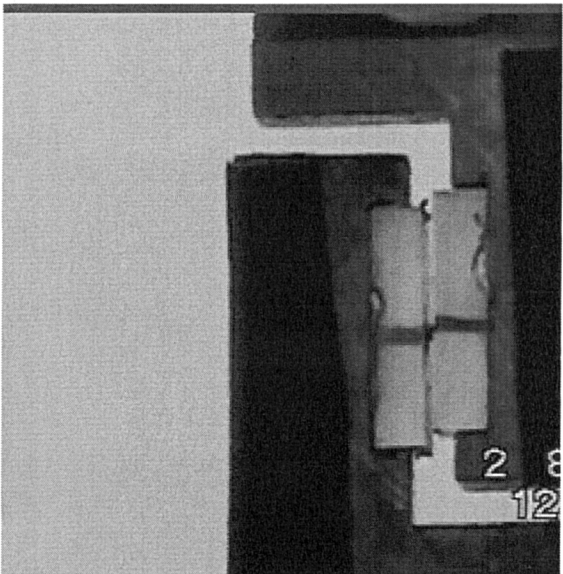
Pict 1



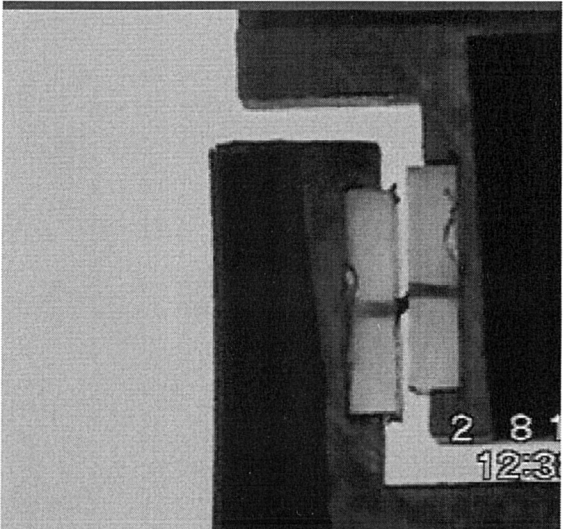
Pict 2



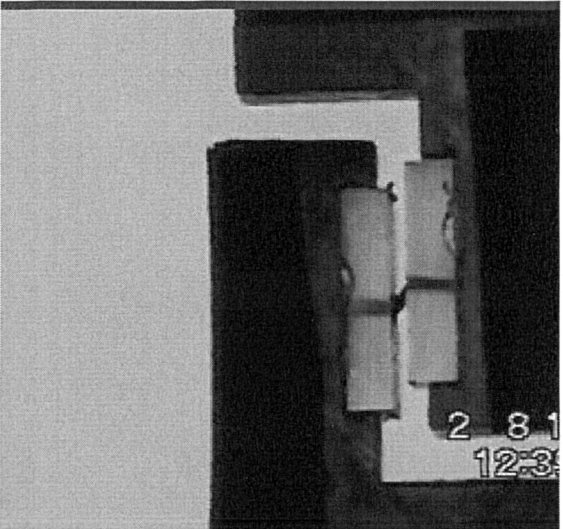
Pict 3



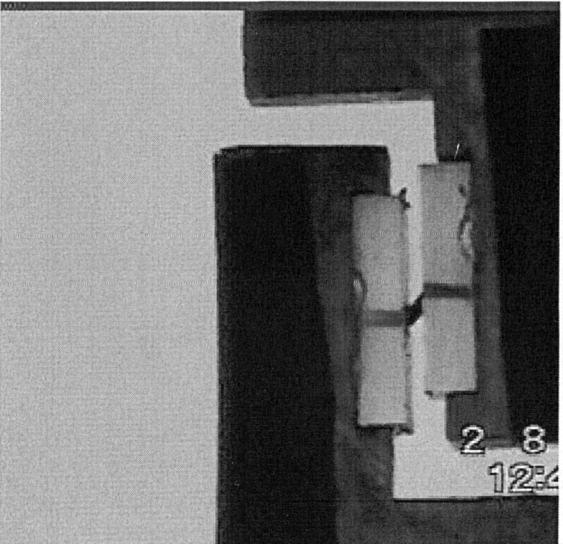
Pict 4



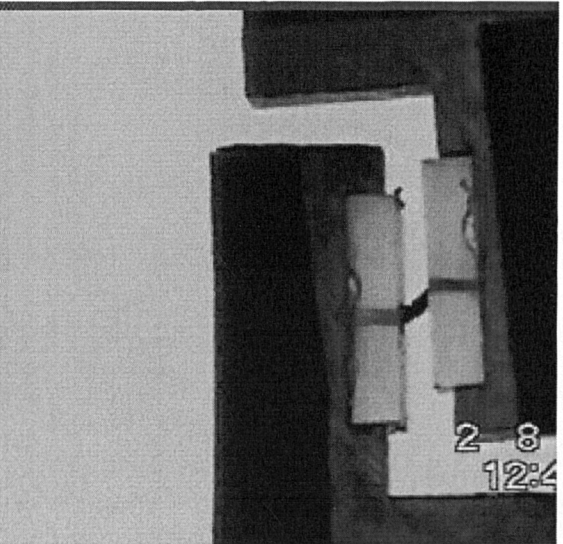
Pict 5



Pict 6



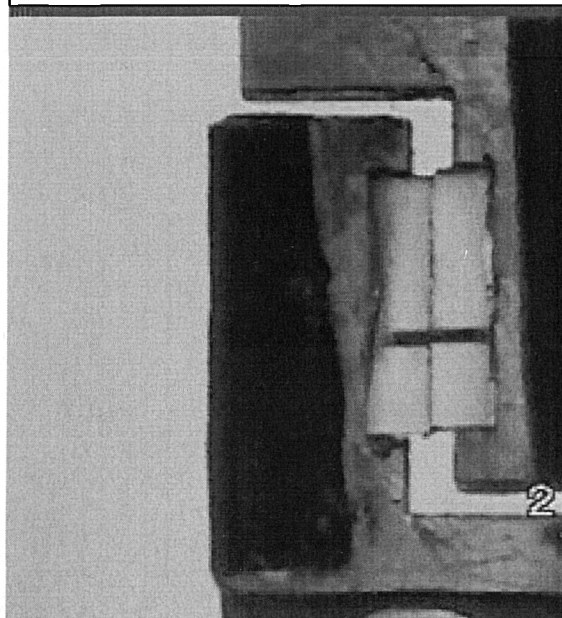
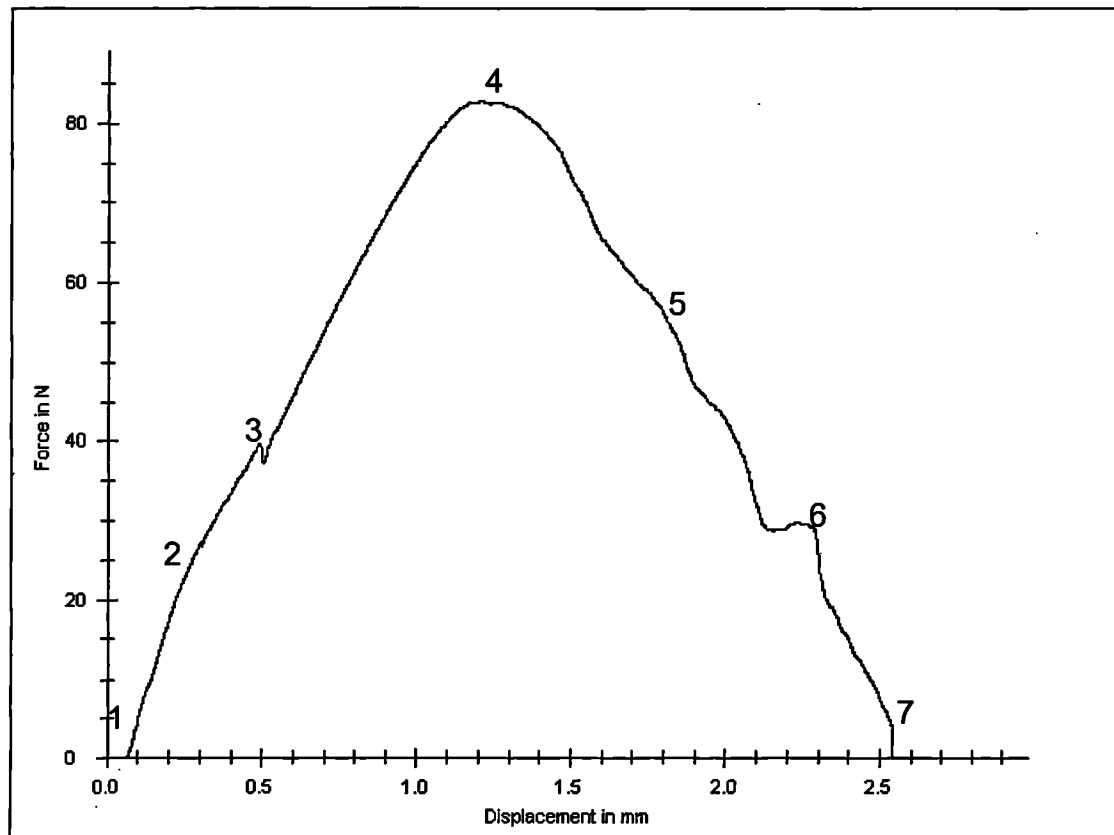
Pict 7



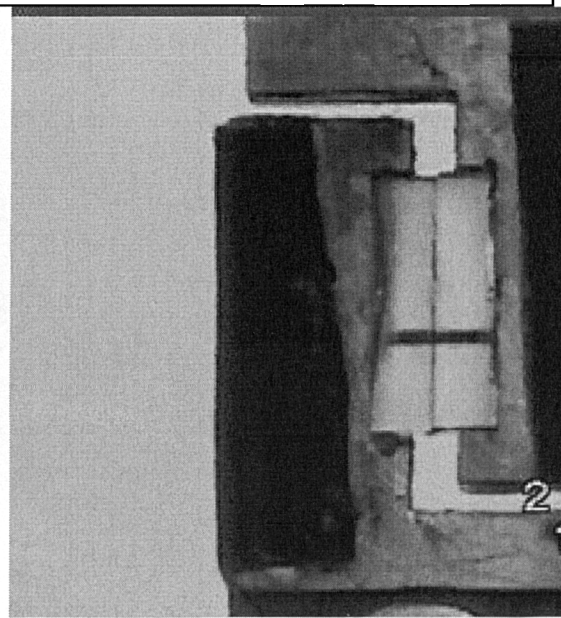
Pict 8

Appendix C_5: Composite Z-Fibre™ in polycarbonate

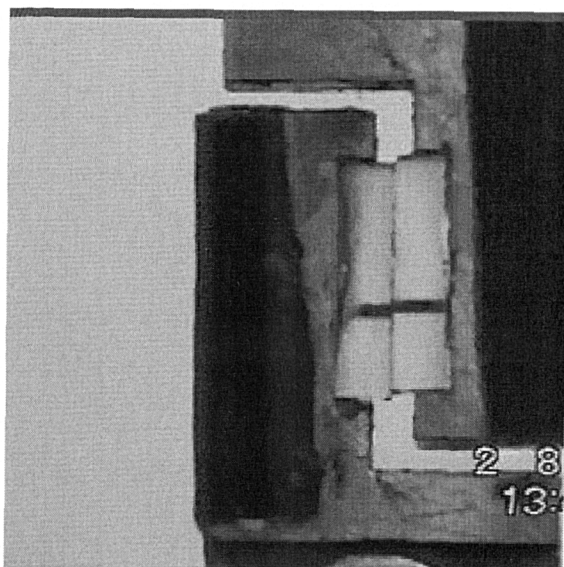
Angle of the pin $\phi = 0^\circ$
High Friction



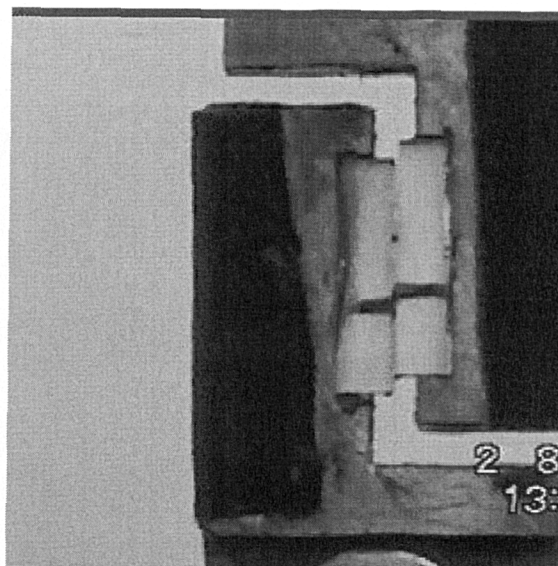
Pict 1



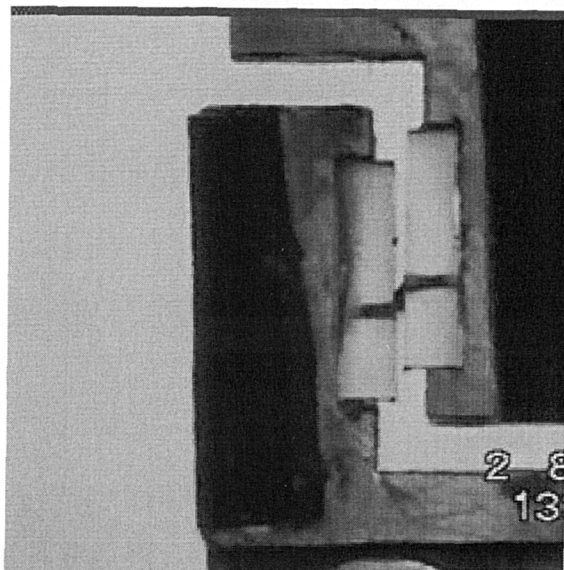
Pict 2



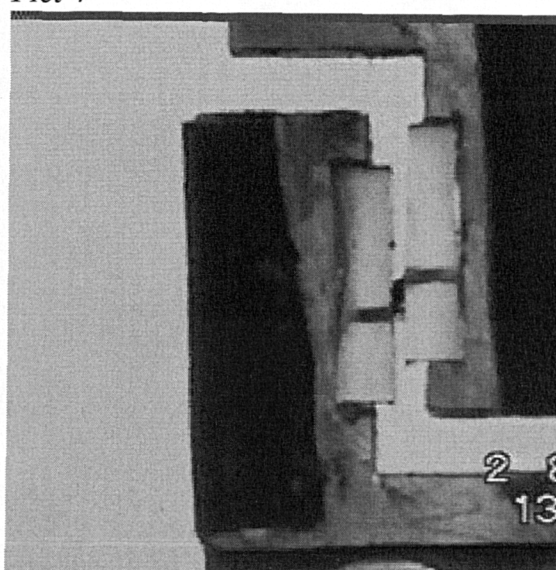
Pict 3



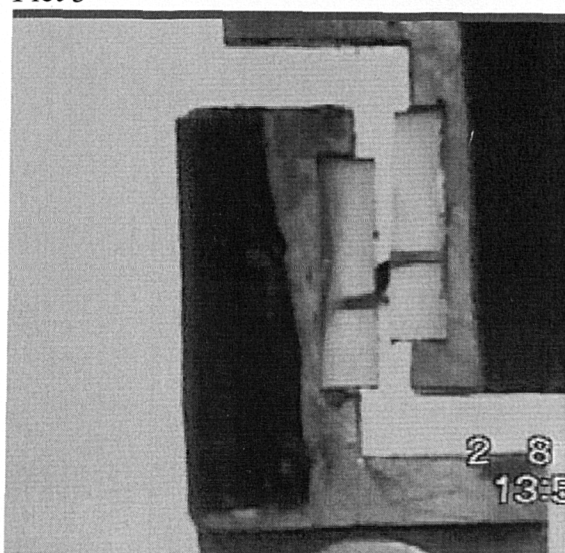
Pict 4



Pict 5



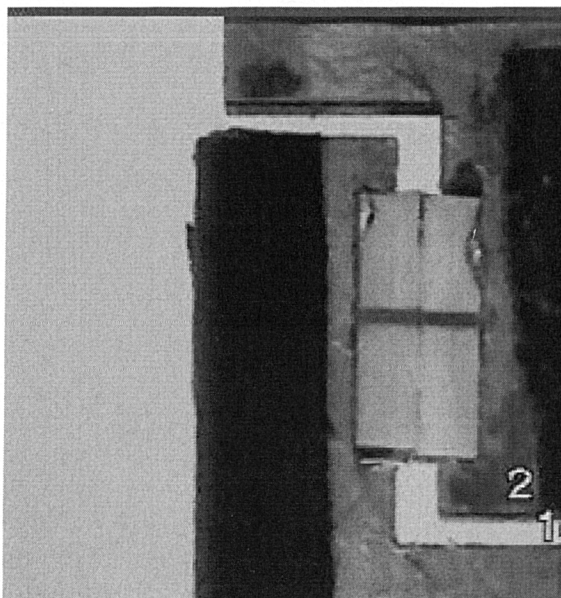
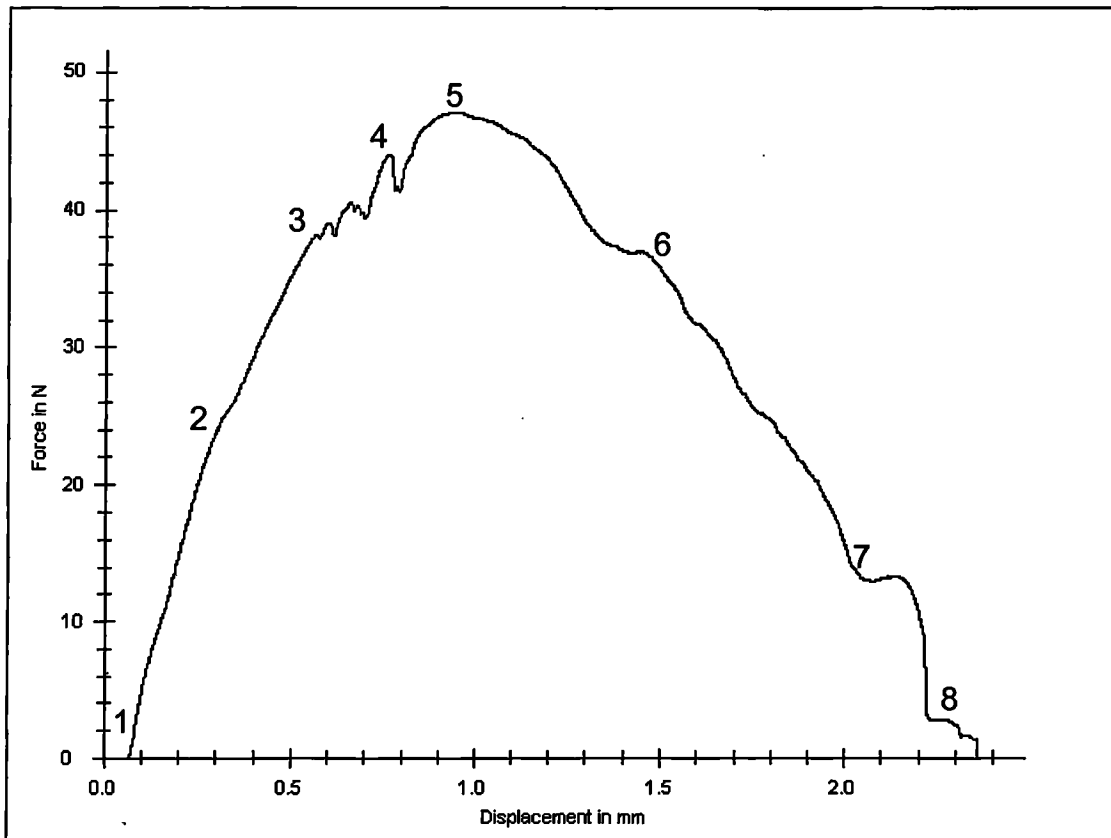
Pict 6



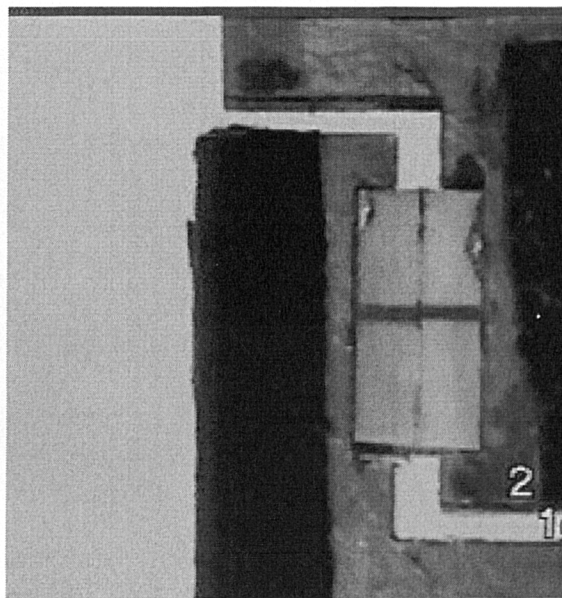
Pict 7

Appendix C_6: Composite Z-Fibre™ in polycarbonate

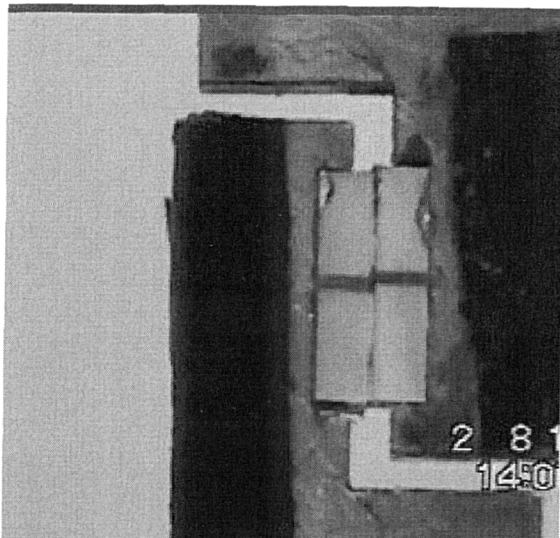
Angle of the pin $\phi = -2^\circ.2$



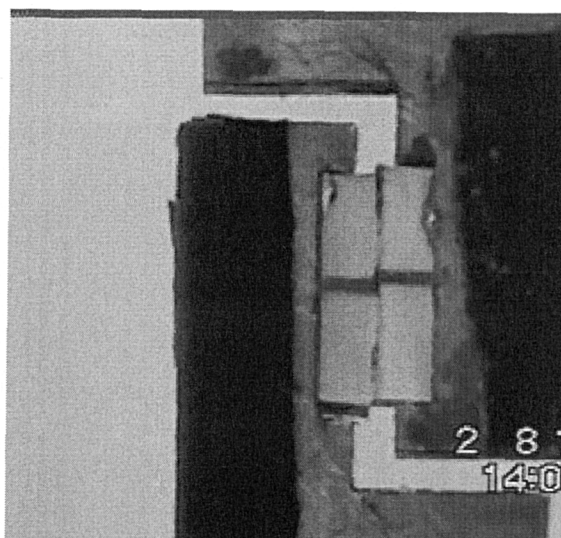
Pict 1



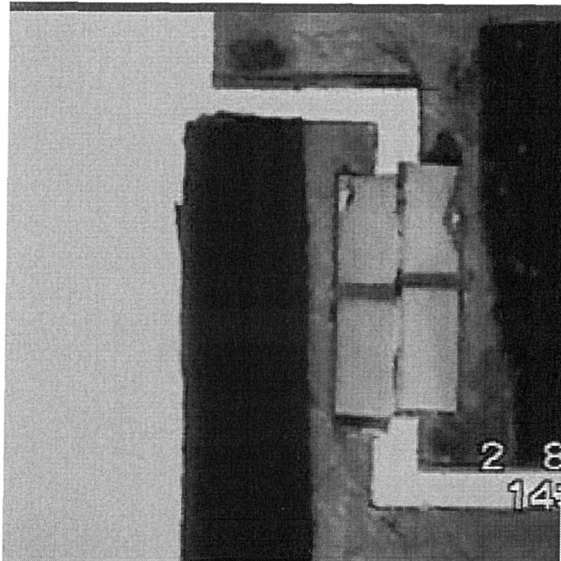
Pict 2



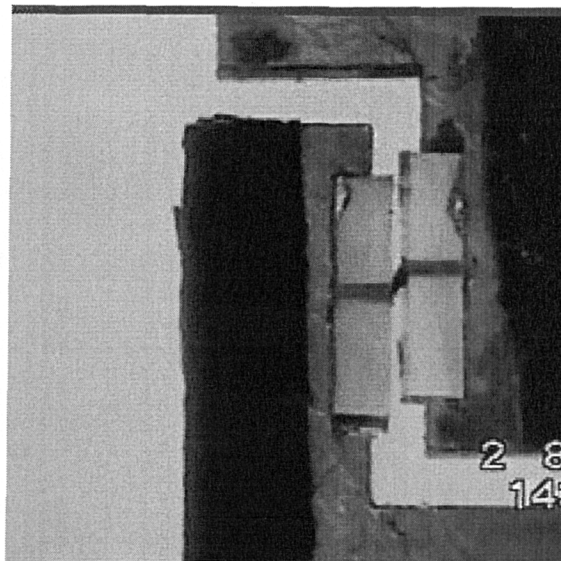
Pict 3



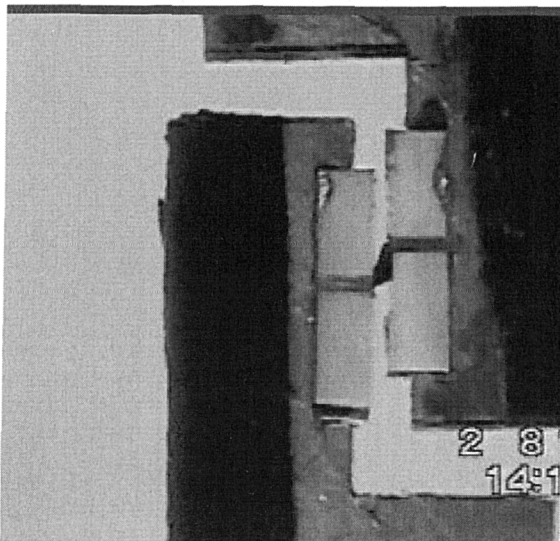
Pict 4



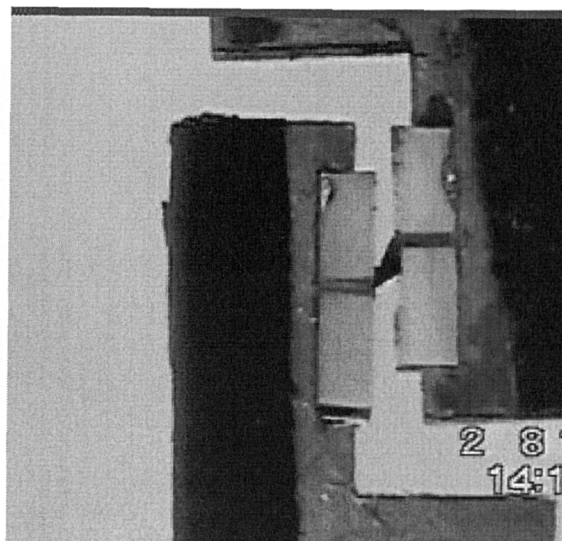
Pict 5



Pict 6



Pict 7



Pict 8

Appendix D: Code of F.E. Procedures

Procedure DCBCAL.DGIBI

```

*
* DEBUT MAILLAGE DCB
* Calibration of the DCB Beam
* UNIT mm
*
TITR MAILLAGE DCB;
OPTI DIME 2 ELEM QUA8 MODE PLAN
DEFO;
*
*
* GEOMETRY AND MESHING
*
* MESH OF THE CIRCLES
*
* EPAISSEUR DE LA POUTRE 2h =
4mm
* LONGUEUR DE LA FISSURE lg
lg=100mm
* NOMBRE D'ELEMENTS PAR
EPAISSEUR ne
* NOMBRE D'ELEMENTS PAR LONGUEUR
nl
* LONGUEUR DE LA POUTRE DE
L'AUTRE
* COTE DE LA FISSURE 50mm l
* DENISTE DU MAILLAGE t
* NOMBRE DE CERCLES
CONCENTRIQUES
* POUR MAILLAGE CRACK TIP
5
* EPAISSEUR DU MAILLAGE
* DE CERCLE a = 1mm
*
h = 1.6; a = 1. ;
lg = 49.6; le = 25.;
ne = enti ((h - a) * 4.); nl =
100.;
*
pf = 0. 0.;
t = a / 50. ; dens t;
*
* MAILLAGE CERCLES
*
C1 = (C (pf moin (t 0.))
pf (pf plus (0. T)))
C pf (pf plus (t 0.))
C pf (pf moin (0. t))
C pf (pf moin (t -0.));
*
sf = COUT pf C1;
r1 = t; rrl = t;
repeter bhomo 7;
ri = r1 + ( 0.3 * r1);
rr1 = rrl + ri;
dens ri;
PC4 = pf moin (rr1 0.);
PC5 = pf moin (rr1 0.);

Ci = (C PC4
pf ( pf plus (0. rri)))
C pf ( pf plus (rr1 0.))
C pf ( pf moin (0. rri))
C pf ( PC5);
sf1 = sf et (COUT C1 Ci);
C1 = Ci; r1 = ri; rrl = rri;
sf = sf1;
fin bhomo;
PC0 = NOEU 36;
PC1 = NOEU 16;
PC2 = NOEU 33;
PC3 = NOEU 40;
da = t;
*
* CONNECTION CERCLES POUTRES
*
* POINTS ET LIGNES
*
dens (a / 5.);
P0 = a * -1. 0.;
P1 = a 0.;
P2 = P0 plus (0. a);
P3 = P1 plus (0. a);
P5 = P1 moin (0. a);
P7 = a * -1. 0.;
P6 = P7 moin (0. a);
PI1 = Ci poin 1; l1 = PI1 d P0;
n = (nbel l1) * -1 ;
PI2 = Ci poin 5 ; l2 = PI2 d n
P2;
PI3 = Ci poin 9 ; l3 = PI3 d n
P3;
n2 = (nbel ( Ci comp PI3 PI2));
PI4 = Ci poin 13 ; l4 = PI4 d P1
;
ligh = P2 d n2 P3 ;
PI5 = Ci poin 17; l5 = PI5 d n
P5;
PI6 = Ci poin 21; l6 = PI6 d n
P6;
PI7 = Ci poin 25; l7 = PI7 d P7;
ligb = P5 d n2 P6;
lc1 = P0 d 4 P2;
lc2 = P3 d 4 P1;
lc3 = P1 d 4 P5;
lc4 = P6 d 4 P7;
Ci = inve Ci;
*
* SURFACES
*
sc1 = DALL l1 lc1
(inve l2) (Ci comp PI2
PI1);
sc2 = DALL l2 ligh (inve l3)
(Ci comp PI3 PI2);
sc3 = DALL l3 lc2

```

```

      (inve 14) (Ci comp PI4
PI3);
sc4 = DALL 14 lc3
      (inve 15) (Ci comp PI5
PI4);
sc5 = DALL 15 ligb (inve 16)
      (Ci comp PI6 PI5);
sc6 = DALL 16 lc4
      (inve 17) (Ci comp PI7
PI6);
sc = sc1 et sc2 et sc3 et sc4
      et sc5 et sc6;
*
* RATRAPPAGE EPAISSEUR
*
P8 = P0 plus (0. h) ; lc5 = P2
d ne P8;
P9 = P1 plus (0. h) ; ligh2 =
P8 d n2 P9;
lc6 = P9 d ne P3;
P10 = P1 moins (0. h) ; lc7 = P5
d ne P10;
P11 = P7 moins (0. h) ; lc8 =
P11 d ne P6;
ligb2 = P10 d n2 P11;
se1 = DALL lc5 ligh2 lc6 (inve
ligh);
se2 = DALL lc7 ligb2 lc8 (inve
ligb);
*
* PARTIE DROITE DE LA POUTRE
*
LD1 = lc6 et lc2 et lc3 et lc7;
P12 = (le h) ; P13 = (le (h * -
1.));
LD2 = P9 d 49 P12;
n3 = enti (2. * ne + 8.);
LD3 = P12 d n3 P13;
LD4 = P13 d 49 P10;
sd = DALL (inve LD1) LD2 LD3
LD4;
*
* MAILLAGE PARTIES GAUCHES
*
* POINT (2i + 1) de LGj = point
abcisse -i
* de la ligne g
*
PT1 = P0; PT4 = P11;
PT2 = P2; PT5 = P6;
PT3 = P8; PT6 = P7;
LGA0 = lc1 et lc5 ; LGB0 = lc8
et lc4;
i = 0 ; x = a * -1. ;

* DEBUT BOUCLE
i = i + 1 ; xi = x - a ;
* PREMIER TOUR
PTI1 = (xi 0.);

PTI6 = (xi 0.);
PTI2 = (xi a);
PTI5 = (xi (a * -1));
PTI3 = (xi h);
PTI4 = (xi (h * -1));
LGAI0 = (PTI1 d 4 PTI2 d ne
PTI3);
LGBI0 = (PTI4 d ne PTI5 d 4
PTI6);
LG1 = (PT1 d 2 PTI1);
LG2 = (PT2 d 2 PTI2);
LG3 = (PT3 d 2 PTI3);
SGA = DALL LGAI0 (inve LG3)
(inve LGA0) LG1;
LG4 = PT4 D 2 PTI4;
LG5 = PT5 D 2 PTI5;
LG6 = PT6 D 2 PTI6;
SGB = DALL LGBI0 (INVE LG6)
(INVE LGB0) LG4;
PT1 = PTI1 ; PT2 = PTI2;
PT3 = PTI3 ; PT4 = PTI4;
PT5 = PTI5 ; PT6 = PTI6;
LGA0 = LGAI0 ; LGB0 = LGBI0;
babs = enti (lg - 2.);
REPETER bomai babs;
i = i + 1;
xi = xi - a;
*
PTI1 = (xi 0.);
PTI6 = (xi 0.);
PTI2 = (xi a);
PTI5 = (xi (a * -1));
PTI3 = (xi h);
PTI4 = (xi (h * -1));
LGAI0 = (PTI1 d 4 PTI2 d ne
PTI3);
LGBI0 = (PTI4 d ne PTI5 d 4
PTI6);
LG1 = LG1 et (PT1 d 2 PTI1);
LG2 = LG2 et (PT2 d 2 PTI2);
LG3 = LG3 et (PT3 d 2 PTI3);
SGA = SGA et (DALL LGAI0
(inve (LG3 comp PT3
PTI3))
(inve LGA0)
(LG1 comp PT1 PTI1));
LG4 = LG4 et (PT4 D 2 PTI4);
LG5 = LG5 et (PT5 D 2 PTI5);
LG6 = LG6 et (PT6 D 2 PTI6);
SGB = SGB et (DALL LGBI0
(INVE (LG6 comp PT6
PTI6))
(INVE LGB0)
(LG4 comp PT4 PTI4));
PT1 = PTI1 ; PT2 = PTI2;
PT3 = PTI3 ; PT4 = PTI4;
PT5 = PTI5 ; PT6 = PTI6;
LGA0 = LGAI0 ; LGB0 = LGBI0;
FIN bomai;

```



```

*
* MAILLAGE TOTAL
*
BEAM1 = sf et sc et se1 et se2
et sd et SGA et SGB;
*
* LEVRES DE FISSURE
*
ccont = ORIE ( cont BEAM1) ;
lfs = (ccont comp PC4 pf) ;
lfi = (ccont comp pf PC5) ;
*trac (sf et sc et se1 et se2 et
sd et SGA ET SGB);
*
* CHOIX DU COMPORTEMENT
*
* Materiau IMS/924
M1 = MODE BEAM1 MECANIQUE
ELASTIQUE ORTHOTROPE;
*M1 = mode beam1 mecanique
elastique isotrope;
*
* MATERIAL AND ELEMENT DATA
*
E11 = 138E3; E22 = 11E3; E33 =
1E2;
N12 = 0.3434; GX = 4.4E3;
* matériaux fabrice ducept
*E11 = 27.5E3 ; E22 = 6.5E3; E33
= 6.5E3;
*N12 = 0.32; GX = 2.5E3;
MAT1 = MATE M1 DIRE (1. 0.) YG1
E11 YG2 E22
      NU12 N12 YG3 E33 NU23 0.3
NU13 0.3 G12 GX;
*MAT1 = mate M1 YOUN E11 NU 0.3;
*
* CONDITIONS AUX LIMITES
*
COND1 = BLOQ DEPL DIRE (0. 1.)
PT4;
COND2 = BLOQ DEPL DIRE (1. 0.)
PT4;
COND3 = BLOQ DEPL DIRE (1. 0.)
PT3;
CL1 = COND1 ET COND2 ET COND3;
*
* CHARGEMENT
*
FOR1 = FORC (0. 2.14) (PT3);
FORT = FOR1 ;
*
* RESOLUTION
*
RIGI1 = RIGI M1 MAT1;
RIGICL1 = RIGI1 et CL1;
DEPL1 = RESO RIGICL1 FORT;
SIG0 = SIGM M1 MAT1 DEPL1;
VM1 = VMIS M1 SIG0;
*
* POST PROCESS
*
DEFO = DEFO BEAM1 DEPL1 0. BLAN;
DEF1 = DEFO BEAM1 DEPL1 ROUG;
*
* CALCUL DE G-ENERGY RELEASE
RATE
*
SUPTAB = TABLE ;
SUPTAB.'OBJECTIF' = MOT 'J' ;
SUPTAB.'LEVRE_SUPERIEURE' = lfs;
SUPTAB.'LEVRE_INFERIEURE' = lfi;
SUPTAB.'FRONT_FISSURE' = pf ;
SUPTAB.'MODELE' = M1;
SUPTAB.'CARACTERISTIQUES' =
MAT1;
SUPTAB.'SOLUTION_RESO' = DEPL1;
SUPTAB.'CHARGEMENTS_MECANIQUES'
= FORT;
SUPTAB.'COUCHE' = 4;
*
* calcul de G
*
G_ORTHO SUPTAB;
G = suptab.'RESULTATS';
*
* tentative d'extraction des
deplacments
*
aa = coor 1 PT3;
delt1 = extr depl1 uy PT3;
mess ' uy pt3' delt1;
mess 'crack length' aa;
mess 'G de gtheta' (g * 1000.);

```

Procedure DELARCU8.DGIBI

```

* DEBUT MAILLAGE DCB
* pas d'iteration
* procedure calcul en grand depl
* UNITS mm, N , degree
* introduction d une loi de contact
*
TITR MAILLAGE DCB;
OPTI DIME 2 ELEM QUA8 MODE PLAN DEFO;
*
*
* GEOMETRY AND MESHING
*
* MESH OF THE CIRCLES
*
* EPAISSEUR DE LA POUTRE 2h
* LONGUEUR DE LA FISSURE lg
* NOMBRE D'ELEMENTS PAR EPAISSEUR ne
* NOMBRE D'ELEMENTS PAR LONGUEUR nl
* LONGUEUR DE LA POUTRE DE L'AUTRE
* COTE DE LA FISSURE le
* DENISTE DU MAILLAGE t
* NOMBRE DE CERCLES CONCENTRIQUES
* POUR MAILLAGE CRACK TIP 5
* EPAISSEUR DU MAILLAGE
* DE CERCLE a = 1mm
*crack propagation max PPMAX
*
gprop = .250;
*
* position du pin par rapport a pf
*
* pin position 53mm
*
lpe = 102 + 10;
lpe1 = 106 + 10;
lpe2 = 110 + 10;
lpe3 = 114 + 10;
lpe4 = 118 + 10;
lpe5 = 122 + 10;
lpe6 = 126 + 10;
lpe7 = 130 + 10;
lpe8 = 134 + 10;
lpe9 = 138 + 10;
lpe10 = 142 + 10;
lpe11 = 146 + 10;
lpe12 = 150 + 10;
lpe13 = 154 + 10;
*
*
* pin force info
*
ap1 = 1015.;
ap2 = -6.3836;
bp2 = 10.210;
x1 = 0.01;
x2 = 1.60;
*
*
*
gil = 3.;
h = 1.6; a = 1. ;
lg = 55; le = 15.;
ne = enti ((h - a) * 4.); nl = 100.;
*
tabreal = table;
tabdell = table;
tabgl = table;
tablgl = table;
tabdvp1 = table;

tabdvp11 = table;
tabdvp12 = table;
tabdvp13 = table;
tabdvp14 = table;
tabdvp15 = table;
tabdvp16 = table;
tabdvp17 = table;
tabdvp18 = table;
tabfo1 = table;
tabfo11 = table;
tabfo12 = table;
tabfo13 = table;
tabfo14 = table;
tabfo15 = table;
tabfo16 = table;
tabfo17 = table;
tabfo18 = table;
*
stab1 = 0.;
*
* boucle crack propa & chargement
*
* valeur initiale
*
g = 0.;
dell = 0.00;
dvp1 = 0.;
dvp11 = 0.;
dvp12 = 0.;
dvp13 = 0.;
dvp14 = 0.;
dvp15 = 0.;
dvp16 = 0.;
dvp17 = 0.;
dvp18 = 0.;
dvp19 = 0.;
dvp110 = 0.;
dvp111 = 0.;
dvp112 = 0.;
dvp113 = 0.;
*
inc1 = 0.10;
fo1 = 0.;
fo11 = 0.;
fo12 = 0.;
fo13 = 0.;
fo14 = 0.;
fo15 = 0.;
fo16 = 0.;
fo17 = 0.;
fo18 = 0.;
fo19 = 0.;
fo110 = 0.;
fo111 = 0.;
fo112 = 0.;
fo113 = 0.;
*
*
opti elem QUA8;
*
*
pf = 0. 0.;
t = a / 50. ; dens t;
*
* MAILLAGE CERCLES
*
C1 = (C (pf moin (t 0.))
      pf (pf plus (0. T)))
      C pf (pf plus (t 0.))
      C pf (pf moin (0. t))
      C pf (pf moin (t -0.));

```

```

*
sf = COUT pf C1;
r1 = t; rrl = t;
repetier bhomo 7;
  ri = r1 + ( 0.3 * r1);
  rri = rrl + ri;
  dens ri;
  PC4 = pf moin (rri 0.);
  PC5 = pf moin (rri 0.);
  Ci = (C PC4
        pf ( pf plus (0. rri)))
        C pf ( pf plus (rri 0.))
        C pf ( pf moin (0. rri))
        C pf ( PC5);
  sf1 = sf et (COUT C1 Ci);
  C1 = Ci; r1 = ri; rrl = rri;
  sf = sf1;
fin bhomo;
da = t;
*
* CONNECTION CERCLES POUTRES
*
* POINTS ET LIGNES
*
dens (a / 5.);
P0 = a * -1. 0.;
P1 = a 0.;
P2 = P0 plus (0. a);
P2B = pf plus (0. a);
P3 = P1 plus (0. a);
P5 = P1 moin (0. a);
P7 = a * -1. 0.;
P6 = P7 moin (0. a);
P6B = pf moin (0. a);
PI1 = Ci poin 1; l1 = P0 d PI1;
n = (nbel l1) * -1 ;
PI2 = Ci poin 5 ; l2 = P2 d n PI2;
PI3 = Ci poin 9 ; l3 = P3 d n PI3;
n2 = (nbel ( Ci comp PI3 PI2));
PI4 = Ci poin 13 ; l4 = P1 d PI4 ;
ligh = P2 d 2 P2B d 2 P3 ;
PI5 = Ci poin 17; l5 = P5 d n PI5;
PI6 = Ci poin 21; l6 = P6 d n PI6;
PI7 = Ci poin 25; l7 = P7 d PI7;
ligb = P5 d 2 P6B d 2 P6;
lc1 = P0 d 4 P2;
lc2 = P3 d 4 P1;
lc3 = P1 d 4 P5;
lc4 = P6 d 4 P7;
Ci = inve Ci;
*
* SURFACES
*
sc1 = DALL l1
      (Ci comp PI1 PI2) (inve l2) (inve
lc1);
sc2 = DALL l2
      (inve (Ci comp PI3 PI2)) (inve l3)
(inve ligh);
sc3 = DALL l3
      (inve (Ci comp PI4 PI3)) (inve l4)
(inve lc2);
sc4 = DALL l4
      (inve (Ci comp PI5 PI4)) (inve l5)
(inve lc3);
sc5 = DALL l5
      (inve (Ci comp PI6 PI5)) (inve l6)
(inve ligb);
sc6 = DALL l6
      (inve (Ci comp PI7 PI6)) (inve l7)
(inve lc4);
sc = sc1 et sc2 et sc3 et sc4
      et sc5 et sc6;
*

* RATRAPPAGE EPAISSEUR
*
P8 = P0 plus (0. h) ; lc5 = P2 d ne
P8;
P9 = P1 plus (0. h) ; ligh2 = P8 d n2
P9;
lc6 = P9 d ne P3;
P10 = P1 moin (0. h) ; lc7 = P5 d ne
P10;
P11 = P7 moin (0. h) ; lc8 = P11 d ne
P6;
ligb2 = P10 d n2 P11;
sel = DALL lc5 ligh2 lc6 (inve ligh);
se2 = DALL lc7 ligb2 lc8 (inve ligb);
*
* PARTIE DROITE DE LA POUTRE
*
* premier tour
*
xi = a * 2.;
PDI9 = (xi h);
PDI3 = (xi a);
PDI5 = (xi (a * -1.));
PDI10 = (xi (h * -1.));
LD1 = lc6 et lc2 et lc3 et lc7;
LDI1 = PDI9 d ne PDI3 d 8 PDI5 d ne
PDI10;
LD2 = P9 d 2 PDI9;
LD4 = PDI10 d 2 P10;
sd = DALL (inve LD1) LD2 LDI1 LD4;
LD1 = LDI1;
PD9 = PDI9;
PD10 = PDI10;
*
* boucle
*
cabs = entier (le - (2 * a));
repetier bbmail cabs;
  xi = xi + a;
  PDI9 = (xi h);
  PDI3 = (xi a);
  PDI5 = (xi (a * -1.));
  PDI10 = (xi (h * -1.));
  LDI1 = PDI9 d ne PDI3 d 8 PDI5 d ne
PDI10;
  LD2 = PD9 d 2 PDI9;
  LD4 = PDI10 d 2 PD10;
  sd = sd et (DALL (inve LD1) LD2 LDI1
LD4);
  LD1 = LDI1;
  PD9 = PDI9;
  PD10 = PDI10;
*
* position du pin
*
fin bbmail;
*
* MAILLAGE PARTIES GAUCHES
*
* POINT (2i + 1) de LGj = point abscisse
-i
* de la ligne g
mess 'points';
*
P20 = -90. 0.;
P27 = -90. 0.;
P22 = -90. a;
P26 = -90. (a * -1.);
P28 = -90. h;
P24 = -90. (h * -1.);
*
* LIGNES
*
mess 'lignes';

```

```

lf1 = P20 d 198 P0;
lf2 = P7 d 198 P27;
lp1 = P2 d 198 P22;
lp2 = P26 d 198 P6;
lt1 = P28 d 198 P8;
lt2 = P11 d 198 P24;
lc9 = P22 d 4 P20;
lc10 = P22 d ne P28;
lc11 = P27 d 4 P26;
lc12 = P24 d ne P26;
*
* SURFACES
*
mess 'surfaces';
SGA = dall lf1 lc1 lp1 lc9;
SGA = SGA et (dall lp1 lc10 lt1 (inve
lc5));
SGB = dall lf2 lc11 lp2 lc4;
SGB = SGB et (dall lp2 (inve lc8) lt2
lc12);
*
* MAILLAGE TOTAL
*
mess 'maillage total';
BEAM1 = sf et sc et sel et se2 et sd et
SGA et SGB;
*
* LEVRES DE FISSURE
*
*ccont = ORIE ( cont BEAM1 ) ;
mess 'contour';
ccont = cont BEAM1;
lfs = (ccont comp PC4 pf) ;
lfi = (ccont comp pf PC5) ;
*trac (sf et sc et sel et se2 et sd et
SGA ET SGB);
*
*
* CHOIX DU COMPORTEMENT
*
* Materiau IMS/924
mess 'loi de comportement';
M1 = MODE BEAM1 MECANIQUE ELASTIQUE
ORTHOTROPE;
MTOT1 = M1;
*
* MATERIAL AND ELEMENT DATA
*
mess 'loi materiaux';
E11 = 138E3; E22 = 11E3; E33 = 1E2;
N12 = 0.3434; GX = 4.4E3;
MAT1 = MATE M1 DIRE (1. 0.) YG1 E11 YG2
E22
      NU12 N12 YG3 E33 NU23 0.3 NU13
0.3 G12 GX;
MATOT1 = MAT1;
*
* boucle de propagation
*
repeter bouclé 400;
*
* condition 1 non propagation
*
xp = lpe - (lg * 2);
xp1 = lpe1 - (lg * 2);
xp2 = lpe2 - (lg * 2);
xp3 = lpe3 - (lg * 2);
xp4 = lpe4 - (lg * 2);
xp5 = lpe5 - (lg * 2);
xp6 = lpe6 - (lg * 2);
xp7 = lpe7 - (lg * 2);
xp8 = lpe8 - (lg * 2);
xp9 = lpe9 - (lg * 2);
xp10 = lpe10 - (lg * 2);

xp11 = lpe11 - (lg * 2);
xp12 = lpe12 - (lg * 2);
xp13 = lpe13 - (lg * 2);
*
mess 'lg' lg (lg * 3.1 / 3.);
*
* maillage pins
*
mess 'maillage pins';
si (((flot xp)/2.) < (-0.6));
  np1 = (-1 - xp);
  np2 = (201 + xp);
  pp1 = lp1 poin np1;
  pp2 = lp2 poin np2;
finsi;
si (((flot xp)/2.) > -0.6);
  si (xp < 0.6);
    pp1 = P2B;
    pp2 = P6B;
  finsi;
finsi;
si (((flot xp)/2.) > 0.6);
  pp1 = P3;
  pp2 = P5;
finsi;
*
si (((flot xp1)/2.) < (-0.6));
  np11 = (-1 - xp1);
  np21 = (201 + xp1);
  pp11 = lp1 poin np11;
  pp21 = lp2 poin np21;
finsi;
si (((flot xp1)/2.) > -0.6);
  si (xp1 < 0.6);
    pp11 = P2B;
    pp21 = P6B;
  finsi;
finsi;
si (((flot xp1)/2.) > 0.6);
  pp11 = P3;
  pp21 = P5;
finsi;
*
si (((flot xp2)/2.) < (-0.6));
  np12 = (-1 - xp2);
  np22 = (201 + xp2);
  pp12 = lp1 poin np12;
  pp22 = lp2 poin np22;
finsi;
si (((flot xp2)/2.) > -0.6);
  si (xp2 < 0.6);
    pp12 = P2B;
    pp22 = P6B;
  finsi;
finsi;
si (((flot xp2)/2.) > 0.6);
  pp12 = P3;
  pp22 = P5;
finsi;
*
si (((flot xp3)/2.) < (-0.6));
  np13 = (-1 - xp3);
  np23 = (201 + xp3);
  pp13 = lp1 poin np13;
  pp23 = lp2 poin np23;
finsi;
si (((flot xp3)/2.) > -0.6);
  si (xp3 < 0.6);
    pp13 = P2B;
    pp23 = P6B;
  finsi;
finsi;
si (((flot xp3)/2.) > 0.6);
  pp13 = P3;

```



```

    pp23 = P5;
finsi;
*
si (((flot xp4)/2.) < (-0.6));
    np14 = (-1 - xp4);
    np24 = (201 + xp4);
    pp14 = lp1 poin np14;
    pp24 = lp2 poin np24;
finsi;
si (((flot xp4)/2.) > -0.6);
    si (xp4 < 0.6);
        pp14 = P2B;
        pp24 = P6B;
    finisi;
finsi;
si (((flot xp4)/2.) > 0.6);
    pp14 = P3;
    pp24 = P5;
finsi;
*
si (((flot xp5)/2.) < (-0.6));
    np15 = (-1 - xp5);
    np25 = (201 + xp5);
    pp15 = lp1 poin np15;
    pp25 = lp2 poin np25;
finsi;
si (((flot xp5)/2.) > -0.6);
    si (xp5 < 0.6);
        pp15 = P2B;
        pp25 = P6B;
    finisi;
finsi;
si (((flot xp5)/2.) > 0.6);
    pp15 = P3;
    pp25 = P5;
finsi;
*
si (((flot xp6)/2.) < (-0.6));
    np16 = (-1 - xp6);
    np26 = (201 + xp6);
    pp16 = lp1 poin np16;
    pp26 = lp2 poin np26;
finsi;
si (((flot xp6)/2.) > -0.6);
    si (xp6 < 0.6);
        pp16 = P2B;
        pp26 = P6B;
    finisi;
finsi;
si (((flot xp6)/2.) > 0.6);
    pp16 = P3;
    pp26 = P5;
finsi;
*
si (((flot xp7)/2.) < (-0.6));
    np17 = (-1 - xp7);
    np27 = (201 + xp7);
    pp17 = lp1 poin np17;
    pp27 = lp2 poin np27;
finsi;
si (((flot xp7)/2.) > -0.6);
    si (xp7 < 0.6);
        pp17 = P2B;
        pp27 = P6B;
    finisi;
finsi;
si (((flot xp7)/2.) > 0.6);
    pp17 = P3;
    pp27 = P5;
finsi;
*
si (((flot xp8)/2.) < (-0.6));
    np18 = (-1 - xp8);
    np28 = (201 + xp8);
    pp18 = lp1 poin np18;
    pp28 = lp2 poin np28;
finsi;
si (((flot xp8)/2.) > -0.6);
    si (xp8 < 0.6);
        pp18 = P2B;
        pp28 = P6B;
    finisi;
finsi;
si (((flot xp8)/2.) > 0.6);
    pp18 = P3;
    pp28 = P5;
finsi;
*
si (((flot xp9)/2.) < (-0.6));
    np19 = (-1 - xp9);
    np29 = (201 + xp9);
    pp19 = lp1 poin np19;
    pp29 = lp2 poin np29;
finsi;
si (((flot xp9)/2.) > -0.6);
    si (xp9 < 0.6);
        pp19 = P2B;
        pp29 = P6B;
    finisi;
finsi;
si (((flot xp9)/2.) > 0.6);
    pp19 = P3;
    pp29 = P5;
finsi;
*
si (((flot xp10)/2.) < (-0.6));
    np110 = (-1 - xp10);
    np210 = (201 + xp10);
    pp110 = lp1 poin np110;
    pp210 = lp2 poin np210;
finsi;
si (((flot xp10)/2.) > -0.6);
    si (xp10 < 0.6);
        pp110 = P2B;
        pp210 = P6B;
    finisi;
finsi;
si (((flot xp10)/2.) > 0.6);
    pp110 = P3;
    pp210 = P5;
finsi;
*
si (((flot xp11)/2.) < (-0.6));
    np111 = (-1 - xp11);
    np211 = (201 + xp11);
    pp111 = lp1 poin np111;
    pp211 = lp2 poin np211;
finsi;
si (((flot xp11)/2.) > -0.6);
    si (xp11 < 0.6);
        pp111 = P2B;
        pp211 = P6B;
    finisi;
finsi;
si (((flot xp11)/2.) > 0.6);
    pp111 = P3;
    pp211 = P5;
finsi;
*
si (((flot xp12)/2.) < (-0.6));
    np112 = (-1 - xp12);
    np212 = (201 + xp12);
    pp112 = lp1 poin np112;
    pp212 = lp2 poin np212;
finsi;
si (((flot xp12)/2.) > -0.6);
    si (xp12 < 0.6);
        pp112 = P2B;

```

```

    pp212 = P6B;
    finsi;
finsi;
si (((flot xpl2)/2.) > 0.6);
    pp112 = P3;
    pp212 = P5;
finsi;
*
si (((flot xpl3)/2.) < (-0.6));
    np113 = (-1 - xpl3);
    np213 = (201 + xpl3);
    pp113 = lp1 poin np113;
    pp213 = lp2 poin np213;
finsi;
si (((flot xpl3)/2.) > -0.6);
    si (xpl3 < 0.6);
        pp113 = P2B;
        pp213 = P6B;
    finsi;
finsi;
si (((flot xpl3)/2.) > 0.6);
    pp113 = P3;
    pp213 = P5;
finsi;
*
* points de chargement
*
mess 'calcul des forces';
    np3 = (lg * 2 - 1);
    np4 = (201 - (lg * 2));
    PT3 = lp1 poin np3;
    PT4 = lp2 poin np4;
*
*
* CONDITIONS AUX LIMITES
*
mess 'conditions aux limites';
COND1 = BLOQ PT4 UX;
COND2 = BLOQ PT4 UY;
COND3 = BLOQ PT3 UX;
COND4 = BLOQ PT3 UY;
*CRAC1 = IMPO IMPA MAIT lf1 ESCL lf2;
*COND5 = IMPO IMPA CRAC1;
CL1 = COND1 ET COND2 ET COND3 ET COND4;
*
* boucle sur chargement
*
* condition initiale
*
list pp1;
list pp2;
list pp11;
list pp21;
list pp12;
list pp22;
list pp13;
list pp23;
list PT3;
list PT4;
*
* chargement
*
del1 = del1 + incl;
del2 = del1 * -1.;
*
* boucle force sur pin
*
gil = 3.;
*
repetier bouclef 10;
*
* calcul des forces pins
*

```

```

*
* condition de convergence
*
*
si (abs (g-gil) > 0.000051);
*
    si (dvp1 > 0.);
        si (dvp1 < x1);
            fol = ap1 * dvp1;
        finsi;
    finsi;
    si (dvp1 > x1);
        si (dvp1 < x2);
            fol = bp2 + (ap2 * dvp1) ;
        finsi;
    finsi;
    si (dvp1 > x2);
        fol = 0;
    finsi;
*
    si (dvp11 > 0.);
        si (dvp11 < x1);
            fol1 = ap1 * dvp11;
        finsi;
    finsi;
    si (dvp11 > x1);
        si (dvp11 < x2);
            fol1 = bp2 + (ap2 * dvp11);
        finsi;
    finsi;
    si (dvp11 > x2);
        fol1 = 0.;
    finsi;
*
    si (dvp12 > 0.);
        si (dvp12 < x1);
            fol2 = ap1 * dvp12;
        finsi;
    finsi;
    si (dvp12 > x1);
        si (dvp12 < x2);
            fol2 = bp2 + (ap2 * dvp12);
        finsi;
    finsi;
    si (dvp12 > x2);
        fol2 = 0.;
    finsi;
*
    si (dvp13 > 0.);
        si (dvp13 < x1);
            fol3 = ap1 * dvp13;
        finsi;
    finsi;
    si (dvp13 > x1);
        si (dvp13 < x2);
            fol3 = bp2 + (ap2 * dvp13);
        finsi;
    finsi;
    si (dvp13 > x2);
        fol3 = 0.;
    finsi;
*
    si (dvp14 > 0.);
        si (dvp14 < x1);
            fol4 = ap1 * dvp14;
        finsi;
    finsi;
    si (dvp14 > x1);
        si (dvp14 < x2);
            fol4 = bp2 + (ap2 * dvp14);
        finsi;
    finsi;
    si (dvp14 > x2);
        fol4 = 0.;
    finsi;

```

```

finsi;
*
si (dvp15 > 0.);
  si (dvp15 < x1);
    fol5 = ap1 * dvp15;
  finisi;
finsi;
si (dvp15 > x1);
  si (dvp15 < x2);
    fol5 = bp2 + (ap2 * dvp15);
  finisi;
finsi;
si (dvp15 > x2);
  fol5 = 0.;
finsi;
*
si (dvp16 > 0.);
  si (dvp16 < x1);
    fol6 = ap1 * dvp16;
  finisi;
finsi;
si (dvp16 > x1);
  si (dvp16 < x2);
    fol6 = bp2 + (ap2 * dvp16);
  finisi;
finsi;
si (dvp16 > x2);
  fol6 = 0.;
finsi;
*
si (dvp17 > 0.);
  si (dvp17 < x1);
    fol7 = ap1 * dvp17;
  finisi;
finsi;
si (dvp17 > x1);
  si (dvp17 < x2);
    fol7 = bp2 + (ap2 * dvp17);
  finisi;
finsi;
si (dvp17 > x2);
  fol7 = 0.;
finsi;
*
si (dvp18 > 0.);
  si (dvp18 < x1);
    fol8 = ap1 * dvp18;
  finisi;
finsi;
si (dvp18 > x1);
  si (dvp18 < x2);
    fol8 = bp2 + (ap2 * dvp18);
  finisi;
finsi;
si (dvp18 > x2);
  fol8 = 0.;
finsi;
*
si (dvp19 > 0.);
  si (dvp19 < x1);
    fol9 = ap1 * dvp19;
  finisi;
finsi;
si (dvp19 > x1);
  si (dvp19 < x2);
    fol9 = bp2 + (ap2 * dvp19);
  finisi;
finsi;
si (dvp19 > x2);
  fol9 = 0.;
finsi;
*
si (dvp110 > 0.);
  si (dvp110 < x1);
    fol10 = ap1 * dvp110;
  finisi;
finsi;
si (dvp110 > x1);
  si (dvp110 < x2);
    fol10 = bp2 + (ap2 * dvp110);
  finisi;
finsi;
si (dvp110 > x2);
  fol10 = 0.;
finsi;
*
si (dvp111 > 0.);
  si (dvp111 < x1);
    fol11 = ap1 * dvp111;
  finisi;
finsi;
si (dvp111 > x1);
  si (dvp111 < x2);
    fol11 = bp2 + (ap2 * dvp111);
  finisi;
finsi;
si (dvp111 > x2);
  fol11 = 0.;
finsi;
*
si (dvp112 > 0.);
  si (dvp112 < x1);
    fol12 = ap1 * dvp112;
  finisi;
finsi;
si (dvp112 > x1);
  si (dvp112 < x2);
    fol12 = bp2 + (ap2 * dvp112);
  finisi;
finsi;
si (dvp112 > x2);
  fol12 = 0.;
finsi;
*
si (dvp113 > 0.);
  si (dvp113 < x1);
    fol13 = ap1 * dvp113;
  finisi;
finsi;
si (dvp113 > x1);
  si (dvp113 < x2);
    fol13 = bp2 + (ap2 * dvp113);
  finisi;
finsi;
si (dvp113 > x2);
  fol13 = 0.;
finsi;
*
fo2 = fol1 * -1.;
fo21 = fol1 * -1.;
fo22 = fol2 * -1.;
fo23 = fol3 * -1.;
fo24 = fol4 * -1.;
fo25 = fol5 * -1.;
fo26 = fol6 * -1.;
fo27 = fol7 * -1.;
fo28 = fol8 * -1.;
fo29 = fol9 * -1.;
fo210 = fol10 * -1.;
fo211 = fol11 * -1.;
fo212 = fol12 * -1.;
fo213 = fol13 * -1.;
*
DEP1 = DEPI COND4 del1;
DEP2 = DEPI COND2 del2;
*
* application des forces pins

```

```

*
mess 'application des forces';
FOR1 = FORC (0. fo2) pp1;
FOR2 = FORC (0. fo1) pp2;
FOR11 = FORC (0. fo21) pp11;
FOR21 = FORC (0. fo11) pp21;
FOR12 = FORC (0. fo22) pp12;
FOR22 = FORC (0. fo12) pp22;
FOR13 = FORC (0. fo23) pp13;
FOR23 = FORC (0. fo13) pp23;
FOR14 = FORC (0. fo24) pp14;
FOR24 = FORC (0. fo14) pp24;
FOR15 = FORC (0. fo25) pp15;
FOR25 = FORC (0. fo15) pp25;
FOR16 = FORC (0. fo26) pp16;
FOR26 = FORC (0. fo16) pp26;
FOR17 = FORC (0. fo27) pp17;
FOR27 = FORC (0. fo17) pp27;
FOR18 = FORC (0. fo28) pp18;
FOR28 = FORC (0. fo18) pp28;
FOR19 = FORC (0. fo29) pp19;
FOR29 = FORC (0. fo19) pp29;
FOR110 = FORC (0. fo210) pp110;
FOR210 = FORC (0. fo110) pp210;
FOR111 = FORC (0. fo211) pp111;
FOR211 = FORC (0. fo111) pp211;
FOR112 = FORC (0. fo212) pp112;
FOR212 = FORC (0. fo112) pp212;
FOR113 = FORC (0. fo213) pp113;
FOR213 = FORC (0. fo113) pp213;
*
FORT = DEP1 ET DEP2 ET FOR1 ET FOR2 ET
FOR11 ET FOR21 ET
FOR12 ET FOR22 ET FOR13 ET FOR23 ET
FOR14 ET FOR24 ET FOR15
ET FOR25 ET FOR16 ET FOR26 ET FOR17 ET
FOR27 ET FOR18 ET
FOR28 ET FOR19 ET FOR29 ET FOR110 ET
FOR210 ET FOR111 ET
FOR211 ET FOR112 ET FOR212 ET FOR113 ET
FOR213;
*
*
* RESOLUTION
*
mess 'resolution';
rigi1 = RIGI MTOT1 MATOT1;
rigic11 = rigi1 et c11;
depl1 = reso rigic11 fort;
sig0 = sigm mtot1 matot1 depl1;
vm1 = vmis m1 sig0;
*
* POST PROCESS
*
def1 = defo beam1 depl1;
*trac def1;
*trac vm1 m1 def1;
*
* CALCUL DE G-ENERGY RELEASE RATE
*
*
SUPTAB = TABLE ;
SUPTAB.'OBJECTIF' = MOT 'J' ;
SUPTAB.'LEVRE_SUPERIEURE' = lfs;
SUPTAB.'LEVRE_INFERIEURE' = lfi;
SUPTAB.'FRONT_FISSURE' = pf ;
SUPTAB.'COUCHE' = 4;
SUPTAB.'SOLUTION_RESO' = depl1;
SUPTAB.'MODELE' = M1;
SUPTAB.'CARACTERISTIQUES' = MAT1;
SUPTAB.'CHARGEMENTS_MECAIQUES' =
FORT;
*
* calcul de G

```

```

*
gil = g;
G_ORTHO SUPTAB;
G = suptab.'RESULTATS';
*
si (g < 0.25);
stab1 = 0.;
finsi;
*
mess 'lg' lg (&bouclef) 'pas'
(&boucléd);
*
real = REAC rigic11 depl1;
load1 = extr real PT3 fy;
*
delta1 = extr depl1 UY PT3;
*
vp1 = extr depl1 UY pp1;
vp2 = extr depl1 UY pp2;
dvp1 = vp1 - vp2;
*
vp11 = extr depl1 UY pp11;
vp21 = extr depl1 UY pp21;
dvp11 = vp11 - vp21;
*
vp12 = extr depl1 UY pp12;
vp22 = extr depl1 UY pp22;
dvp12 = vp12 - vp22;
*
vp13 = extr depl1 UY pp13;
vp23 = extr depl1 UY pp23;
dvp13 = vp13 - vp23;
*
vp14 = extr depl1 UY pp14;
vp24 = extr depl1 UY pp24;
dvp14 = vp14 - vp24;
*
vp15 = extr depl1 UY pp15;
vp25 = extr depl1 UY pp25;
dvp15 = vp15 - vp25;
*
vp16 = extr depl1 UY pp16;
vp26 = extr depl1 UY pp26;
dvp16 = vp16 - vp26;
*
vp17 = extr depl1 UY pp17;
vp27 = extr depl1 UY pp27;
dvp17 = vp17 - vp27;
*
vp18 = extr depl1 UY pp18;
vp28 = extr depl1 UY pp28;
dvp18 = vp18 - vp28;
*
vp19 = extr depl1 UY pp19;
vp29 = extr depl1 UY pp29;
dvp19 = vp19 - vp29;
*
vp110 = extr depl1 UY pp110;
vp210 = extr depl1 UY pp210;
dvp110 = vp110 - vp210;
*
vp111 = extr depl1 UY pp111;
vp211 = extr depl1 UY pp211;
dvp111 = vp111 - vp211;
*
vp112 = extr depl1 UY pp112;
vp212 = extr depl1 UY pp212;
dvp112 = vp112 - vp212;
*
vp113 = extr depl1 UY pp113;
vp213 = extr depl1 UY pp213;
dvp113 = vp113 - vp213;
*

```



```

mess load1 (2. * delta1) G;
mess fo1 fo11 fo12 fo13 fo14;
mess dvp1 dvp11 dvp12 dvp13 dvp14;
mess fo2 fo21 fo22 fo23 fo24;
*
finsi;
*
*
fin bouclef;
*
si (stab1 < 0.5);
  dvp11 = dvp1;
  dvp111 = dvp11;
  dvp112 = dvp12;
  dvp113 = dvp13;
  dvp114 = dvp14;
  dvp115 = dvp15;
  dvp116 = dvp16;
  dvp117 = dvp17;
  dvp118 = dvp18;
  dvp119 = dvp19;
  dvp1110 = dvp110;
  dvp1111 = dvp111;
  dvp1112 = dvp112;
  dvp1113 = dvp113;
finsi;
*
tabreal.(&boucled) = load1;
tabdel1.(&boucled) = delta1;
tabg1.(&boucled) = G;
tablg1.(&boucled) = lg;
tabdvp1.(&boucled) = dvp1;
tabdvp11.(&boucled) = dvp11;
tabdvp12.(&boucled) = dvp12;
tabdvp13.(&boucled) = dvp13;
tabdvp14.(&boucled) = dvp14;
tabdvp15.(&boucled) = dvp15;
tabdvp16.(&boucled) = dvp16;
tabdvp17.(&boucled) = dvp17;
tabdvp18.(&boucled) = dvp18;
*
tabfo1.(&boucled) = fo1;
tabfo11.(&boucled) = fo11;
tabfo12.(&boucled) = fo12;
tabfo13.(&boucled) = fo13;
tabfo14.(&boucled) = fo14;
tabfo15.(&boucled) = fo15;
tabfo16.(&boucled) = fo16;
tabfo17.(&boucled) = fo17;
tabfo18.(&boucled) = fo18;
*
*
mess 'pas' (&boucled);
*
*trac vm1 m1 def1;
*
finsi;
*
* condition2 crack propagation
*
si (g > 0.25);
  stab1 = 1.;
  mess 'propagation';
  lg = lg + 1;
  dell = dell - inc1;
  dvp1 = dvp11;
  dvp12 = dvp112;
  dvp13 = dvp113;
  dvp14 = dvp114;
  dvp15 = dvp115;
  dvp16 = dvp116;
  dvp17 = dvp117;
  dvp18 = dvp118;
  dvp19 = dvp119;
  dvp110 = dvp110;
  dvp111 = dvp111;
  dvp112 = dvp112;
  dvp113 = dvp113;
  g = 0.;
  gil = 3.;
finsi;
*
fin boucled;
*
trac vm1 m1 def1;

```