

IMPERIAL COLLEGE LONDON
Department Of Aeronautics
PhD Thesis

AN INVESTIGATION OF THE MECHANICAL PERFORMANCE OF Z-PIN REINFORCED COMPOSITES

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ABSTRACT

Fibrous composites, having excellent mechanical properties in the direction of the fibres, have lower mechanical properties in the through thickness direction, controlled by resin. Z-pinning improves the delamination toughness (up to 500%) with a relatively modest reduction to the in-plane mechanical properties (typically 5–15%).

This experimental study investigates the mechanical performance of Z-Pins bridging an existing delamination in fibre reinforced resin composites under pull-out (Mode I), shear-out (Mode II) and mixed mode loading conditions using a specially designed testing rig. In Mode II the opening displacement was restricted and measured by springs of three different stiffnesses.

A new technique of needle assisted Z-Pin insertion was developed, in which prepreg panels were perforated with a steel needle in order to insert Z-Pins. This technique ensured the desired orientation of Z-Pins, improved pinning quality and removed the necessity of costly preforms used in the traditional UAZ method.

Test specimens were blocks (15 mm x 15 mm x 6mm thick) of carbon-epoxy IM7/8552 composite in unidirectional (UD) and quasi-isotropic (QI) stacking sequences, with PTFE delamination film in the mid-plane recreating an existing crack, bridged with a single T300/9310 Z-Pin or a group of four pins of either 0.28 mm or 0.51 mm diameter.

Three phases of pull-out were identified: Linear Phase (linear force-displacement curve), Crack Formation (unstable crack propagation phase) and Frictional Sliding (friction-controlled pull-out). Two phases of shear-out were identified: Linear Phase (with no energy loss) and Breaking Phase (where the fibrous structure of the Z-Pins is fractured, ending with Z-Pin breakage). In mixed mode specimens behaved similarly to pull-out for the pin angles up to 45°. For higher angles the behaviour was more similar to pure shear-out. The influence of the Z-Pin diameter, z-pinning depth, distance between adjacent Z-Pins, composite stacking sequence and pull-out speed on the Z-Pins behaviour were investigated. The results will be useful in the formulation of improved Z-Pin bridging laws for use in finite element models.

INDEX OF FIGURES:

Figure 1.1 Structure of composite material: pure composite and composite with Z-Pin reinforcement	15
Figure 2.1 Geometry of lap joint specimens, [40].....	26
Figure 2.2 Post delamination damage of the Z-Pin and damage of the laminate caused by z-pinning, [53]	28
Figure 2.3 Single stitch pull-out process: a) elastic stretching stage, b) slip-out stage, stitched DCB specimen, [56]	31
Figure 2.4 Results: the effect of beam thickness H (a), initial crack length a_0 (b), matrix critical stress intensity factor K_m (c), thread/matrix interface shear stress τ (d), stitch density S_D and thread diameter d_f (e) and thread stiffness E_f (f) on $K_R\Delta a$ curve, [58]	36
Figure 2.5 Fibre pull-out model, [59]	37
Figure 2.6 Model basics, [66]	40
Figure 2.7 Comparison of load-displacement plots: model predictions - thick red lines; average experimental values - thick black lines; standard deviation scatter bands on mean load - thin grey lines, [66]	41
Figure 2.8 Predicted maximum normal and shear stress distribution at failure for $\phi = 0.550$; Position of delamination surfaces in red continuous lines; the dashed red lines give the axial locations of the stress peaks, [66]	41
Figure 2.9 Axisymmetric model of Z-Pin, [54]	44
Figure 2.10 Geometry of the model and mesh features, [44]	47
Figure 2.11 Z-Pin insertion angle, [44]	47
Figure 2.12 Geometry of the “star pattern”, [44].....	47
Figure 2.13 Finite element mesh of the Unit Cell, arrows indicate fibre directions in relevant regions, [45]	50
Figure 2.14 Three-dimensional FE model of the Z-Pins near the edge of the laminate, [54]	53
Figure 2.15 Axisymmetric model of the Z-Pin embedded into precracked laminate, [54]	55
Figure 2.16 Finite element model of the Z-Pins near the edge of the laminate, [54]	56
Figure 2.17 Two-dimensional mesh of the part of DCB specimen with the crack tip in the centre, crack propagation by re-meshing, [72]	57
Figure 2.18 Geometry of the model, including the location of coercive elements (red lines), [43]	63
Figure 2.19 Full FE model of z-pinned quasi-isotropic laminates, [68]	65
Figure 2.20 Ply level mesh of z-pinned laminates (a), Z-Pin misalignment (b), cohesive elements along the Z-Pin fibres (c), [68].....	65
Figure 2.21 Load-displacement curves, Mode I, QI laminate, [68,67]	66
Figure 2.22 Load-displacement curves, Mode I, UD laminate, [66]	66
Figure 2.23 Pull-out of Z-Pin and enhanced friction zone	67
Figure 2.24 Z-Pin failure initiation (a) and corresponding split status (b), [68]	67
Figure 2.25 Load-displacement curves, Mode II, QI laminate [68,67]	68
Figure 2.26 Pull-out load-displacement graphs for different crosshead speeds, [80,81]	71
Figure 2.27 Load-displacement curves, [47]	72
Figure 2.28 Single Z-Pin pull-out test, T-shaped parts of the rig, [72]	74
Figure 2.29 Typical experimental pull-out curves, [72]	74
Figure 2.30 Idealised pull-out curve, [72]	75
Figure 2.31 Specimen in the testing rig and definition of insertion angle, [82]	77
Figure 2.32 Examples of Force vs. displacement plots, [72,82]	79
Figure 2.33 Examples of Force vs. Displacement plots, [72,82]	79
Figure 2.34 Specimen with release film inserts at mid-plane dimensions before testing, [67]	82
Figure 2.35 Population of pin offset angle after the manufacturing process, [67]	83
Figure 2.36 Fixture for the Mode II shear testing, highlighting the movement of the loading blocks inside the outer guide and the relative sample position, [67]	83
Figure 2.37 Fixture for the mixed mode I/II testing, [67,48]	84
Figure 2.38 Representative QI laminate load vs. displacement results, [67]	84
Figure 2.39 Representative UD laminate load vs. displacement results (mixed mode and Mode II curves from sample loaded in “soft” direction) , [67]	85
Figure 2.40 Two stage bridging mechanism in mode I and some mixed mode I/II cases, [67]	85
Figure 2.41 Absorbed energy vs. corrected mixed mode angle for failure/pull-out of Z-Pins in QI and UD laminate, [67]	86

Figure 3.1 Z-Pinning process (UAZ machine) – drawing based on the machine used in QinetiQ, Farnborough	95
Figure 3.2 Manual Z-Pin insertion – the actual needle, chuck and Z-Pinned panel made at the Imperial College London for the sole purpose of this thesis.	98
Figure 3.3 A pistol and a Z-Pin in rubber cylinder used in air gun insertion method.	100
Figure 3.4 Geometry of the Z-Pinning pattern - the way of cutting single and four Z-Pins specimens out of the panel (similar for all methods).	103
Figure 3.5 Single Z-Pin specimen with visible chamfer, fibre waviness caused by the insertion of Z-Pin, working and holding part – Method A.	104
Figure 3.6 Lost and proper specimens prepared using Method A, before the tests.	105
Figure 3.7 Single Z-Pin specimen – Method B, C and D.	108
Figure 3.8 Drilling the specimens in order to change pinning depth	109
Figure 3.9 The specimen set in the testing rig (pull-out test)	117
Figure 3.10 The original test rig developed by Arcan, [83]	119
Figure 3.11 Multi mode testing rig: assembly view of the rig in shear-out position, with springs and weights attached.	120
Figure 3.12 Multi mode rig with opening displacement controlling springs and weights attached.	122
Figure 3.13 Scheme of strain gauge set for opening displacement and force measurement in shear-out tests.	122
Figure 3.14 Multi mode rig in 45° mixed mode configuration, with laser gauge attached.	124
Figure 3.15 Testing rig for shear tests.	125
Figure 4.1 Resin pockets, fibre waviness and fibres deformations - damage made to the composite and quality of Z-Pinning in Method A and B (UAZ insertion) and Method C (needle assisted manual insertion).	131
Figure 4.2 Resin pockets in a four pin, 0.51 mm Z-Pins, QI, Method C specimen.	132
Figure 4.3 Resin pockets in a four pin, 0.51 mm Z-Pins, QI and UD, Method B specimen.	132
Figure 4.4 Post mortem micrographs of QI and UD single 0.51 mm Z-Pin, pull-out tests, Method B specimens (Z-Pins broken during handling after tests).	134
Figure 4.5 Post mortem micrographs of QI and UD single 0.51 mm Z-Pin, pull-out tests, Method B specimens (Z-Pins broken during handling after tests).	136
Figure 4.6 Z-Pins inserted into BlueTac	138
Figure 4.7 Irregularity of cross-sections of Z-Pins.	139
Figure 4.8 The voids in the structure of Z-Pin, [54]	141
Figure 4.9 Longitudinal cross-sections of 0.51 mm Z-Pins.	141
Figure 4.10 Subsequent, made every 0.2 mm, cross-sections of a Z-Pin.	143
Figure 5.1 The method of post mortem measurement of the pulled-out part of Z-Pin, Method A.	147
Figure 5.2 Pull-out curves – Method A, single 0.51 mm Z-Pin: QI vs. UD laminate	150
Figure 5.3 Pull-out curves - Method A, group of four 0.51 mm Z-Pins: QI vs. UD laminate, “close” vs. “far” Z-Pin pattern, various embedded lengths.	150
Figure 5.4 Pull-out curves –Method C, single 0.51 mm Z-Pin: QI vs. UD laminate	153
Figure 5.5 Pull-out curves – Method C, single 0.28 mm Z-Pin: QI vs. UD laminate	153
Figure 5.6 Pull-out curves, group of four 0.51 mm Z-Pin, UD laminate: “far” vs. “close” Z-Pin pattern	154
Figure 5.7 Pull-out curves – Method C, group of four 0.51 mm Z-Pin, QI laminate: “far” vs. “close” Z-Pin pattern	154
Figure 5.8 Pull-out curves - Method C, single 0.51 mm Z-Pin, QI laminate: various embedded lengths	155
Figure 5.9 Pull-out curves - Method C, single 0.51 mm Z-Pin, QI laminate: various pull-out speeds	155
Figure 5.10 Pull-out curve.	156
Figure 5.11 Pull-out energy chart – Method A.	158
Figure 5.12 Pull-out “adhesion” and “frictional” stress chart – Method A, single 0.51 mm Z-Pins	159
Figure 5.13 Pull-out force at specific points and corresponding displacement chart – Method A, single 0.51 mm Z-Pins	160
Figure 5.14 Pull-out energy chart – Method C.	162
Figure 5.15 Pull-out “adhesion” and “frictional” stress chart – Method C, single 0.51 mm Z-Pins	164
Figure 5.16 Pull-out force at specific points and corresponding displacement chart – Method C, single 0.28 mm Z-Pins (black lines indicate standard deviation)	166
Figure 5.17 Pull-out force at specific points and corresponding displacement chart – Method C, single 0.51 mm Z-Pins (black lines indicate standard deviation)	167
Figure 5.18 Pull-out force at specific points and corresponding displacement chart – Method C, group of four 0.51 mm Z-Pins (black lines indicate standard deviation)	168

Figure 5.19 Phases of the pull-out process – UD laminate (red zone indicates the range of curves recorded in tests).....	170
Figure 5.20 Phases of the pull-out process – QI laminate (green zone indicates the range of curves recorded in tests).....	171
Figure 5.21 Force-displacement curves of specimens reused after accidental debonding from the rig during testing.....	172
Figure 5.22 Pull-out – push-in tests results, QI, 1 x 0.51 mm Z-Pin.....	176
Figure 5.23 Shear-out curves - Method B, single Z-Pin, QI laminate: 0.51 mm vs. 0.28 mm Z-Pins.....	178
Figure 5.24 Shear-out curves - Method B, single 0.51 mm Z-Pin, medium spring: QI vs. UD “along” and “across” laminate.....	178
Figure 5.25 Shear-out curves - Method B, single 0.28 mm Z-Pin, medium spring: QI vs. UD “along” and “across” laminate.....	179
Figure 5.26 Shear-out curves - Method B, single 0.51 mm Z-Pin, QI laminate, soft spring: various embedded lengths.....	179
Figure 5.27 Shear-out curves - Method B, single 0.28 mm Z-Pin, QI laminate, soft spring: various embedded lengths.....	180
Figure 5.28 Shear-out curves - Method B, group of four 0.51 mm Z-Pin, medium spring: “far” vs. “close” Z-Pin pattern.....	180
Figure 5.29 Shear-out curves - Method B, group of four 0.51 mm Z-Pin, “close” pattern, medium spring: QI vs. UD “along” and “across” laminate.....	181
Figure 5.30 Shear-out curves - single 0.51 mm Z-Pin, QI laminate, medium spring: Method B vs. Method C.....	183
Figure 5.31 Shear-out curves - Method C, single 0.51 mm Z-Pins, soft spring: QI vs. UD “along” and “across” laminate.....	183
Figure 5.32 Shear-out curves - Method C, single 0.28 mm Z-Pins, soft spring: QI vs. UD “along” and “across” laminate.....	184
Figure 5.33 Shear-out curves - Method C, single 0.51 mm Z-Pins, QI laminate, soft spring: various spring stiffnesses.....	185
Figure 5.34 Shear-out curves - Method C, single 0.28 mm Z-Pins, QI laminate, soft spring: various spring stiffnesses.....	185
Figure 5.35 Shear-out curves - Method C, single 0.51 mm Z-Pins, medium spring: QI vs. UD “along” and “across” laminate.....	186
Figure 5.36 Shear-out curves - Method C, single 0.51 mm Z-Pins, stiff spring: QI vs. UD “along” and “across” laminate.....	186
Figure 5.37 Shear-out curves - Method C, single 0.28 mm Z-Pins, stiff spring: QI vs. UD “along” laminate.....	187
Figure 5.38 Shear-out curves - Method C, single 0.51 mm Z-Pin, QI laminate, stiff spring: various embedded lengths.....	187
Figure 5.39 Shear-out curves - Method C, group of four 0.51 mm Z-Pins, soft spring: QI vs. UD laminate, “far” vs. “close” Z-Pin pattern.....	188
Figure 5.40 Shear-out curves - Method C, group of four 0.51 mm Z-Pins, stiff spring: QI vs. UD laminate, “far” vs. “close” Z-Pin pattern.....	188
Figure 5.41 Shear-out curve.....	189
Figure 5.42 Shear-out energy chart – Method B.....	191
Figure 5.43 Shear-out force at specific points and corresponding displacement chart – Method B, single 0.28 mm Z-Pins (black lines indicate standard deviation).....	192
Figure 5.44 Shear-out force at specific points and corresponding displacement chart – Method B, single 0.51 mm Z-Pins (black lines indicate standard deviation).....	193
Figure 5.45 Shear-out force at specific points and corresponding displacement chart – Method B, group of four 0.51 mm Z-Pins (black lines indicate standard deviation).....	194
Figure 5.46 Shear-out energy chart – Method C (along and across grouped together in four Z-Pin specimens due to low number of specimens).....	196
Figure 5.47 Shear-out force at specific points and corresponding displacement chart – Method C, single 0.28 mm Z-Pins (black lines indicate standard deviation).....	197
Figure 5.48 Shear-out force at specific points and corresponding displacement chart – Method C, single 0.51 mm Z-Pins (black lines indicate standard deviation).....	198
Figure 5.49 Shear-out force at specific points and corresponding displacement chart – Method C, group of four 0.51 mm Z-Pins (along and across grouped together in four Z-Pin specimens due to low number of specimens - black lines indicate standard deviation).....	198

Figure 5.50 QI and UD sheared along versus UD sheared across (red and green zones indicate the range of curves recorded in tests).....	202
Figure 5.51 Phases of shear-out process.	202
Figure 5.52 Mixed mode curves - Method C, single 0.51 mm Z-Pin, rigid rig: various testing angles.....	204
Figure 5.53 Mixed mode curves - 45° angle, Method C, 0.51 mm Z-Pin, rigid rig: QI vs. UD “along” and “across” laminate.....	205
Figure 5.54 Mixed mode curves - 45° angle, Method C, 0.28 mm Z-Pin, rigid rig: QI vs. UD “along” and “across” laminate.....	205
Figure 5.55 Mixed mode curves - 45° angle, Method C, 0.51 mm Z-Pin, QI laminate: rigid vs. swivelling rig	206
Figure 5.56 Mixed mode curves - 45° angle, Method C, 0.51 mm Z-Pin, QI laminate, rigid rig: various embedded lengths	206
Figure 5.57 Mixed mode energy chart – Method C	208
Figure 5.58 Displacements in mixed mode tests – global and local coordinates.....	210
Figure 5.59 Pull-out, 45° mixed mode and shear-out processes in local coordinates – stiff spring	211
Figure 5.60 Pull-out, 45° mixed mode and shear-out processes in local coordinates – soft spring	212
Figure 5.61 Examples of the 45° mixed mode curves along with the opening displacement recording.....	213
Figure 5.62 Results of the shear tests. The colours in each graph distinguish the specimens.	217
Figure 6.1 Proposition of an alternative pinning device	224

INDEX OF TABLES:

Table 2.1 Advantages and disadvantages of common methods of interlaminar reinforcement, in comparison to the unidirectional laminates without through thickness reinforcement, based on [7]	23
Table 2.2 Material properties used in the model, [58]	35
Table 2.3 Material properties of Z-Pin (T300/5208) and laminate (AS4/3501-6), [54]	44
Table 2.4 Material input properties for the Unit Cell model, [44]	46
Table 2.5 Results: percent change from the control case without Z-Pins, approximate values read from graphs, [44].....	48
Table 2.6 Material properties used in FE models, [45].....	50
Table 2.7 Influence of the Z-Pinning process on composite stiffness, Unit Cell model, [45]	51
Table 2.8 Material properties used in FE model, [72]	58
Table 2.9 Comparison between experiment and FE modelling results, [72]	59
Table 2.10 Friction stresses of titanium and composite Z-Pins from pull-out tests on IMS/924 Z-Pins, 2 mm embedded length, [72]	76
Table 2.11 Results of single Z-Pin shear-out tests [72,82]	78
Table 3.1 Material properties of the composite and Z-Pins used in this project (according to [43, 76] and manufacturer’s internet resources).....	92
Table 3.2 Manufacturing process of a laminate with Z-Pins – Method A.	101
Table 3.3 Manufacturing process of a laminate with Z-Pins – Method B.	106
Table 3.4 Manufacturing process of a laminate with Z-Pins – Method C.	111
Table 3.5 Manufacturing process of a laminate with Z-Pins – Method D.	111
Table 3.6 Quantities of specimens used in various tests (There were only a few specimens of the Method D tested).....	114
Table 3.7 Spring calibration and stiffness measurement results.	123
Table 4.1 Results of the measurements of Z-Pins diameters.....	138

Declaration of Originality

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ABSTRACT.....	2
1 INTRODUCTION.....	11
2 LITERATURE SURVEY.....	16
2.1 INTRODUCTION.....	17
2.2 TECHNIQUES FOR IMPROVING INTERLAMINAR TOUGHNESS IN COMPOSTES.....	19
2.2.1 INTRODUCTION	19
2.2.2 TOUGHENED RESIN	19
2.2.3 INTERLEAVING	19
2.2.4 2D AND 3D WEAVING, BRAIDING	20
2.2.5 TUFTING	20
2.2.6 STITCHING	20
2.2.7 Z-PINNING	20
2.2.8 SUMMARY	23
2.3 Z-PINS IN THE COMPOSITE STRUCTURE	24
2.3.1 INTRODUCTION	24
2.3.2 INFLUENCE OF Z-PINNING ON THE CRACK PROPAGATION AND DELAMINATION RESISTANCE IN COMPOSITES	24
2.3.3 DAMAGE RESISTANCE AND IMPACT TOLERANCE OF Z-PINNED STRUCTURES	24
2.3.4 INFLUENCE OF Z-PINNING ON THE LAMINATE PROPERTIES	26
2.3.5 MANUFACTURING QUALITY OF Z-PINS AND Z-PINNING	27
2.3.6 SUMMARY	29
2.4 MATHEMATICAL MODELS OF FIBRE PULL-OUT PROCESS.....	30
2.4.1 INTRODUCTION	30
2.4.2 MATHEMATICAL MODELS.....	30
2.4.3 SUMMARY	42
2.5 FINITE ELEMENT MODELS OF SINGLE Z-PIN.....	43
2.5.1 INTRODUCTION	43
2.5.2 EFFECT OF THE PRESENCE OF THE Z-PIN ON MATERIAL PROPERTIES	43
2.5.3 THE EFFECT OF Z-PINNING ON INTERLAMINAR CRACK PROPAGATION	53
2.5.4 MICROMECHANICS OF THE Z-PIN BRIDGING IN MODE I OR MODE II	60
2.5.5 SUMMARY	69

2.6	SINGLE Z-PIN PULL-OUT AND SHEAR-OUT TESTS.....	70
2.6.1	INTRODUCTION	70
2.6.2	PULL OUT TESTS ON GROUPS OF Z-PINS EMBEDDED IN COMPOSITE 70	
2.6.3	PULL-OUT AND SHEAR-OUT TESTS ON SINGLE Z-PINS EMBEDDED IN COMPOSITE.....	73
2.6.4	SUMMARY	86
2.7	OVERALL SUMMARY OF LITERATUR REVIEW.....	88
3	EXPERIMENTAL DETAILS	90
3.1	OVERVIEW.....	91
3.2	MATERIALS	92
3.3	Z-PIN INSERTION METHODS	93
3.3.1	OVERVIEW	93
3.3.2	UAZ INSERTION	93
3.3.3	MANUAL INSERTION	96
3.3.4	AUTOCLAVE INSERTION	98
3.3.5	AIR GUN INSERTION	99
3.3.6	SUMMARY	100
3.4	SPECIMEN MANUFACTURE AND PREPARATION	101
3.4.1	INTODUCTION	101
3.4.2	METHOD A – PULL-OUT	101
3.4.3	METHOD B – SHEAR-OUT	106
3.4.4	METHOD C AND D - PULL-OUT, SHEAR-OUT AND MIXED MODE ...	109
3.4.5	SUMMARY	112
3.5	TESTING RIGS	115
3.5.1	OVERVIEW	115
3.5.2	SIMPLE TESTING RIG	115
3.5.3	MULTI MODE TESTING RIG.....	118
3.5.4	OPENING DISPLACEMENT MEASUREMENT AND CONTROL FOR THE SHEAR-OUT TESTS	121
3.5.5	OPENING DISPLACEMENT MEASUREMENT WITH LASER GAUGE FOR MIXED MODE TESTS	123
3.5.6	Z-PIN IN PURE SHEAR AND SHEAR WITH BENDING CONDITIONS .	124
3.5.7	SUMMARY	126
4	MICROSCOPIC OBSERVATIONS	127
4.1	OVERVIEW.....	128

4.2	Z-PINS EMBEDDED IN THE COMPOSITE STRUCTURE	130
4.3	Z-PINS EMBEDDED INTO COMPOSITE STRUCTURE – OBSERVATIONS POST MORTEM	134
4.4	TRANSVERSE CROSS-SECTION OF Z-PIN	137
4.5	LONGITUDINAL CROSS-SECTION OF Z-PIN	140
4.6	SEQUENTIAL TRANSVERSE CROSSECTION OF Z-PIN	142
4.7	SUMMARY	144
5	RESULTS OF PULL-OUT, SHEAR-OUT AND MIXED MODE TESTS	145
5.1	OVERVIEW	146
5.2	PULL-OUT TESTS	147
5.2.1	RESULTS	147
5.2.2	DATA REDUCTION	156
5.2.3	MICROMECHANICS OF PULL-OUT	169
5.3	SHEAR-OUT TESTS	177
5.3.1	RESULTS	177
5.3.2	DATA REDUTION	189
5.3.3	MICROMECHANICS OF SHEAR-OUT	200
5.4	MIXED MODE TESTS	203
5.4.1	RESULTS	203
5.4.2	DATA REDUCTION	207
5.5	MIXED MODE TESTS WITH OPENING DISPLACEMENT MEASUREMENT 209	
5.6	PURE SHEAR AND SHEAR IN THE PRESENCE OF BENDING TESTS	214
5.6.1	OVERVIEW	214
5.6.2	OBSERVATIONS AND RESULTS	214
6	CONCLUSIONS AND FUTURE WORK	218
6.1	CONCLUDING REMARKS	219
6.2	FUTURE WORK	222
7	REFERENCES	225
	APPENDIX – TABLES OF RESULTS	233

1 INTRODUCTION

Fibre reinforced polymer matrix composites (PMCs) are characterised by high strength (and stiffness) to weight ratio in comparison to metals. They offer superior mechanical properties in the direction of the fibres, which can be used to design and optimise their internal structure for particular loading conditions, which cannot be achieved with isotropic materials. Due to their advantages, the composites are often used in aerospace or automotive components.

Although the properties of the polymer composites are excellent in the direction of the fibres, the properties of the matrix, or resin, which joins the fibres are considerably lower, leaving the structure sensitive to delamination as its interlaminar toughness is governed by the properties of the resin. The mechanisms of the structural damage are not yet fully understood, hence the damage tolerance of the composite structure cannot be easily predicted at the design level and the internal damage is difficult to assess. Hence the more predictable metal materials are often used in the highly loaded primary structures, most critical for the safety.

Reliable, predictable and low cost methods of improving resistance to delamination and damage tolerance of fibre-polymer composites are sought by aerospace and automotive industry, where the structures may encounter various forms damage (from bird strike or dropped tool, to collisions or “hard landing”.) The impacts may cause internal damage, e.g. delamination, which may be invisible on the surface but cause a significant drop in the load carrying capacity of the structure.

Various methods of improving interlaminar toughness are available, including toughened resins, interleaving, fibre surface treatment, three-dimensional weaving, stitching, z-anchoring, tufting. These methods however increase the cost and complexity of the manufacturing process, and not all of them can be applied to the commonly used prepreg materials.

A fairly new and highly promising method of through thickness reinforcement is z-pinning. Z-Pin (also referred to as Z-Fibre after the original manufacturer Aztec Inc., 303 Bear Hill Road, Waltham, MA, 02154, USA) reinforcement is based on the insertion before cure of stiff rods through the thickness of polymer matrix composite laminates (**Figure 1.1**). After the composite is cured, the Z-Pin physically “nails” the layers of the composite structure together

introducing extra strength and stiffness in the Z direction (perpendicular to the plane of structure) making the composite a real 3D fibre structure. The Z-Pins are usually less than 1 mm in diameter and are made of unidirectional fibre composite, titanium, steel, or other strong material and their volume fraction in the structure ranges between 0.5% and 5% in most applications.

A key benefit of Z-Pins is the improvement of the interlaminar crack propagation resistance and impact damage tolerance with modest increase in manufacturing costs and complexity. The Z-Pins can be used to reinforce laminate shell structures as well as to attach stiffeners (e.g. T-joints). One of the commercial applications of z-pinning is F-18 Super Hornet aircraft. Recently Rolls-Royce has also been investing in the research and development of the Z-Pins.

Z-Pins have also negative influence on the laminate properties, causing damage to the microstructure. The waviness of the fibres caused by the Z-Pins, the transfer of the fibres between layers, and the pockets rich in resin reduce the in-plane mechanical properties (e.g. stiffness, strength, and fatigue life), which has to be accounted for in the composite structure design.

The aim of this study is to experimentally investigate the mechanism of Z-Pin reinforcement, focusing particularly on the behaviour of Z-Pins (single and in groups) bridging an already existing interlaminar crack under Mode I (pull-out), Mode II (shear-out) and Mixed Mode I/II loading conditions in carbon-epoxy composites. Introduction of the crack recreates the conditions in the laminate in the crack wake, following the initiation of delamination.

Microscopic observations of the Z-Pins (of the pins themselves and in the composite structure, before and after test) were carried out to investigate the internal structure of the Z-Pin and the damage caused by the Z-Pin insertion using various insertion methods.

In this study IM7/8552 carbon-epoxy prepreg reinforced with carbon-BMI Z-Pins was tested. Z-Pins in diameters of 0.28 mm and 0.51 mm were inserted into 48-ply (6 mm) Unidirectional (UD, $[0^\circ]_{48}$) or Quasi-isotropic (QI, $[[0^\circ/\pm 45^\circ/90^\circ]_s]_6$) prepreg assemblies.

In addition to the standard ultrasonically assisted insertion method (UAZ), a unique method of manually inserting Z-Pins into the laminate perforated with a steel needle (Manual Insertion) was used. The following Z-Pin insertion methods were applied:

- Method A - UAZ Insertion, with the excess Z-Pins removed from pre-form before Z-Pinning
- Method B - UAZ Insertion, with the excess Z-Pins removed from prepreg panel before preconsolidation
- Method C - Manual Insertion, with Z-Pins inserted after preconsolidation (panel heated up to 50°C)
- Method D - Manual Insertion, with Z-Pins inserted directly after laying up

The PTFE release film was inserted in the mid-plane during layup of the laminates in order to simulate an existing crack. After curing, the assemblies were cut into specimens containing either single pin or group of four pins. The specimens were tested with a specially designed universal testing rig, which allowed the following tests:

- Mode I (pull-out): three different pinning depths (1.0 mm, 2.0 mm and 3.0 mm) and three different pull-out speeds (0.05 mm/min, 0.5 mm/min and 5 mm/min) were investigated
- Mode II (shear-out): again three different pinning depths were investigated. Also force control (three sets of springs of different stiffness) was implemented to constrain tendency of the sliding surfaces to move apart
- Mixed Mode: in this test the load was applied at angles 30°, 45°, 60°, 70°, 80° to the pin (representing Mode II to Mode I displacement ratio of 0.58, 1, 1.73, 2.75, 5.67 respectively).

The structure of the thesis is as follows:

Chapter 2 Publications are reviewed, which consider methods of interlaminar reinforcement, influence of the z-pinning on the properties of the laminate, mathematical and FE models of Z-Pins in the laminate structure and physical tests of Z-Pin pull-out and shear.

Chapter 3 The details of the tests performed during this study are presented, including materials used, methods of specimen preparation and descriptions of testing rigs. Methods of Z-Pin insertion are presented, including the traditional, commonly used method and novel approaches, developed for the purpose of this study.

Chapter 4 Microscopic observations of Z-Pins themselves and when embedded into the composite structure are presented. The quality of the Z-Pin manufacturing and the damage caused by the Z-Pin insertion in the structure of the laminate is discussed.

Chapter 5 Results of pull-out (Mode I), shear-out (Mode II) and mixed mode tests are presented, including data reduction and discussion of the observations. Additional tests considering standalone Z-Pins in pure shear and in shear with bending are presented, including descriptions of materials and testing rig used, observations and results.

Chapter 6 Final conclusions, remarks, observations and results are summarised. Possible future work is discussed.

Chapter 7 References to the literature survey are listed.

APPENDIX Tabularised results of the tests performed during this study are presented.

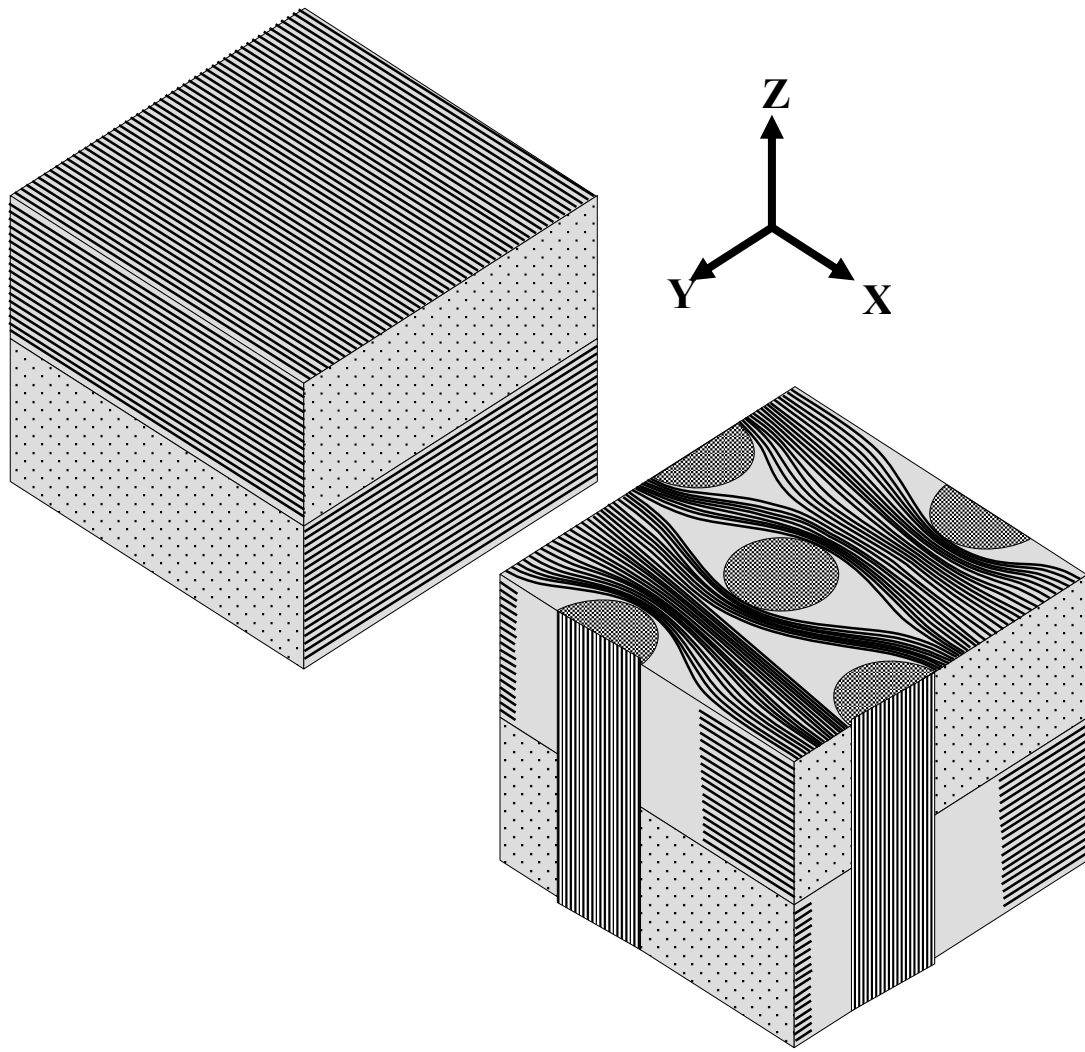


Figure 1.1 Structure of composite material: pure composite and composite with Z-Pin reinforcement

2 LITERATURE SURVEY

2.1 INTRODUCTION

Due to the interlaminar toughness being the “Achilles heel” of the laminates, numerous methods of interlaminar reinforcement, leading to greater resistance to delamination have been proposed, including using tougher resins or additional layers of tough material, introducing fibres in the Z direction and inserting stiff fibrous or metallic rods – Z-Pins - through the thickness.

The majority of the experimental work done has considered the influence of Z-Pins on the properties of the z-pinned laminates. The increase in delamination resistance as well as improvement in post impact properties of z-pinned laminates was investigated. The main interest of these works was the smeared properties of Z-Pins, rather than the mechanism of pull-out and shear-out of individual pins.

Mathematical models of the pull-out process were created in a number of studies. However, they mainly regard the process of pull-out of a long fibre or a tow from a block of homogenous material, which can be only partially used for Z-Pins, as different phenomena take place in laminated composites.

In many studies Finite Element (FE) modelling was employed in order to simulate the behaviour of Z-Pins embedded in the laminate. The influence of the Z-Pins on the properties of the laminates - the improvement of crack resistance and the decrease in the in-plane properties due to damage caused by Z-Pins, were investigated. A model of a Z-Pin bridging a delamination in pull-out, shear-out and mixed mode loading conditions was also recently proposed.

A number of physical tests focused on the behaviour of single Z-Pins bridging an interlaminar crack in the composite have been reported. The most interesting of them from the point of view of this thesis, seems to be the recent work, in which tests of single Z-Pin pull-out, shear-out and mixed mode behaviours were described. The amount of research done on single Z-Pin micromechanics, especially using experimental approaches is limited.

This thesis is focused on the behaviour of Z-Pins, which bridge a propagating delamination. Previous work examining Z-Pin pull-out and shear-out characteristics is reviewed in detail in the next section.

2.2 TECHNIQUES FOR IMPROVING INTERLAMINAR TOUGHNESS IN COMPOSTES

2.2.1 INTRODUCTION

The delamination toughness of composite material is defined by the toughness of fibre, toughness of resin and the strength of the bond between the fibre and resin. Various methods of enhancing interlaminar toughness, delamination and impact resistance of the composite structure have been developed. The methods include using toughened resin or layers of tough material between the layers of the laminate (interleaving). Other methods include using fabrics with interwoven threads, rather than layers of unidirectional material (weaving, braiding). However the most promising techniques include embedding tows of fibres or stiff rods through the thickness of the laminate (stitching, tufting, z-pinning). Other, less common techniques include embroidery and z-anchoring [1]. A review of those methods was presented in [2,3,4,5,6,7].

2.2.2 TOUGHENED RESIN

Strategies for toughening resin include modification of the resin with rubber particles or using a tough thermoplastic matrix. Toughness can be further enhanced by coating the fibres with rubber or a ductile plastic that enhances the fibre-matrix interface [8,9,10,11]. These measures can significantly increase delamination resistance and can be used with common fibres, but may compromise fatigue performance and/or compression properties. Some of these strategies may also require different, more complex processing routes than for the more commonly used materials.

2.2.3 INTERLEAVING

Interleaving is the insertion of a layer of tough “interleaf” material, usually adhesive film or resin, in-between the layers of prepreg. The geometry [12], chemistry [13], and fracture suppression potential of this technique in various fracture modes was investigated in [14,15,16].

2.2.4 2D AND 3D WEAVING, BRAIDING

Weaving or braiding technique uses layers of fabric with interwoven threads to create a 3D fibre architecture instead of the 2D architecture of unidirectional tape laminates, enhanced by the introduction of through-thickness fibres. 2D woven fabrics may utilise the same processing route as unidirectional preregs, but the 3D woven materials demand resin infusion. In-plane properties in woven or braided materials are degraded due to the waviness of the fibres.

2.2.5 TUFTING

Tufting is a technology used to locally reinforce laminates in the Z direction by inserting a thread using a needle which retracts, leaving a loop of the thread in the structure [17,18]. It was designed to be used with dry fabrics (with resin injection), however preregs can also be tufted. Tufting is more economical compared to weaving or braiding. Similar to stitching, this method requires access from one side of the laminate only.

2.2.6 STITCHING

Stitching, an example of an alternative through the thickness reinforcement technique to Z-Pinning, includes inserting a dry fibre thread through the layers of prepreg or laminate before cure, where the threads remain connected with “loops” on both sides of laminate (unlike in case of Z-Pins) [19,20]. This technique improves the interlaminar toughness [21,22,23,24,25], but it also reduces the in-plane toughness of laminate by damaging the fibres during the stitching process, causing waviness in the vicinity of the stitches and under the “loops” on the external layers of the laminate [26].

2.2.7 Z-PINNING

Z-pinning is a method of inserting rods made of fibrous composite or metal through the thickness of the laminate prior to the curing process. Short, stiff Z-Pins are mechanically pushed into the laminate after thermal softening of the matrix, usually by ultrasonic vibrations. This technique, developed by Aztex (www.aztex-z-fiber.com), can be used with unidirectional preregs and cured in autoclave. The Z-Pins introduce fibre waviness, and resin-rich regions

into the structure, which degrade the in-plane properties of the laminate, however the increase in the interlaminar toughness offered by z-pinning greatly compensates these losses.

Z-Pins

Any material may be used to manufacture Z-Pins, 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. Z-Pins rods are typically composite but can also be metal for specific applications. Some of the materials commonly used for the rods include:

- SiC/BMI
- T650/BMI
- T300/Epoxy
- T300/BMI
- P100/Epoxy
- S-Glass/Epoxy
- Titanium, Stainless Steel, Aluminium

In the case of the T300/BMI Z-Pins, which are used in this project, the process of manufacturing is as follows:

- A continuous, small diameter composite rod is formed
- The rod is cut into pins
- The pins are inserted in a two layer foam

In the first stage, carbon fibres are pulled off a bobbin and goes to the bath of resin in elevated temperature. The material exits the bath through a nozzle, where the fibres are drawn together forming a structure similar to a string, and immediately enters a long oven. Cured material is cut into single pins and inserted into the foam in an automated process. Pins are cut with an acute angle at the ends. The angle (sharp end) assists the penetration of the pin into the composite and minimizes breakage and distortion of the fibres. The number of fibres used in the formation process determines the Z-Pin diameter (about 1000 T300 fibres form a 0.28 mm Z-Pin and about 3000 T300 fibres form a 0.51 mm Z-Pin).

Pre-forms

The Z-Pins are supplied embedded in double-layer foam. The foam with pins inserted is called a pre-form. The low-density layer of pre-form, called the support foam is usually made of polystyrene and located at the top (looking from the direction of pinning). The high-density layer, called the base foam, is located under the support foam and made of Rohacell LastaFoam material. The support foam is used to hold the pins prior to pinning process and designed to collapse easily. The base foam locates Z-Pins accurately and offers stability to the lower parts of the pins preventing them from buckling during the insertion process.

The following parameters characterize a pre-form:

- Z-Pin material
- Insertion angle
- Z-Pin density (areal)
- Type and thickness of the base foam
- Type and thickness of the support foam

Pre-forms can be produced in shapes of blocks, strips or grids. Pre-forms can be designed for use for the reinforcement of 1 mm to 45 mm thick composites with Z-Pins of diameters ranging from 0.28 mm to over 1 mm. Standard areal densities of reinforcement range from 0.75% (for damage tolerance) to 4% (for fastener replacement / stiffener attachment).

2.2.8 SUMMARY

All techniques described in this section are effective for improving the delamination resistance and impact damage tolerance, however other mechanical properties may be compromised. The advantages and disadvantages of various interlaminar reinforcement methods are summarised in **Table 2.1** after Greenhalgh et al [7]

Method	Advantages	Disadvantages
Tougher matrix	Same architecture No need for redesign	Reduced fatigue and compression properties Increased sensitivity to processing Can require different processing routes
Plain woven	Usually same processing route Improved drape and manufacturability More elastic response during impact	Some redesign and requalification needed Poor undamaged properties Weave needs to be balanced
3D composites	Reduced cost Lends itself to design of substructure	Needs resin infusion Can reduce undamaged properties Requires redesign and requalification
Tufting	Same processing route	Can reduce undamaged properties
Stitching	Same processing route Offers fail-safe design	Can reduce undamaged properties Difficult to fabricate with stiffeners
Z-pinning	Same processing route Optimisation can limit drop in undamaged properties Offers fail-safe design	High cost Difficult to fabricate using commercial method

Table 2.1 Advantages and disadvantages of common methods of interlaminar reinforcement, in comparison to the unidirectional laminates without through thickness reinforcement, based on [7]

2.3 Z-PINS IN THE COMPOSITE STRUCTURE

2.3.1 INTRODUCTION

Offering significant improvements in interlaminar fracture toughness, impact resistance, damage tolerance, z-pinning negatively affects the in-plane mechanic properties of z-pinned laminate, mainly due to the changes and damage the insertion of the Z-Pins causes in the internal structure of the laminate, i.e. fibre waviness, transfer of the fibres between layers, fibre breakage. Although these investigations reported in the literature differ significantly from the research performed for this thesis, they add to the general knowledge about Z-Pins. A significant number of papers dealing with general application of Z-Pins composite structures have been published. In particular structures with Z-Pins in high quantities have been summarised here.

2.3.2 INFLUENCE OF Z-PINNING ON THE CRACK PROPAGATION AND DELAMINATION RESISTANCE IN COMPOSITES

Typical tests were carried out using double cantilever beam specimens (DCB), made of the composite of desired lay-up and subjected to various load and support conditions. Depending on the actual fracture mode being investigated, usually a particular length of the specimen being pre-cracked, Z-Pins were introduced in various parts of specimens, bridging the expected crack wake. The influence of Z-Pinning on the crack propagation was investigated by Bizien [27], Das [28]. The improvement in delamination resistance in composites, again usually utilising the DCB approach was investigated also by Cartie et al in [29,30,31,32,33,34,35,36]. Linear growth of the apparent delamination toughness with Z-Pins volume content was reported in [35,36]

2.3.3 DAMAGE RESISTANCE AND IMPACT TOLERANCE OF Z-PINNED STRUCTURES

The damage tolerance improvement in primary aircraft structures as a benefit of the Z-Pinning as a through-thickness reinforcement was investigated by Clarke et al in [37]. Stiffened panels, made of unidirectional IM7/8552 composite structure, were subjected to low velocity impacts (35 J) outside of the Z-Pinned zones and then tested to failure under uniaxial compression. The

panels were inspected post mortem using fractographic techniques. The results indicated little influence of the Z-Pins on buckling strain but the damage area appeared to be significantly reduced. The authors concluded that introducing Z-Pins in relatively small areas, adjacent to stiffeners, can significantly improve the post-impact performance of the structures, even in cases where impact occurs far from the Z-Pinning areas.

In order to examine the critical impact force and the post impact performance (the laminate in-plane stiffness and strength) of Z-Pinned composites was investigated by Bitsianis [38] and Cartie et al in [39]. Carbon/epoxy T300/914C specimens with thicknesses of 2, 4, and 6 mm [38] showed 19-64% reduction in impact damage area and approximately 45% increase in the compression after impact strength. The positive influence of the Z-Pinning aerial density (especially at high densities of 4%) on the interlaminar fracture resistance during low velocity impact, indicated by the reduction in damage area, was shown in [39]. Contrary to other observations, the authors also reported an improvement in compressive strength of partially pinned undamaged laminates in comparison to unpinned samples. The authors concluded that, although Z-Pinning did not improve the resistance to the onset of delamination, it greatly affected the delamination growth by local crack arrest, significantly reducing the extent of the impact damage.

Damage mechanisms around “short fibrous rods” under nominal shear loading in lap joints were investigated by Rugg et al [40]. The coupon-type specimens, containing two overlapping carbon-epoxy (M46J/7714A), 50 ply quasi-isotropic flat panels bolted together with four rows of 1.7 mm thick (7 mm long) Z-Pins inserted under either at +45° or -45° angle (i.e. “in the nap” and “against the nap”, using terminology introduced by Cartie), as shown in **Figure 2.1**.

Z-Pins were inserted into the holes made with “sharply pointed punches” in the laminate warmed up to 71°C (to allow easier fibre movement). The process was believed to reduce (mainly out-of-plane) damage during Z-Pin insertion by smoothly spreading fibres in the in-plane direction.

Z-Pinned specimens were compared to specimens without Z-Pins in the same loading configurations. In the specimens without reinforcement the force growth after the failure was rather small, but in the z-pinned specimens, 100% increase in load was reported.

Z-Pins in orientation in-the-nap were reported to be pulled out of the laminate with fairly small damage to the surrounding structure as well as to themselves. Only a small s-shape bend was reported in this case. As for the Z-Pins oriented against-the-nap, they were reported to show much higher deformations: much larger angles of bending and internal splitting between the fibres. Also much greater damage of the composite was observed for against-the-nap Z-Pins, including traces of ploughing.

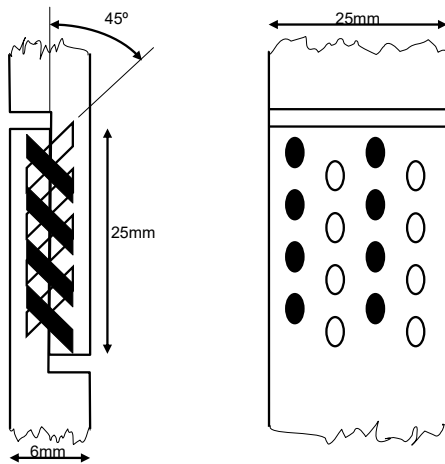


Figure 2.1 Geometry of lap joint specimens, [40]

The author remarked that all the Z-Pins, regardless of orientation, eventually pulled out of the laminate, and concluded that the energy absorption in the overall damage in and around Z-Pins, rather than the single Z-Pin shear strength, was important for the toughness of the joint. Hence, as the authors concluded, Z-Pins with rough surface seemed to be better for application purposes and expensive techniques of producing Z-Pin rods of high fibre alignment seem to be unnecessary.

2.3.4 INFLUENCE OF Z-PINNING ON THE LAMINATE PROPERTIES

The positive influence of the z-pinning on the delamination toughness and unavoidable decrease of the in-plane tension, compression, bending and fatigue properties of carbon-epoxy composites were investigated by Mouritz et al [35] and Mouritz [36].

Research into the influence of Z-Pinning on in-plane laminate properties, i.e. on tensile strength and stiffness, were undertaken by Troulis et al in [41,42]. The standard coupon specimens of z-pinned laminate were subjected to the tensile strength testing. The results indicated 12% to 14% reduction of E_{11} and E_{22} moduli. The authors concluded that Z-Pins fail under shear-out

(Mode II) conditions through combination of laminate resin and fibre breakage, and Z-Pin shear, bending and pull-out. It was also indicated that the increase in Z-Pin diameter or pinning density reduces laminate strength; however, any increase of complexity of stacking sequence diminishes the above effect. A linear decrease (less than 10% for the volume fractions up to 4%) of the in-plane elastic properties with the Z-Pin volume fraction and Z-Pin diameter was reported in [43]. The authors concluded that the best z-pinning results were achieved for 2%-4% Z-Pin volume fraction, using thin (0.28 mm) Z-Pins. These observations corresponded with the predictions of FE models [44,45].

The degradation of the in plane properties of laminates caused by Z-Pins was also investigated by Steeves et al in [46]. Coupon type specimens of 1 mm thick, unidirectional IMS/924C laminate reinforced with square pattern of 9 CFRP 0.28 mm Z-Pins were subjected to in-plane compression until failure. The specimens were observed during testing with a scanning electron microscope and fibre waviness (the local angle of a fibre to the global fibre direction in the laminate) distribution was recorded. The results clearly showed fibre waviness reaching 10° and that the compression strength decreased by approximately 33%.

2.3.5 MANUFACTURING QUALITY OF Z-PINS AND Z-PINNING

Various forms of damage introduced to the laminate via z-pinning were discussed in [36,47,48]. These included fibre waviness and resin-rich pockets (due to fibres of the base laminate being pushed apart in-plane), crimp (interlaminar fibre waviness due to fibres of the laminate being pushed between layers by the Z-Pin), Z-Pin fibres splicing, post-cure stresses and swelling, Z-Pin angle offset (irregular Z-Pin insertion angles, ranging from 2° to 30° - mean of approximately 14° - unavoidable during standard insertion procedure). Irregularities in the internal structure of the Z-Pins, including voids or cracks along fibres, as well as lack of continuous bond between the Z-Pin and surrounding laminate was reported in [47]. Quality of the manufacturing and behaviour of Z-Pins in composite structure has been undertaken by Partridge et al [49]. The standard Z-Pin insertion method by ultrasonic hammer, manufacture of materials and properties of the resulting composite reinforced with Z-Pins using this method, were discussed by Cartie [50]. Properties of the Z-Pins out of composite were investigated by Ustamujic [51]. Also, a behaviour of short fibres in brittle matrix composites, which may be partially applicable for Z-Pins, was studied by Jain [52].

An extensive study of Z-Pin failure mechanisms due to tension and shear was reported by Greenhalgh et al [53]. The authors observed failure of the Z-Pin due to tensile and shear fracture, damage of the Z-Pin close to the delamination surface caused by bending, splitting of the Z-Pin fibres (Figure 2.2). Together with the energy consumed by the pull-out, the numerous ways the Z-Pins failed contributed to the suppression of the delamination of the laminate.

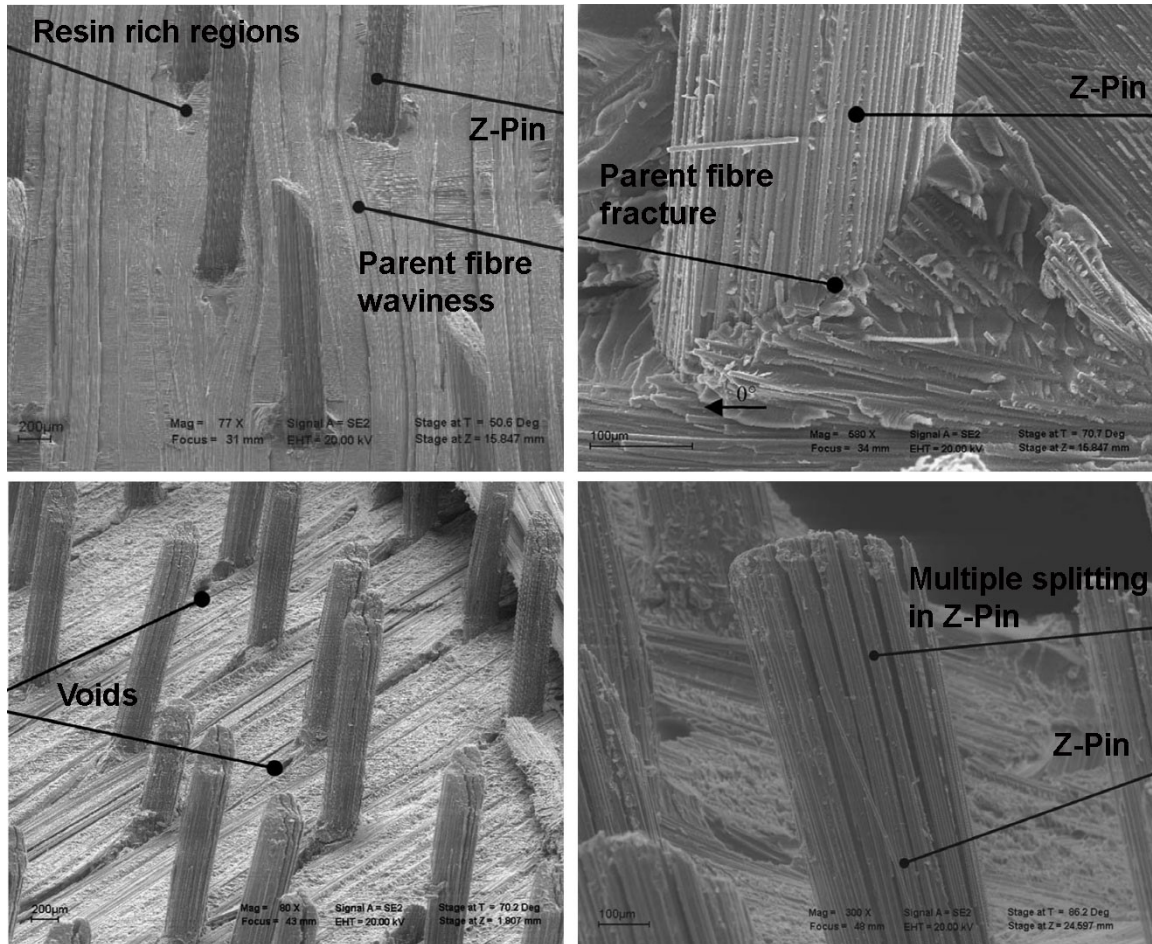


Figure 2.2 Post delamination damage of the Z-Pin and damage of the laminate caused by z-pinning, [53]

Damage to the laminate caused by Z-Pin was observed, including resin-rich pockets, local in-plane waviness of the fibres in the base laminate. According to the authors air pockets or voids were also observed close to the Z-Pin.

The compliance of Z-Pinned T-joints tested by the authors was approximately half of the unpinned laminate – the deflection and strain at failure was considerably lower, even though the loads were similar.

The authors' observations confirmed that the failure initiation was not affected by z-pinning, however the delamination propagation was observed to be stable (contrary to the un-pinned laminate, in which failure took place soon after the crack initiation) and load carrying capacity of the structure after the delamination was greatly improved.

2.3.6 SUMMARY

The positive effect of the z-pinning on the delamination resistance, interlaminar toughness, damage tolerance has been well documented. Z-pinning has negligible effect on the initiation of delamination but the energy needed for the Z-Pin's pull-out, shear or longitudinal fibre splitting resulted in stabilisation of delamination propagation and great improvement in load bearing capacity after delamination

Unfortunately a decrease of the in-plane mechanical properties, mainly the in-plane tension and compression strength, of the Z-Pinned composites was also observed. Noticeable damage to the structure of the laminate due to introduction of the Z-Pins was also reported. The damage included fibre waviness, which was the direct cause of the drop of the in-plane-strength, as well as pushing the fibres between the layers (crimp), fibres breakage and resin-rich pockets, which negatively influenced the fibre volume fraction and were suspected to initiate the delamination.

The general rule of z-pinning density between 2% and 4% causing substantial growth of the interlaminar toughness with modest drop of the in-plane properties could be derived. This observations closely follow results of the FE models investigating influence of the Z-Pins on the material properties [54,44,45,55].

The gains in the delamination resistance and simultaneous losses in the in-plane mechanical properties of the laminate caused by z-pinning must be considered in the design of the composite structure containing Z-Pins [53].

2.4 MATHEMATICAL MODELS OF FIBRE PULL-OUT PROCESS

2.4.1 INTRODUCTION

Several mathematical models dealing with the process of pulling a tow or a rod out of homogenous material have been proposed. Although restricted by numerous simplifying assumptions, the models are considered helpful for developing a universal “bridging law” and the observations, assumptions and results are useful for guiding the investigation of the mechanics of a single Z-Pin being pulled out of the laminate.

2.4.2 MATHEMATICAL MODELS

Model of single stitch pull-out process

A mathematical model to study the micromechanics of single stitch pull-out process and the effect of stitching on the crack growth resistance in DCB precracked specimens was presented by Jain et al in [56]. In this model the loops connecting stitches were neglected (as if the surfaces of modelled laminate were ground off), hence the model could be applied to investigate the micromechanics of Z-Pins (assuming the properties of the stitch material were similar to the Z-Pin). The influence of factors like stitch density, matrix/stitch interface shear strength, stitch diameter, stitch volume fraction on the Mode I delamination toughness of the composite were studied.

The following assumptions were made:

- There was no connection between single stitches, hence each stitch can be treated independently.
- Each stitch thread was cylindrical.
- The bond between matrix and stitch was perfectly frictional with a constant shear stress value (elastic bond strength was neglected).
- There was no deformation in the matrix.
- The tensile strength of the single stitch had a single value σ_{fu} .
- Stitch threads pull-out from one side of the laminate only.

The model of the stitch embedded in resin can be seen in **Figure 2.3**. At the beginning of the process, the stitch was embedded in laminate over a length **H**. The process of extracting of Z-Pin from a laminate can be divided into two stages:

- The stage of the elastic stretching of the Z-Pin connected with progressive debonding over the length **Y**, with the pulling force **F** increasing from 0 to a maximum as the “slip length” **Y** increases from 0 to **H**. At the end of the debonding process the entire load was carried by friction over the length **Y** of the stitch.
- The stage of friction controlled slip-out of the whole Z-Pin. The pulling force **F** decreases gradually from maximum to zero while the “slippage distance” **S** of embedded end increase from 0 to **H**. The entire load in this stage was carried by the friction over the length **(H-S)**.

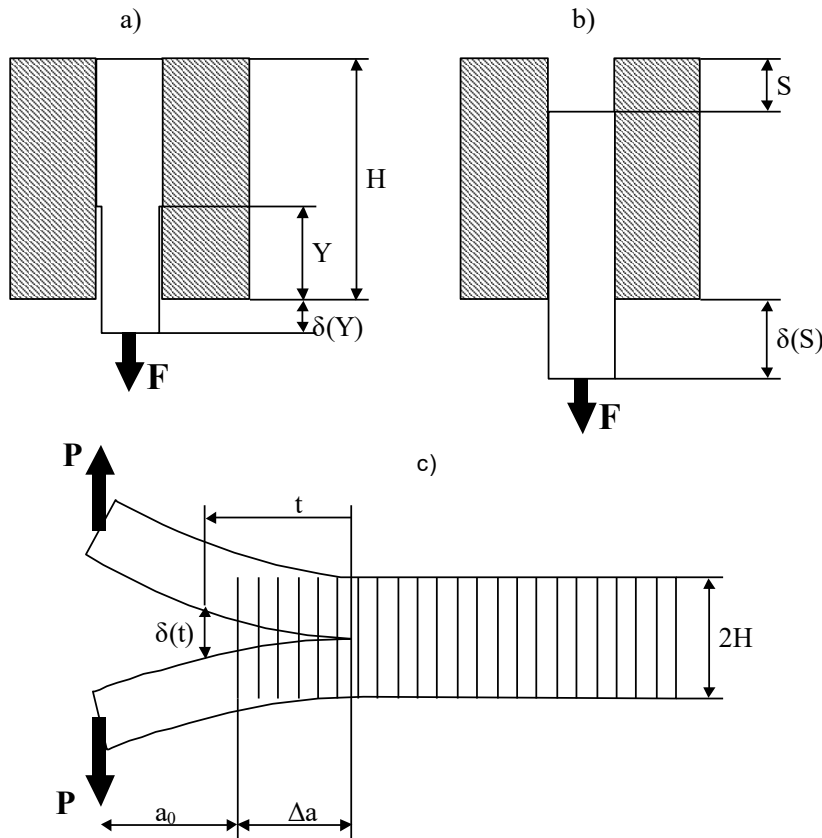


Figure 2.3 Single stitch pull-out process: a) elastic stretching stage, b) slip-out stage, stitched DCB specimen, [56]

Following the explanation of Jain et al [56] the relationship between the force **F** and the displacement δ of the loaded end of the stitch was assumed to be as follows:

During the elastic stretching:

$$F[\delta(Y)] = \pi \tau d_f Y$$

$$\delta(Y) = \left[Y - \frac{H}{r} \ln \left(\frac{Y \cdot r}{H} + 1 \right) \right] \left[1 + \frac{Y \cdot r}{H} \right]$$

During the slip-out:

$$F[\delta(S)] = \pi \tau d_f (H - S)$$

$$\delta(S) = \left[H - \frac{H}{r} \ln \left(\frac{(H - S) \cdot r}{H} + 1 \right) \right] \left[1 + \frac{(H - S) \cdot r}{H} \right]$$

where the shear stress at the matrix/stitch interface τ and the extensibility ratio r were defined as:

$$r = \frac{\pi \tau d_f H}{A_f E_f}$$

for the stitch thread (Z-Pin) cross-section area A_f and stitch material Young's modulus E_f .

The critical embedded length L_c was defined as:

$$L_c = \frac{d_f \cdot \sigma_{fu}}{4 \cdot \tau} \text{ where } \sigma_{fu} \text{ was the tensile strength of the stitch thread.}$$

If $H \geq L_c$ then the thread will stretch and break, while if $H < L_c$ the pull-out process will continue.

This model of the single stitch pull-out process was applied to simulate the through the thickness reinforcement in the model of the whole DCB specimen, see **Figure 2.3**. The purpose of this model was obtaining crack growth resistance curves (R-curves) for the Mode I delamination process.

The geometry of the DCB model is shown in **Figure 2.3**. The opening force **P** was applied at the ends of the specimen arms. The half thickness of the specimen was **H**, the initial crack length was **a₀** and the length of bridging zone was **Δa**. The crack opening displacement **δ** at the distance **t** from the tip of the crack was governed by the functions **δ(Y)** and **δ(S)** described above. The action of the individual stitches was replaced by the distributed load **p(t)** which was a function of the stitching density **S_D** (the number of stitches per unit area) and the bridging force **F** at the distance **t** from the crack tip **p(t)=2S_DF(t)** (factor 2 accounts for the two threads of each stitches). The differential equation governing the deflection of the beam arm was found as:

$$EI \frac{d^4 \delta}{dt^4} = \begin{cases} -2p(t) \dots for \dots 0 < t \leq \Delta a \\ 0 \dots for \dots t \geq \Delta a \end{cases}$$

where:

$$p(t) = 2 \cdot S_D \cdot \pi \pi d_f \cdot [Y(t) \cdot U_1 \cdot U_3 + [H - S(t)] \cdot (1 - U_1) \cdot U_2 \cdot U_4]$$

EI was the bending stiffness of the arm of the DCB specimen (E was Young's modulus in the case of unidirectional composite).

U_i are the step functions in the form:

$$U_i(x) = \begin{cases} 1 & for \quad x > 0 \\ 0 & for \quad x \leq 0 \end{cases} \quad i = 1, \dots, 4 \text{ defined as follows:}$$

$$U_1 = U_1 \left(2 \cdot \left[H - \frac{H}{r} \ln(1+r) \right] \cdot (1+r) - \delta(t) \right)$$

$$U_2 = U_2 (H - \delta(t))$$

$$U_3 = U_3 (L_c - Y(t))$$

$$U_4 = U_4 (L_c - H)$$

If the strain energy release rate **G_I** for orthotropic composites (with the crack in the plane of symmetry) may be given in term of the stress intensity factor **K_I** as:

$$G_I = \frac{K_I^2}{E_0}$$

E_0 was an orthotropic modulus of the composite given as:

$$\frac{1}{E_o} = \left(\frac{S_{11}S_{22}}{2} \right)^{1/2} \left[\left(\frac{S_{22}}{S_{11}} \right)^{1/2} + \left(\frac{2S_{12} + S_{66}}{2S_{11}} \right) \right]^{1/2}$$

in which S_{ij} are the compliance matrix terms.

Assuming that for orthotropic materials without through-thickness reinforcement crack propagates in matrix material only, then crack growth occurs when $G_I = G_{IC}$, in which:

$$G_{IC} = \frac{K_m^2}{E_m}$$

where:

K_m was the stress intensity factor for the unreinforced matrix material,

E_m was Young's moduli of the unreinforced matrix,

and so the Mode I critical stress intensity factor, K_{IC} , associated with crack propagation in an orthotropic composite with a crack in the plane of symmetry, was defined as:

$$K_{IC} = \sqrt{\frac{E_0}{E_m}} K_m$$

The critical energy release rate G_{IC} can be found as:

$$G_{IC} = \frac{K_{IC}^2}{E_0}$$

The equilibrium crack growth condition was fulfilled when the stress intensity factor due to applied load P , $K_R(\Delta a)$, reaches the value of critical stress intensity factor of the un-pinned composite, K_{IC} reduced by the value of $K_r(\Delta a)$, which was the stress intensity factor due to the bridging actions of the stitches:

$$K_R(\Delta a) = K_{IC} - K_r(\Delta a)$$

where $K_r(\Delta a)$ was defined as:

$$K_r(\Delta a) = C \cdot \int_{t=0}^{\Delta a} p(t) \cdot \frac{1}{\sqrt{H}} f\left(\frac{t}{H}\right) dt$$

in which (after Ye [57]):

$C = \sqrt{\frac{E_o}{E}}$ was the correction factor including elastic anisotropy of the material ($E=E_0$ for isotropic materials),

$f\left(\frac{t}{H}\right) = \sqrt{12} \cdot \left(\frac{t}{H} + 0.673\right) + \sqrt{\frac{2 \cdot H}{\pi \cdot t}} - \frac{1}{0.815 \cdot \left(\frac{t}{H}\right)^{0.619} + 0.429}$ was the function found by

Foot et al [58] for the stress intensity factor at the tip of the crack in DCB specimens. The value of $K_R(\Delta a)$ at the onset of crack growth can be considered as the critical stress intensity factor of the pinned composite.

The model, which was used to predict the influence of the stitching on the delamination toughness K_R , was tested for unidirectional CFRP, under plane stress condition, stitched with Kevlar threads. The material properties used in the model are given in **Table 2.2**.

K_{IC} [MPa√m]	1.28	Composite delamination toughness
K_m [MPa√m]	0.8	Stress intensity factor for matrix material
E_x [GPa]	130	Young's modulus in x direction
E_o [GPa]	10.2	Orthotropic modulus
E_m [GPa]	4	Young's modulus of matrix material
E_f [GPa]	125	Young's modulus of thread material
τ [MPa]	5	Thread-matrix interface shear stress
a_o [mm]	50	Initial crack length
H [mm]	2	Beam thickness
d_f [mm]	0.3	Thread diameter
S_D [mm ⁻²]	1/30	Stitching density (number of stitches in unit area)

Table 2.2 Material properties used in the model, [58]

In the baseline case (shown in **Table 2.2**) K_R increases from the level of composite toughness K_{IC} due to the development of the “bridging stitch thread zone” and reaches an asymptote K_∞ about $2.4 \cdot K_{IC}$ after 30 mm crack growth, when the bridging zone was fully developed. With increasing beam thickness (H) the plateau magnitude increases, which can be an effect of growing bridging zone due to higher beam bending stiffness and increasing embedded length of stitches (see **Figure 2.4 a**). Initial crack length a_o as well as stitch thread stiffness E_f have no significant effect on the $K_R-\Delta a$ curve (see **Figure 2.4 b, f**). An increase in the thread-matrix interface shear stress results in increase in of the crack growth resistance due to increase of

bridging force in each stitch (see **Figure 2.4 d**). With increasing stitch density S_D and thread diameter d_f , hence with increasing volume fraction of stitches the crack growth resistance increases (see **Figure 2.4 d**). An increase in stitch density S_D , while stitches volume fraction was kept constant, raises the crack growth resistance (see **Figure 2.4 e**).

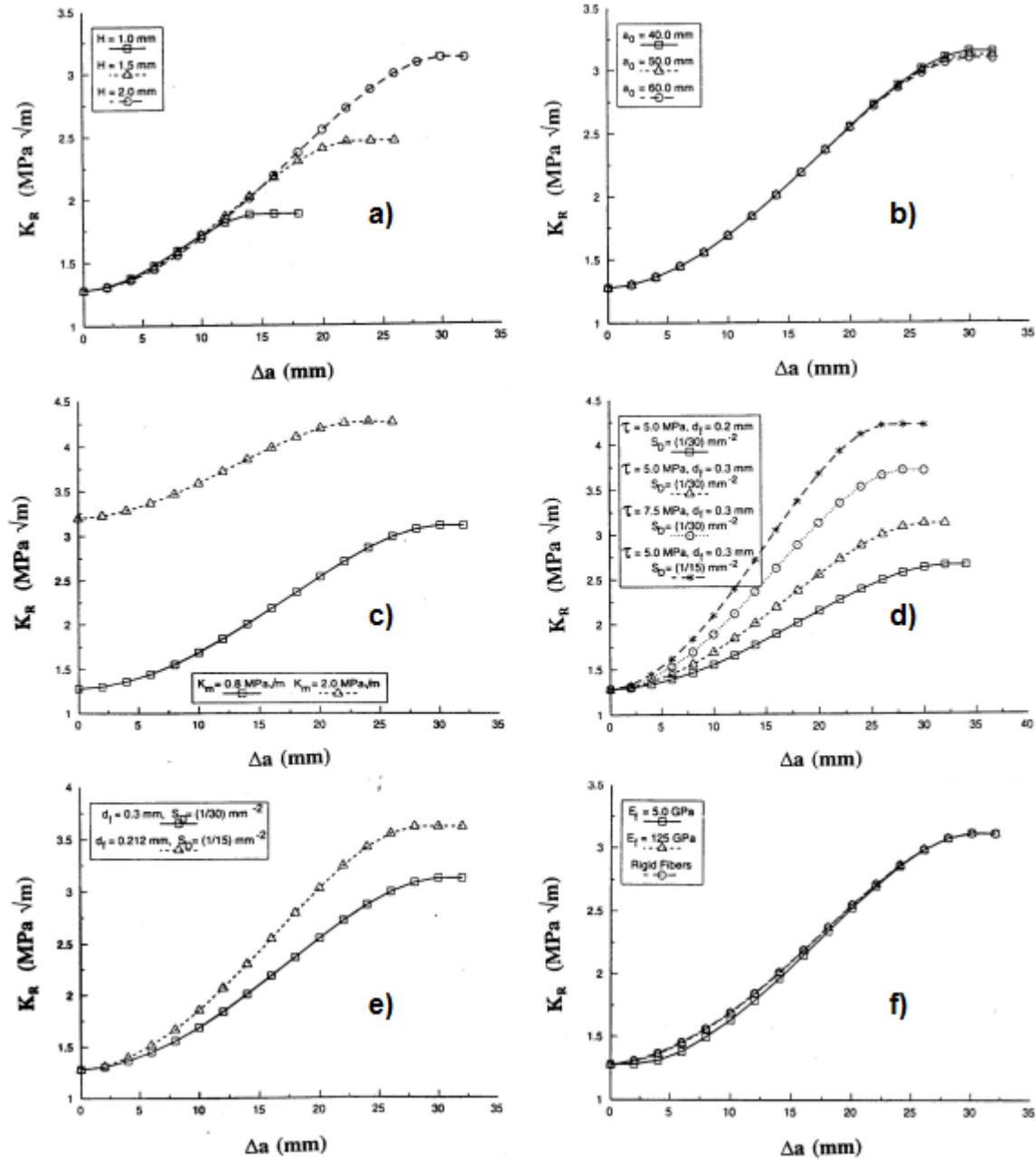


Figure 2.4 Results: the effect of beam thickness H (a), initial crack length a_0 (b), matrix critical stress intensity factor K_{Ic} (c), thread/matrix interface shear stress τ (d), stitch density S_D and thread diameter d_f (e) and thread stiffness E_f (f) on K_R - Δa curve, [58]

Models of long single fibre pull-out process - energy release rate

An energy release rate approach was applied to model a fibre bridging a crack by Williams [59]. The model is shown in **Figure 2.5**. A fibre of diameter **d** was embedded in element of matrix of diameter **D**. The energy release rate of elastic system subjected to the load **P** was given by:

$$G = \frac{P^2}{2} \frac{dC}{dA}$$

where C was the compliance of that system and A was cracked area. Given that in this model:

$$C = \frac{4}{\pi D^2} \frac{1}{(1-V)E_m + VE_f} \left[H + b \left(\frac{1-V}{V} \right) \frac{E_m}{E_f} \right],$$

where $V = \left(\frac{d}{D} \right)^2$, E_f and E_m are fibre and matrix stiffnesses and

$$A = \pi db,$$

the energy release rate at the tip of the crack formed when the fibre is debonded from the matrix was calculated as follows:

$$G_{II} = \frac{\sigma_0^2}{E_f} \frac{d}{8V^2} \left[\frac{E_m / E_f}{E_m / E_f + V / (1-V)} \right],$$

where $\sigma_0 = \frac{4P}{\pi D^2}$. (Note that according to the author, G_{II} was not a function of **b**).

When $G_{II} = G_{IIC} = \text{constant}$, also σ_0 is constant for the fibre pull-out, this model can be used for a fibre bridging a crack, developing a constant stress over the crack faces.

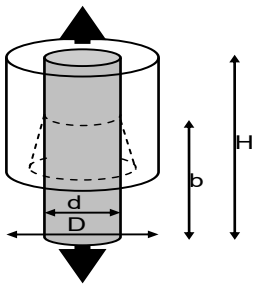


Figure 2.5 Fibre pull-out model, [59]

An analytical solution for energy release rate during crack propagation in single fibre pull-out, including effects of residual stresses and interfacial frictions was also proposed by Nairn et al [60].

Alternative theoretical model, followed by a numerical example, predicting the release energy rate at the fibre/matrix interface during the fibre pull-out process was proposed by Zhang [61]. It was based on shear-lag analysis and assumed equal axial strain in fibre and matrix.

Models of single fibre pull-out process - matrix/fibre stress transfer

Another attempt to model the micromechanics of elastic stress transfer across the fibre/matrix interface during fibre pull-out process was presented by Fu et al [62]. The model used coaxial cylinders to represent fibre, matrix and surrounding composite. Two and three cylinder models were compared. The models consider the influence of local volume fraction, proximity of neighbouring fibres and also the length of the fibre.

A theoretical model and computer simulation of the fibre pull-out process, based on the friction law was presented by Zhang [63,64]. The stress distribution in bonded and debonded regions as well as the influence of pull-out rate, thermal residual stress, material properties and local fibre-matrix volume fraction was investigated.

Numerical simulation

A simple computer simulation of a fibre debonding and then being pulled out of composite was presented by Zhong [65]. The algorithm, considered such phenomena as fibre peeling and partial debonding, fibre breaking and matrix yielding.

Model of a single Z-Pin bridging a delamination in mixed mode loading conditions

In the micro-mechanical model proposed G. Allegri et al [66] a Z-Pin is represented by a brittle, fibrous, slender Euler-Bernoulli beam, bridging two pieces of isotropic, linear-elastic medium (QI laminate), subject to small bending, encountering small sliding displacements, in mixed mode loading conditions. The linear elasticity of the laminate was based on the tests results [67,48], which suggested that the plastic deformation of the laminate was minimal.

The model calculated the distribution of normal and tangential force, bending moment and the distribution of maximum tensile stress along the Z axis of the Z-Pin.

The forces acting on the Z-Pin were modelled as

- Winkler's foundation forces
- “residual” frictional forces – due to thermal residual stresses (which is referred by the authors as compressive)
- Coulomb frictional forces

The derived from the model load-displacement curves correspond closely to test results (**Figure 2.7**). The observations of the curves suggested that for the mode “mixities” below 0.4 (0 representing pure pull-out and 1 representing pure shear-out), the Z-Pins were fully pulled-out (showed Mode I dominated character). For mode “mixities” above 0.8 all Z-Pins failed before reaching full pull-out. For the mode “mixities” of around 0.5 the character of the curves was different, suggesting a transition between full-pull out and failure of the Z-Pin. This corresponds closely to the experimental results [67], where transitional mode “mixities” were characterised by some specimens experiencing pull-out and others failing.

The growth of the force during the frictional pull out was attributed to the “enhanced friction” caused by the curvature of the Z-Pin in the mixed-mode regime. The same mechanism is referred to as “snubbing” in experiments.

The Z-Pin failure was modelled as brittle, fibre dominated, following Weibull's criterion. The distribution of the maximum tensile and shear stresses along the Z-Pin Z axis (**Figure 2.8**) predicted that the Z-Pin tensile fibre failure, due to bending induced tension, occurred slightly

below and above the delamination surfaces (where the Z-Pin was inside the laminate). The maximum shear stresses appeared in the Z-Pin cross-section exactly at the delamination surfaces. These results follow very closely the experimental observations [67], as well as FE model predictions [68,69,43],

Also, the energy absorbed during the pull-out/shear-out of the Z-Pin (representing the delamination toughness of the z-pinned laminate) showed strong dependence on the mode “mixity”. At low mode mixities, below 0.4, the energy is high, dominated by the “enhanced friction” during full pull-out without Z-Pin failure. For higher mode “mixities” the energy is considerably lower, dominated by the premature tensile fibre failure in the Z-Pin, before the full pull-out was achieved. This result agrees well with experimental results [67], and FE models [68,69,43].

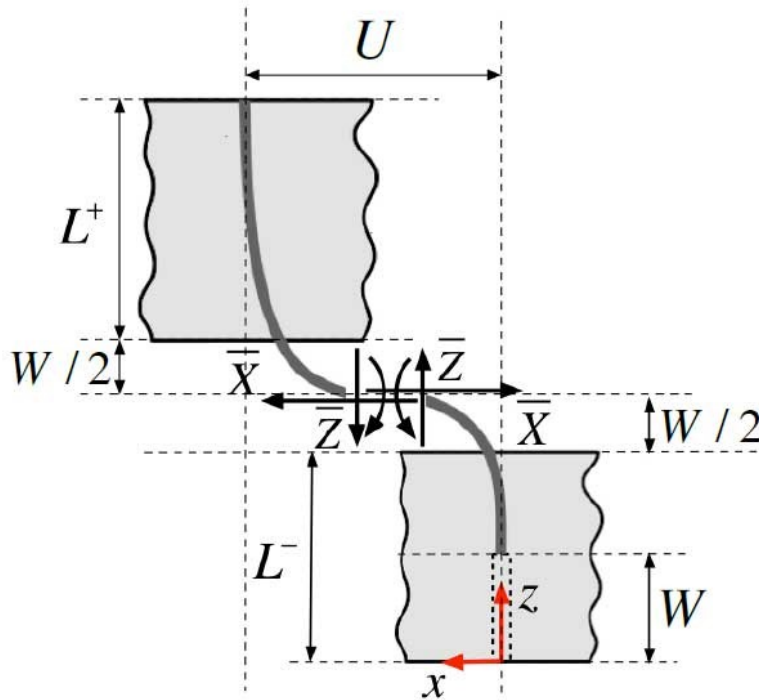


Figure 2.6 Model basics, [66]

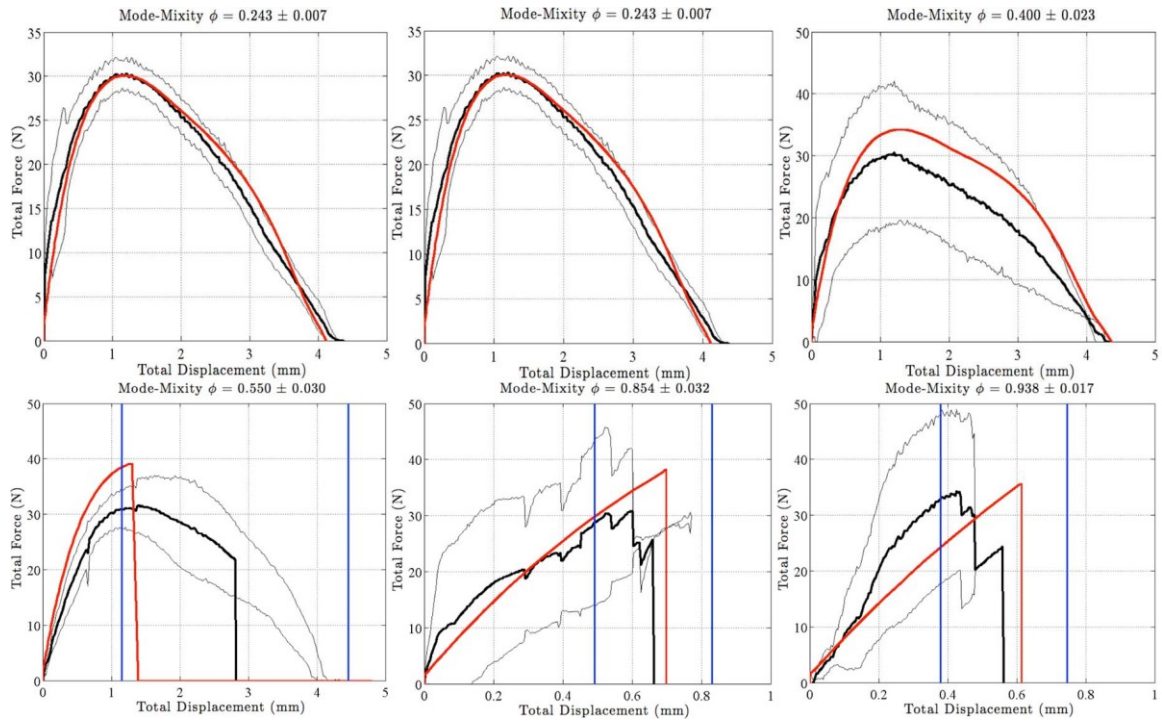


Figure 2.7 Comparison of load-displacement plots: model predictions - thick red lines; average experimental values - thick black lines; standard deviation scatter bands on mean load - thin grey lines, [66]

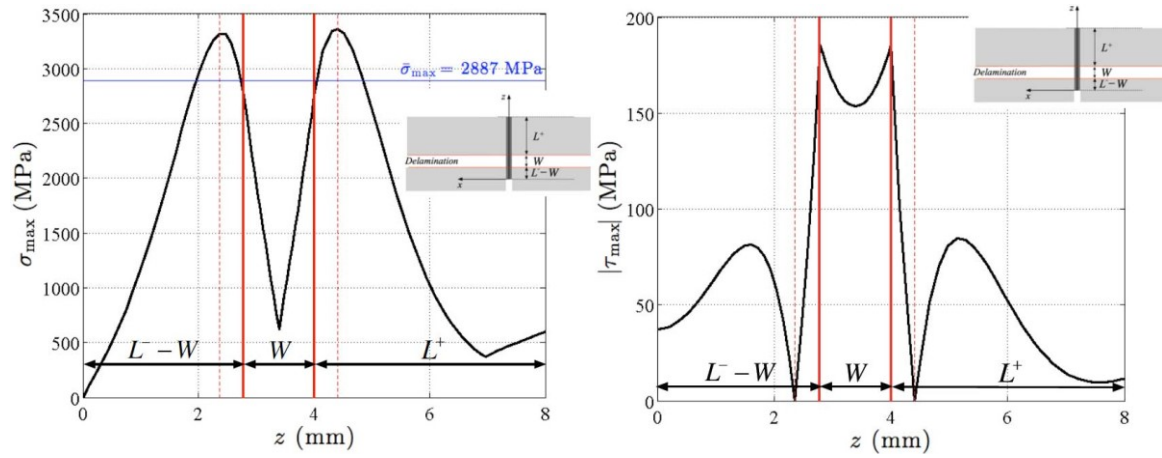


Figure 2.8 Predicted maximum normal and shear stress distribution at failure for $\phi = 0.550$; Position of delamination surfaces in red continuous lines; the dashed red lines give the axial locations of the stress peaks, [66]

2.4.3 SUMMARY

The majority of models dealt with long fibres being pulled out of a block of isotropic resin. The embedded length of the fibre was large enough to consider the stretching of the fibre during the pull out and assumed the influence of this stretching on the development of the debonding between the fibre and surrounding composite. Usually two phases of the pull out process were considered:

- the elastic stretching of the fibre with simultaneous debonding between the fibre and the surrounding material
- slip-out, controlled by the friction between the fibre and the surrounding material

Considering the diameter of the Z-Pin in relation to its embedded length, the long fibre pull out models might not apply, as the stretch of the Z-Pin at the beginning of the pull-out process was negligible. The models also assume that the fibre was being pulled-out of a resin block, which was not subject to any geometry changes.

The most recent model proposed in [66] led to the development of a “bridging law”. The model idealised the laminate as isotropic medium and assumed small rotations of the Z-Pin, but it considered bending of the Z-Pin during the pull-out of the Z-Pin under mixed mode loading conditions and post-cure stress influencing the pull-out friction. The results suggested that at low mode “mixities” the pull-out process was dominated by the “enhanced friction”, and “snubbing” due to the bending of the Z-Pin. The load-displacement curves showed gradual growth of the force followed by gradual decrease with a single maximum. In high “mixities”, in conditions close to pure shear-out, pull-out was not observed and the Z-Pin failed due to bending. The damaging tensile stresses were calculated at the Z-Pin interface slightly below the surface of the laminate.

Following the observations of the unavoidable scatter in the insertion angles during the z-pinning process the possibility of pure pull-out was not considered. The calculations of the model showed close agreement with the results of the FE analyses [68,69,66] presented in the next section.

2.5 FINITE ELEMENT MODELS OF SINGLE Z-PIN

2.5.1 INTRODUCTION

Several modelling approaches were developed to predict the behaviour of the Z-Pins embedded in the composite. There were numerous 2D or 3D unit cell models developed mainly to investigate the influence of the Z-Pins and the z-pinning density on the mechanical properties of the composite – the degradation of the in-plane mechanical properties or the influence of thermal stress during cure. There were also 2D and 3D models of a composite with a crack bridged by Z-Pins represented by single link elements, developed to investigate the influence of the Z-Pin on the interlaminar crack propagation. In addition modelling has been reported, which simulate the entire pull-out and shear out process in a single 3D model of a Z-Pin embedded in composite structure, featuring various lay-ups (UD, QI) including the resin pockets, and allowing for the internal splitting of the Z-Pin fibres.

2.5.2 EFFECT OF THE PRESENCE OF THE Z-PIN ON MATERIAL PROPERTIES

Axisymmetric model

A basic axisymmetric (2D) FE model of a single Z-Pin was presented by Barrett [54]. Thermal stresses caused by the uniform temperature change in the composite were examined.

A plate of 18-ply (3.5 mm) quasi-isotropic (QI) laminate made from AS4/3501-6 reinforced with T300/5208 Z-Pins (diameter 0.28 mm) was considered in this paper. The properties of the modelled materials are summarised in **Table 2.3**.

Z-Pin (transversely isotropic)		Resin (isotropic)		Laminate (quasi-isotropic)	
Axial modulus	152.0 GPa	Extensional modulus	3.52 GPa	In-plane modulus	54.3 GPa
Transverse modulus	10.3 GPa	Shear modulus	1.28 GPa	Through-thickness modulus	10.6 GPa
Axial shear modulus	5.70 GPa	Poisson ratio	0.38	In-plane shear modulus	3.45 GPa
Trans. Shear modulus	3.60 GPa	Tensile strength	40 MPa	Through-thickness shear modulus	20.7 GPa
Axial Poisson ratio	0.31	Compressive strength	69 MPa	Through-thickness Poisson ratio	0.0508
		Shear strength	60 MPa		

Table 2.3 Material properties of Z-Pin (T300/5208) and laminate (AS4/3501-6), [54]

The Z-Pin, the resin pocket and the surrounding laminate were modelled as a three concentric cylinders, see **Figure 2.9**. The external radius of the model was 1.75 mm (which was the half distance between the adjacent Z-Pins at the pinning density 0.5%): the diameter of the internal cylinder featuring Z-Pin was 0.28 mm: the thickness of the resin layer around the Z-Pin was 0.03 mm.

An axisymmetric 2D finite element mesh was used. Because of the mid-plane symmetry of the geometry and load only the half of the thickness was modelled. A finer mesh was used near the Z-Pin/resin interface.

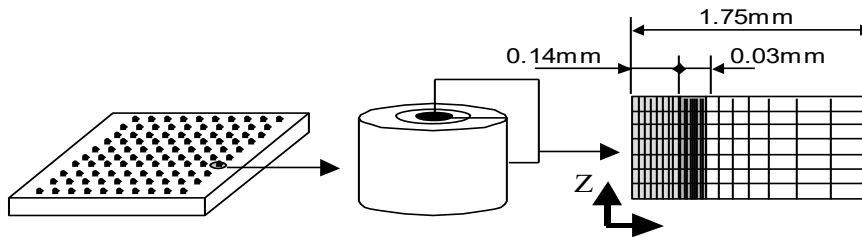


Figure 2.9 Axisymmetric model of Z-Pin, [54]

The model was simplified by two assumptions:

- Layup sequence was assumed to have negligible influence on the examined stresses, therefore the laminate was modelled as “monolithic quasi-isotropic” material.
- Resin pocket shape was assumed to have no influence on the interfacial stresses, hence the resin pocket was modelled as a circular tube around the Z-Pin.

On the example of the uniform thermal loading of 10°C the results shows the intense shearing that occurs in the resin pocket close to the surface of the composite. High stresses were observed at the Z-Pin/resin interface below the surface of the composite.

3D unit cell model used for the material properties of z-pinned laminate analysis

Work dealing with the influence of the z-pining process on material constants was presented by Dickinson et al [44]. A 3D unit cell FE model of the single Z-Pin embedded in a composite was used to examine the effect of the parameters like Z-Pin material, Z-Pin volume fraction, Z-Pin diameter, Z-Pin insertion angle, ply stacking sequence and the geometry of the pure resin pockets and curved fibres regions on the elastic response of the composite. Also shown in this paper were the effect of neglecting the resin pockets (“drilled hole model” in which resin pockets and curved fibres regions were neglected; material properties and fibre direction of the unpinned composite were applied everywhere except for the Z-Pin) and of the curved fibres regions (“straight fibres model” in which resin pockets were modelled but curved fibres regions were neglected). The comparison between the simple stiffness averaging method and the advanced FE model was investigated.

A single Z-Pin embedded in a laminate was modelled as an orthogonal hexahedral Unit Cell (UC) and meshed using a combination of automatic and manual meshing with 3D 8-node solid elements (three transitional degrees of freedom per node). Wedge elements appeared as a result of collapsing sides of the brick elements in sharp corners of the mesh regions. The single UC models ranged in size from 20000 to 75000 degrees of freedom.

AS4/3501-6 symmetric laminates in unidirectional $[0^\circ_2]$, cross-ply $[0^\circ, 90^\circ]$, angle-ply $[\pm 45^\circ]$, and quasi-isotropic $[+45^\circ, 90^\circ, -45^\circ, 0^\circ]$ stacking sequences pinned with 0.025in (0.635 mm) Z-Pins made of Kevlar/3501-6, T300/9310, Titanium and Steel were studied. Material properties of the lamina, Z-Pins and resin are shown in **Table 2.4**.

	Ex[GPa]	Ey[GPa]	Ez[GPa]	Gxy[GPa]	Gxz[GPa]	Gyz[GPa]
Lamina AS4/3501-6	8.69	8.69	133.76	3.15	5.84	5.84
Z-Pins Kevlar/3501-6	8.96	8.96	38.61	5.27	5.45	5.45
Z-Pins T300/9310	7.17	7.17	141.34	2.61	4.37	4.37
Z-Pins Titanium	110.32	110.32	110.32	43.44	43.44	43.44
Z-Pins Steel	206.84	206.84	206.84	82.74	82.74	82.74
Resin 3501-6	4.36	4.36	4.36	1.62	1.62	1.62

Table 2.4 Material input properties for the Unit Cell model, [44]

Important microstructural details of the model based on microscopic observations are shown in **Figure 2.10**. External dimensions of the model in the x-y plane are w_x and w_y . The dimensions of Unit Cell in this study were: $w_x=w_y=0.162$ in (4.1148 mm), $w_z=0.12$ in (3.048 mm). The thickness of the laminate was two or four plies according to the lay-up being modelled. A circular Z-Pin of radius R was situated in the centre of the UC. The border of the resin pocket was assumed to be a straight line from the tip of the pocket, tangential to the outline of the Z-Pin. Parameters θ and l describe the geometry of the resin pocket. The curved fibres regions, where fibres are oriented parallel to the resin pocket borderline, were defined as parallelograms described by parameter L_1 . A fine mesh was used in the circular region containing Z-Pin and the resin pockets; a coarser mesh was used for the rest of the UC. The angle of insertion ψ was defined as an angle between the axis of Z-Pin and the normal to the plane of the laminate, see **Figure 2.11**. In the cases of non-zero insertion angles the 2D geometry was extruded at the angle of ψ and the wedge-shaped empty areas are manually meshed to retain the hexahedral shape. To solve the problem of compatibility between the layers of elements modelling plies of different orientation so called “star pattern approach” was utilized, see **Figure 2.12**. The “star pattern” was made by replication and rotation of the geometry seen in **Figure 2.10**, which ensured the compatibility between the 0° , $+45^\circ$, 90° and -45° layers.

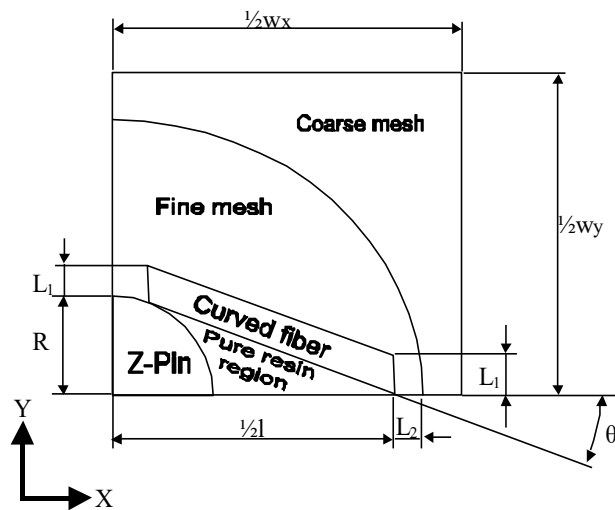


Figure 2.10 Geometry of the model and mesh features, [44]

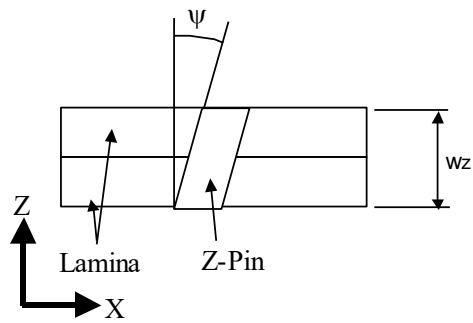


Figure 2.11 Z-Pin insertion angle, [44]

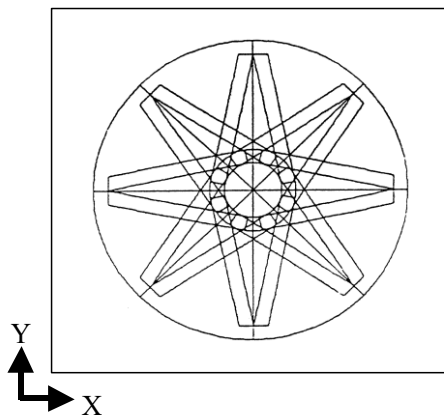


Figure 2.12 Geometry of the "star pattern", [44]

To decrease a potential numerical error in displacement based FE method a known “macrostress” was applied as a loading, the UC was constrained to deform to a certain shape and displacements at the boundaries are used to calculate “macrostrains”.

In this model it was assumed that:

- Neighbouring UCs are subjected to the same constraints; modelled material was subjected to uniform external load. This model was not valid for the free edges and other geometric and material discontinuities.
- There was perfect bond between resin and the fibres.
- Effect of the non-circular cross-section of the Z-Pin at the non-zero insertion angles was neglected.
- Insertion of the Z-Pins does not change the overall thickness of the laminate nor in-plane fibre volume fraction.

In the results, shown in **Table 2.5**, all the percentage change is in relation to the composite without Z-Pins.

	E _x [GPa]	E _y [GPa]	E _z [GPa]	G _{xy} [GPa]	G _{xz} [GPa]	G _{yz} [GPa]
LAYUP						
[0°,0°]	-9%	+1%	+26.5	Changes in a similar manner as E _x ,E _y and E _z . -9% in the worst case		
[0°,90°]	-7%	-7%	+23%			
[±45°] _s	-2%	-2%	+23%			
[+45°,90°,-45°,0°]	-6.5%	-6.5%	+23%			
INSERTION ANGLE						
ψ=45°	no effect		+15%	negligible effect	-1%	negligible effect
ψ=15°			+21.5%		-1%	
ψ=0°			+22.5%		-1%	
VOLUME FRACTION						
V _f =4.9%	-15%		+28.0%	+1.5%	-4%	
V _f =1.9%	-12.5%		+22.5%	-1%	negligible effect	
V _f =0.3%	-1%		+4%	-0.2%		
Z-PIN MATERIAL						
Steel	-6.5%		+35.5%	+1%	+26.5%	
Titanium	-7%		+17.5%	+1%	+12%	
K-E	-7.5%		+4%	-0.5%	-2.5%	
G-E	-7.5%		+22.5%	-1.5%	-3%	
FE MODEL						
“Drilled hole”	-5%		+24.5%	-1.5%	0%	
“Straight fibre”	-7.5%		+22.5%	-5.5%	negligible effect	
Full model	-7.5%		+22.5%	-1.5%	-3%	

Table 2.5 Results: percent change from the control case without Z-Pins, approximate values read from graphs, [44]

The data revealed that the reduction of the in-plane mechanical properties (E_x , E_y), was rather modest (-2% to -15%), compared to greater improvement of E_z (approximately +4% to +35%). This model did not show the effect on delamination toughness.

Resin pockets and curved fibre regions seemed to play an unimportant role in this FE model.

The results of this FE model were compared to the results of simple stiffness averaging method (SAM). In SAM isostrain was assumed across the modelled segment of the composite. Each segment (equivalent to the unit cell) consisted of N “unidirectional” sections with known volume fractions and stiffnesses. The global stiffness of the segment was calculated from the contributions of the individual sections, accordingly to their volume fractions, to the global directions. The results for $[0^\circ_2]$ laminate are within 1% agreement in both methods, except for G_{xz} and G_{yz} where the values differed by 7% to 9%.

The stiffness averaging method was shown to be a good alternative for the much more complicated FE models for estimation of the engineering constants: there was less than 10% difference in the results from both methods.

Unit cell 3D model for stiffness analysis

An example of a 3D finite element model of the Z-Pin was proposed by Grassi et al [45], who used this to investigate a Z-Pin located near a laminate free edge. The aim of this project was to examine stiffness variations and stress field perturbation and redistribution caused by the Z-Pin in laminates of various stacking sequences. In addition to the Z-Pin itself, the surrounding composite, a resin pocket and an area of “curved fibres” were modelled, see **Figure 2.13**. All of the numerous variables of the model (e.g.: length of the resin pocket, dimensions of the curved fibres region) are functions of the Z-Pin diameter.

In the single Unit Cell (UC) different geometric shapes are used to mesh different regions: Z-Pin, laminate, resin pocket, and curved fibres in each layer of elements representing single ply of the composite (**Figure 2.13**). To maintain “mesh compatibility” between the plies the “star pattern” approach (see later **Figure 2.12**) is said to be applied. It is however not visible in **Figure 2.13** or in other figures in the published paper. Eight-node hexahedral elements were

used. Unidirectional $[0^{\circ}_4]$, Cross-ply $[0^{\circ},90^{\circ}]_s$, angle-ply $[\pm 45^{\circ}]_s$, and quasi-isotropic $[+45^{\circ},90^{\circ},-45^{\circ},0^{\circ}]_s$ stacking sequences were modelled. Material properties used in this model are shown in **Table 2.6**.

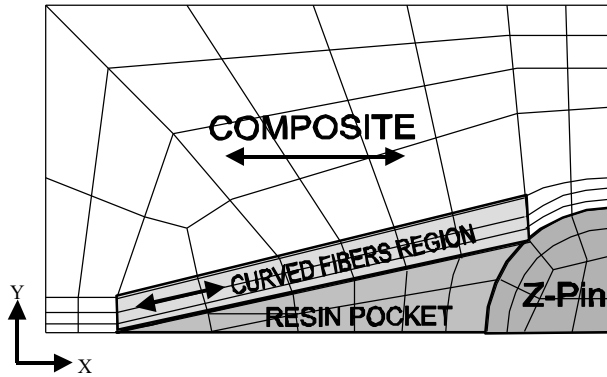


Figure 2.13 Finite element mesh of the Unit Cell, arrows indicate fibre directions in relevant regions, [45]

An averaging technique was applied to describe macroscopically homogenous medium: average macro-stress and macro-strain were derived by relating micro-stress and -strain tensors to the volume of the UC:

$$\overline{\sigma_{ij}} = \frac{1}{V} \int_V \sigma_{ij}(x, y, z) dV$$

$$\overline{\varepsilon_{ij}} = \frac{1}{V} \int_V \varepsilon_{ij}(x, y, z) dV$$

where V is the UC volume.

From the equivalence between the external work and the stored deformation energy:

$$\frac{1}{2} P_i \cdot \delta_i = \frac{1}{2} \overline{\sigma_{ij}} \cdot \overline{\varepsilon_{ij}} \cdot V$$

an average stress tensor component was derived. Using the average stress and strain, the authors were able to determine effective elastic moduli.

	E_x	E_y	E_z	G_{xy}	G_{xz}	G_{yz}
Lamina AS4/3501	136.4	8.9	8.9	5.95	5.94	3.21
Z-Pin T300/9310	144	7.31	7.31	4.45	4.45	2.65

Table 2.6 Material properties used in FE models, [45]

	E_x [GPa]	E_y [GPa]	E_z [GPa]	G_{xy} [GPa]	G_{xz} [GPa]	G_{yz} [GPa]
UNPINNED LAMINATE (control case)						
UD $[0^\circ_4]$	136.4	8.86	8.81	5.95	5.94	3.2
Cross-ply $[0^\circ, 90^\circ]_s$	72.8	72.8	10.05	5.94	4.15	4.15
Angle-ply $[\pm 45^\circ]_s$	20.6	20.6	10.03	35.32	4.29	4.29
QI $[+45^\circ, 90^\circ, -45^\circ, 0^\circ]_s$	53.28	53.28	10.05	20.64	4.21	4.23
Z-PINNED LAMINATE, 2% PINNING DENSITY						
UD $[0^\circ_4]$	121.8	8.6	11.92	5.81	5.67	3.13
Cross-ply $[0^\circ, 90^\circ]_s$	67.3	67.3	12.31	5.82	3.98	3.98
Angle-ply $[\pm 45^\circ]_s$	19.45	19.45	12.27	31.9	4.1	4.1
QI $[+45^\circ, 90^\circ, -45^\circ, 0^\circ]_s$	49.51	49.51	12	18.87	3.98	3.98

Table 2.7 Influence of the Z-Pinning process on composite stiffness, Unit Cell model, [45]

All the layups showed a slight decrease in the in-plane properties (10% E_x decrease in unidirectional laminate in the worst case) and a significant (22-23%) increase in E_z modulus. The interlaminar shear moduli G_{xz} and G_{yz} seemed to be less affected by the presence of the Z-Pin reaching 4% decrease in the worst case. Reduction in G_{xy} modulus is even smaller because of the supporting role of the curved fibers. The UD laminate was characterized by the highest reduction in E_x modulus. The cross-ply laminate showed 7% reduction in E_x and E_y moduli. The angle-ply laminate experienced 9% reduction in G_{xy} shear modulus. The QI laminate showed uniform 6-7% reduction in E_x , E_y and G_{xy} moduli. Increased shear stress in the curved fibre regions after applying uniform strain in x and y directions showed the significant role of curved fibres in the stress field around a Z-Pin. The Z-Pins absorbed up to 25% of the total strain energy of the deformation under through the thickness loading. The authors stated that a non-uniform “shear lag” occurred at the Z-Pin/resin interface and conclude that this region should be taken under careful consideration. (This paper does not deal with this problem).

2D FE Model – Influence of Z-Pin dimensions and pinning density on compression and shear strength

A 2D finite element model of a Z-Pin embedded in quasi-isotropic and orthotropic lay-ups was proposed by O’Brien et al [55] in order to evaluate influence of the compression and shear on strength of the composite. Composites containing 0.28 mm Z-Pins with 2% and 4% areal density, and 0.51 mm Z-Pins with 2% areal density were investigated under pure compression, compression plus 10% shear and compression plus 50% shear. The model representing cross-section perpendicular to the Z-Pin, included finely meshed resin pocket regions and waviness of the fibres caused by the Z-Pin insertion.

“Microbuckling”, corresponding to the fibre waviness, was reported as a cause of the compression strength decrease, with pinning density more influential than the Z-Pin diameter alone. The addition of shear stress drastically reduced the compression strength of the lamina.

Another 2D FE model, investigating the effect of Z-Pin diameter and z-pinning density (and of the fibre waviness caused by z-pinning) on the compression strength of the glass fibre textile composites, was built by Huang et al [70]. According to the authors the compression strength diminishes with increasing Z-Pin density and decreasing Z-Pin diameter.

FE model of thermal stresses caused by the curing cycle of Z-Pinned laminate

This FE model [71] of a solid pin inserted into the laminate prior to curing showed that the difference in the thermal expansion between the Z-Pin and the laminate causes post-cure residual stresses, which are higher than the failure stress of standard resin. Microscopic observations showed cracking around the perimeter of the Z-Pin, which could not be substantially reduced by changing the material properties or dimensions of the models. These results indicated that the improvement of the through-thickness properties was due to mechanical interlocking rather than bonding.

2.5.3 THE EFFECT OF Z-PINNING ON INTERLAMINAR CRACK PROPAGATION

3D model of the edge of z-pinned laminate for crack behaviour analysis

The way in which the presence of Z-Pins in the laminate affect the stress at the crack tip, crack initiation and crack propagation was addressed in [54].

The model, which was to simulate the edge of a laminate, consisted of a rectangular block of 18-ply quasi-isotropic lay-up AS4/3501-6 composite (3.5x7.00 mm, thickness 3.5 mm) containing two 0.28 mm T300/5208 Z-Pins, see **Figure 2.14**. Because of the symmetry of the geometry and loading about the midplane and about the X-Z plane, which goes through axes of the Z-Pins, only the one-quarter of the block was analysed (**Figure 2.14**). The midplane crack, which was introduced by releasing the nodal restraints in part of midplane, stretches from the edge of the modelled laminate to the midpoint between the Z-Pins (**Figure 2.14**).

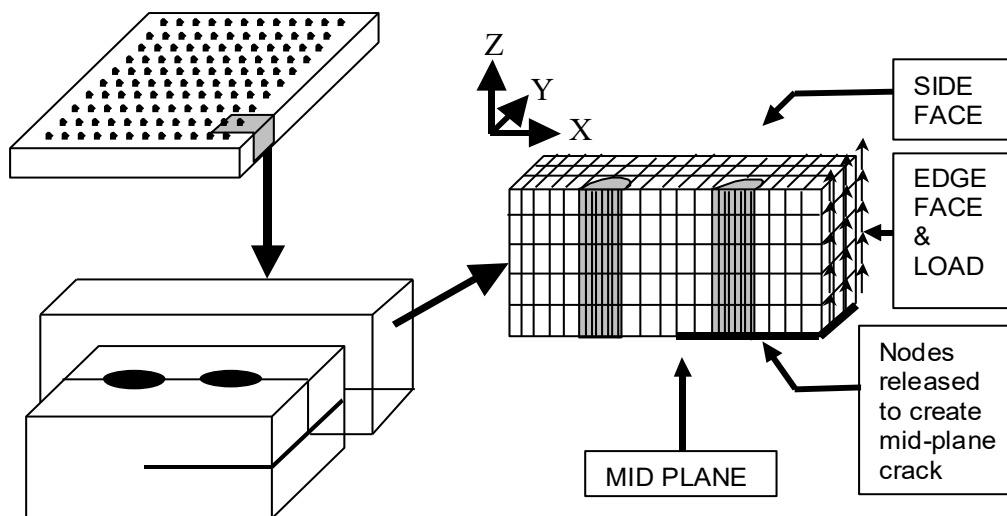


Figure 2.14 Three-dimensional FE model of the Z-Pins near the edge of the laminate, [54]

Eight-node isoparametric solid elements were utilized. The crack opening load of 1 MPa shear stress acting over the edge plane was applied, as shown in **Figure 2.14**.

The model was simplified by the following assumptions:

- Resin pockets were not included in the model.
- X and Y displacements on the side faces of the model were held fixed to achieve quasi-plane strain conditions that exist between the rows of Z-Pins.
- The laminate beyond the second (counting from the edge) pin had no effect on the crack tip stresses.

The case in which the crack is reinforced by two Z-Pins was compared to the case where there is no reinforcement.

The results showed approximately 70% reduction in the first second and third principal nodal stress at the crack tip. This demonstrated that Z-Pins can carry a significant proportion of the through the thickness load and therefore have the potential to arrest the crack propagation.

Axisymmetric model of a single Z-Pin for crack stress analysis

The axisymmetric model of a single Z-Pin proposed by Barrett [54], described earlier, was employed to investigate the stresses in composite structure near the Z-Pin in the crack wake, see **Figure 2.15**. In order to introduce the crack to the model the restraints in the midplane elements from the outer rim to the distance of two Z-Pin diameters from the face of the pin were released. The crack opening loads was applied as 18 nodal forces of 0.1 N acting around the rim of the model. The case of laminate reinforced by Z-Pins was compared to the case without reinforcement where the parts of the mesh representing Z-Pin and resin pocket were assigned the material properties of the laminate.

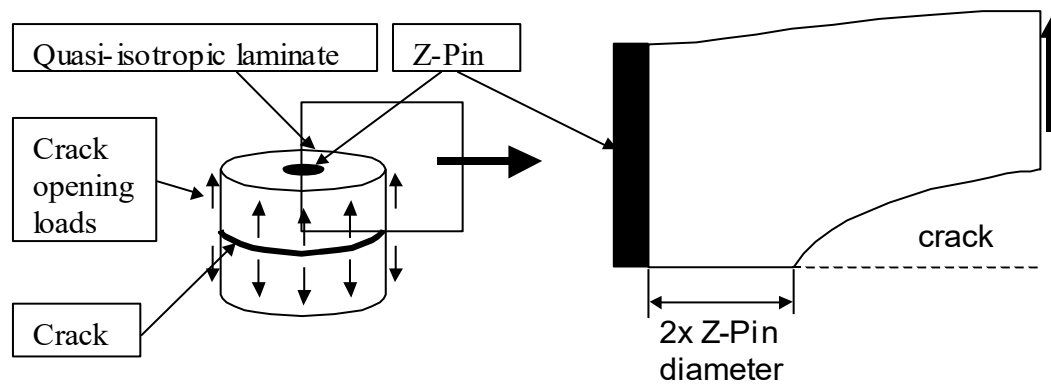


Figure 2.15 Axisymmetric model of the Z-Pin embedded into precracked laminate, [54]

Only 4.8% to 7.4% reduction in the crack tip principal nodal stresses due to presence of Z-Pin was observed. This shows that the stress field at the crack tip is affected only in the immediate vicinity of the Z-Pin. The results seem to prove that Z-Pins can arrest the crack propagation but they have little effect on the initiation of the crack.

3D model of the laminate edge for free edge stress analysis

The 3D model of the free edge of the laminate containing the unit cells, described earlier, was employed to analyze the influence of the location of the Z-Pin, in relation to the free edge of a laminate, on the peeling stress, σ_z and interlaminar shear stress τ_{xz} . The UC was located in three different distances from the free edge. 20-node hexahedral elements were used. For a given case, only one UC was assigned Z-Pin properties while the two others are left with the properties of baseline laminate. Cross-ply $[0^\circ, 90^\circ]_s$ and angle-ply $[+45^\circ, -45^\circ]_s$ laminates were analysed. For the geometry of the model see **Figure 2.16**.

The model of cross-ply laminate was built out of 522 elements (3039 nodes); symmetric boundary conditions were applied on the plane going through the axis of the Z-Pins. The model of angle ply laminate, contained 2088 elements (9489 nodes). The thickness of the laminate was 0.132 mm (4 plies). Three Z-Pin positions were modelled: $d_1=1.25$ mm, $d_2=0.69$ mm and $d_3=0.25$ mm from the free edge, see **Figure 2.16**.

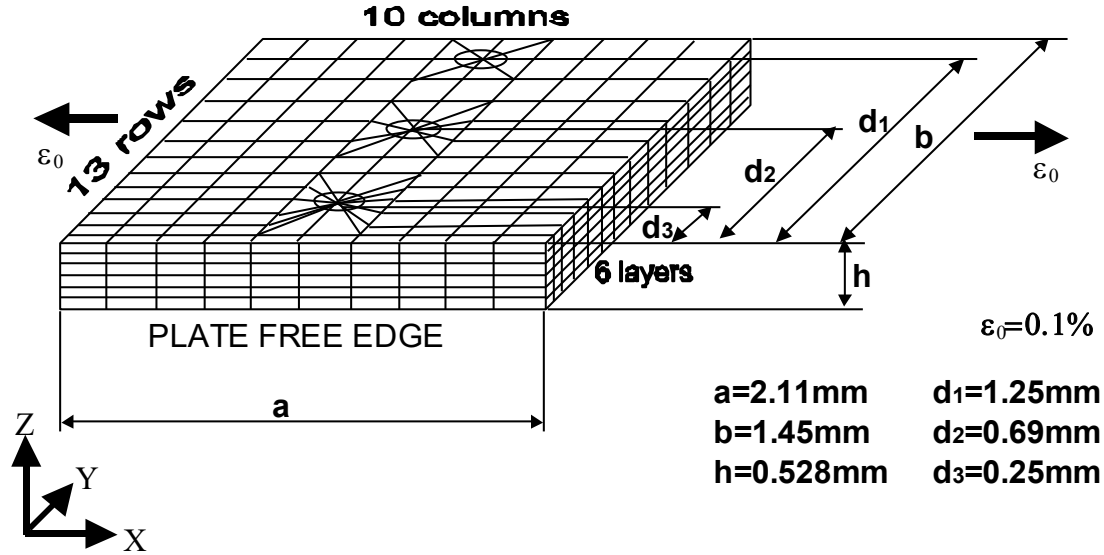


Figure 2.16 Finite element model of the Z-Pins near the edge of the laminate, [54]

Both models were loaded with in-plane strain $\epsilon_0=0.1\%$ in the x direction.

This model of Z-Pinned laminate edge showed that only Z-Pins placed extremely close (distance $d_3=0.25$ mm) to the edge have a significant influence (15% reduction) on the σ_z peeling stress and the τ_{xz} interlaminar shear stress. This suggests that in practice Z-Pins are unlikely to significantly inhibit initiation of a crack due to free edge stresses.

Link elements featuring bridging actions of Z-Pins in the crack

The direct application of the single Z-Pin pull-out test as a finite element method tool was undertaken by Cartié et al [72,73]. The traction law found experimentally in [72] was simplified and applied to “link elements”. These elements, which simulate the actions of Z-Pins during propagation of a crack were applied to “quantify and optimise” the effect of Z-Pins on the crack propagation in real composites. On the example of a standard unidirectional laminate DCB specimen with a pre-crack in the middle plane the effect of the parameters like the DCB thickness ($2h$), DCB width (b), crack length (a), pinning density, Z-Pin diameter (d) and location of the Z-Pin in relation to the tip of the crack on the Z-Pin action were studied. French software CASTEM 2000 (98’ version) with its internal programming language was utilized to

build a 2D model of part of a DCB containing the tip of the crack (initially 50 mm of the cracked part and 15 mm of intact laminate).

A two-dimensional mesh, shown in **Figure 2.17**, centred in the tip of the crack was built of 1588 8-node elements. The mesh is fine around the centre and gets coarser with the distance from the tip of the crack.

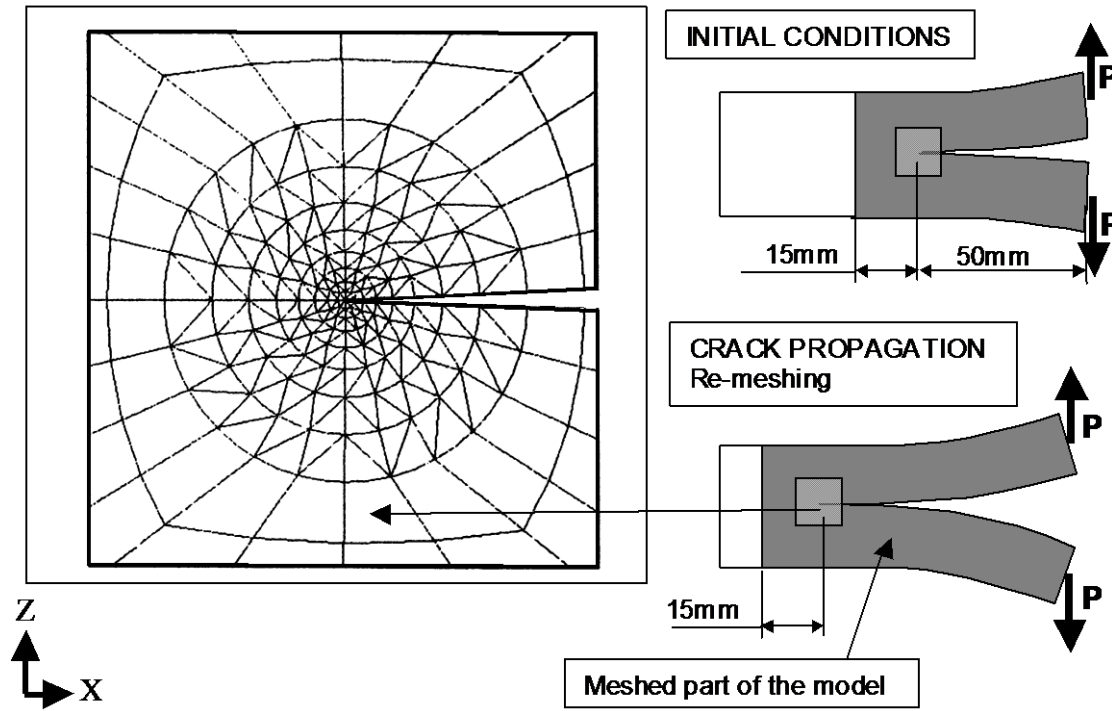


Figure 2.17 Two-dimensional mesh of the part of DCB specimen with the crack tip in the centre, crack propagation by re-meshing, [72]

The link elements simulating Z-Pins linked the nodes on the opposite sides of the crack. The relation between the force in the link elements (F_{pin}) and the crack opening displacement (u) followed the simplified traction law found experimentally. This law was characterized by force F_{max} at the displacement u_{max} and displacement u_{end} when the force drops to zero. An opening displacement was applied at the tips of the DCB specimen arms

An iterative procedure was applied to solve the problem. At each step of iteration the value of the energy release rate at the crack tip was calculated by the software using the J-integral method. The displacement was increased until G reaches G_c that was found experimentally in delamination tests of unpinned representative specimens, i.e. the crack growth criterion was as follows:

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

The crack propagation was simulated by re-meshing of the model and relocation of the link elements relative to the crack tip, see **Figure 2.17**. Crack bridging forces and the associated displacements in each iteration start with the values from the previous step. The following assumptions were applied:

- The in-plane properties of laminate are not affected by the presence of Z-Pins.
- The flexural breakage of the specimen arms was not taken into account.
- The model was 2D, hence, it cannot simulate non-uniform crack propagation.

The material properties used in the model are given in **Table 2.8** (no other material properties could be found in the paper).

The validation of the model seems to show good agreement between FE model and experiment (**Table 2.9**). Results of FE simulation follow closely experimental ones. Even the effects of faults in Z-Pinning process (lack of a Z-Pin, modelled as a lower number of Z-Pins in a row) are visible in FE model results.

Material properties used in FE model: IMS/924	
E ₁₁	138 GPa
E ₂₂	11 GPa
E ₃₃	0.1 GPa (as reported by the author)
ν ₁₂	0.34
G ₁₂	4.4 GPa

Table 2.8 Material properties used in FE model, [72]

The effect of Z-Pin diameter on delamination resistance was examined by comparison between the models with 0.28 mm and 0.51 mm Z-Pin diameters (2% pinning density in both cases). The higher resistance for delamination with 0.28 mm Z-Pins, observed experimentally, was conformed in FE model. Experimental results and the results calculated from the model, showed strikingly good agreement. Mode II model and results were not presented.

Results of:	Experiment	FE model
DCB thickness [mm]	3.21	3.2
Crack length [mm]	49.6	49
Load [P]	42.8	42.8
δ [mm]	4.3	4.3
CBT – corrected beam theory		
FE – calculated by CASTEM		

Table 2.9 Comparison between experiment and FE modelling results, [72]

2D Models – Z-Pins bridging the crack in a double-cantilever beam

A 2D finite element model of Z-Pin reinforced, pre-cracked double-cantilever beam was proposed by Yan et al [74] in order to investigate delamination toughness of the z-pinned laminate. The Z-Pins were represented by non-linear springs, subjected to deformation and breakage, where the bridging force increased rapidly to a peak value and then decreased gradually to zero at the complete pull-out. In Mode II the springs were additionally allowed to bend. Depending on the material configuration, the Z-Pins were observed to completely pull-out or to break before or after the peak force.

Theoretical analysis and 2D finite element model of a double cantilever beam, exploring interlaminar fracture of Z-Pin reinforced laminates under Mode I loading conditions was proposed by Grassi et al [75]. The composite was represented by thick shell elements, while the Z-Pins were introduced as non-linear interface elements bridging the crack. The Z-Pins showed to provide effective bridging and crack growth resistance after the crack propagated into the z-pinned zone.

2.5.4 MICROMECHANICS OF THE Z-PIN BRIDGING IN MODE I OR MODE II

2D Model – shear-out under various angles

A 2D finite element model, investigating the plasticity, stress distribution and the process of debonding of metal Z-Pin bridging the crack in elasto-plastic material in Mode II loading conditions under various inclination angles, was proposed by Legarh [76]. The debonding process is divided into the initial debonding, diametrically at the edges of the crack, and the second debonding, when entire area of the contact between the Z-Pin and matrix fails, and internal failure of the Z-Pin occurs.

Mode I axial pull-out and transverse bending of a single Z-Rod (the term which the author uses to refer to a metallic Z-Pin, which is stiffer than fibrous Z-Pin or Z-Fiber) in the wake of a crack propagating in double cantilever beam, were investigated in a theoretical study by Tong et al [77]. The bending and displacement of the rod embedded in linearly elastic and perfectly plastic matrix were introduced using classical beam theory. According to the authors the bending effect of stiffer rods should not be ignored.

3D Model – Z-Pin pull-out analysis

A 3D (but practically axially symmetric) finite element model of a Z-Pin (cylinder: radius 0.25 mm, height 1.68 mm), surrounded by a concentric resin zone (ring: inner radius 0.25 mm, outer radius 0.5 mm), embedded in a brick representing laminate (4 mm x 4 mm x 1.4 mm) was proposed by Meo et al [78] in order to investigate the Z-Pin pull-out (Mode I) process under quasi-static conditions and the frictional contact between Z-Pin and matrix. The pull-out was introduced by the displacement applied to a cross-section of the Z-Pin at a distance from the laminate surface. Constant friction was supplied by contact elements, which could carry shear stress up to a certain value, and allowed sliding when this value was exceeded. The authors observed three phases of pull-out:

1. Elastic deformation with progressing debonding - load monotonically increasing with displacement
2. Complete debonding characterised by a drop of the load at the maximum
3. Elastic deformation with frictional sliding - linear decrease of the load

According to the authors “the frictional shear stress is already present during the debonding process; therefore, the peak load indicates the onset of unstable crack propagation”.

The author claims that their numerical load/displacement curve closely follows the experimental one. It is simply linear growth followed by a linear decrease, without any rapid drops or secondary growths. Only an increased “static to dynamic friction ratio” resulted in a small but rapid drop in the force after the maximum, followed by the gradual decrease.

2D Model – pull-out, shear-out and mixed mode simulation

A 2D plane-stress finite element model simulating pull-out, shear-out and mixed mode behaviour of a single 0.28 mm Z-Pin in a 3 mm thick UD laminate (T300/BMI) was proposed by Cui et al [43]. The resin pocket and the Z-Pin were covered by 4-node bilinear plane stress elements, which in the Z-Pin were elongated in order to represent single fibres. Additionally, rows of “cohesive elements with negligible thickness” were introduced between the elements representing fibres of the Z-Pin - alongside and in the normal direction, in order to simulate the splitting of the fibres and fracture of the Z-Pin (**Figure 2.18**). The cohesive elements followed “traction-separation failure mechanisms” - initial linear elasticity followed by breakage and stress degradation. The authors also used “interfacial contact” between the Z-Pin and the laminate, which were initially fully bonded. Debonding was followed by frictional sliding, with a constant friction coefficient. The “linear energy criterion” was used to determine failure of the cohesive elements, as follows:

$$\frac{G_I}{G_{IC}} + \frac{G_{II}}{G_{IIC}} + \frac{G_{III}}{G_{IIIC}} = 1 \quad \text{where } G_{iC} - \text{critical strain energy release rate for Mode } i$$

In Mode I pull-out three phases were observed:

1. Linear increase of the force with the opening displacement up to the maximum load (with Z-Pin and resin fully bonded)
2. Debonding, “failure of the interface between Z-Pin and resin”, progressing gradually from the delamination surface to the end of the Z-Pin, characterised by rapid drop of the force over a short displacement

3. Frictional pull-out after complete debonding, characterised by linear or nearly linear decrease of the force, with the Z-Pin structure remaining intact. The friction, nearly constant along the Z-Pin, was assumed to be caused by residual thermal stress.

In Mode II and in mixed mode, the debonding between the Z-Pin and surrounding material (on one side of the Z-Pin, caused by the peeling stress and propagating along the Z-Pin) occurs first, followed by bending of the Z-Pin and longitudinal splitting of the Z-Pin fibres due to the axial shear strains - the splits propagating alongside with the progressing deflection of the Z-Pin (which might lead to a formation of a “brush shape”) . The “deflecting” of the Z-Pin into the resin was observed - the “snubbing effect” [79,47], especially intensive in pure shear out. The authors observed that after initial debonding in mixed-mode process, the bridging force was caused mainly by the deflection of the Z-Pin, rather than the residual thermal stress. Depending of the mode ratio, either a frictional pull-out or breakage of the Z-Pin may follow.

The loading was applied via the relative displacement of the upper and lower laminate, connected by the Z-Pin. The mode ratio r was defined by the amount of movement in z and x direction. The calculations were carried for the following ratios: 0 (pull-out), 0.25, 0.5, 1.00, 2.00, 4.00, ∞ (shear-out). For comparison the ratios used in this thesis were: 0 (pull-out), 0.58, 1, 1.73, 2.75, 5.67 and ∞ (shear-out)

Also the Z-Pin pull-out and shear out of cross-ply laminate was investigated. The matrix elements were exchanged with elements representing transverse UD fibres of UD laminate. The effect on pull-out was reported as negligible. In case of shear-out the forces were higher and Z-Pin more likely to break.

The load/displacement curves resulting from this study showed the characteristic rapid drop followed by secondary growth of the force, which authors did not discuss. Although this model allows for the internal breakage of the Z-Pin fibres, it does not allow for the deformation of the Z-Pin cross-section, which may play important role during shear-out process.

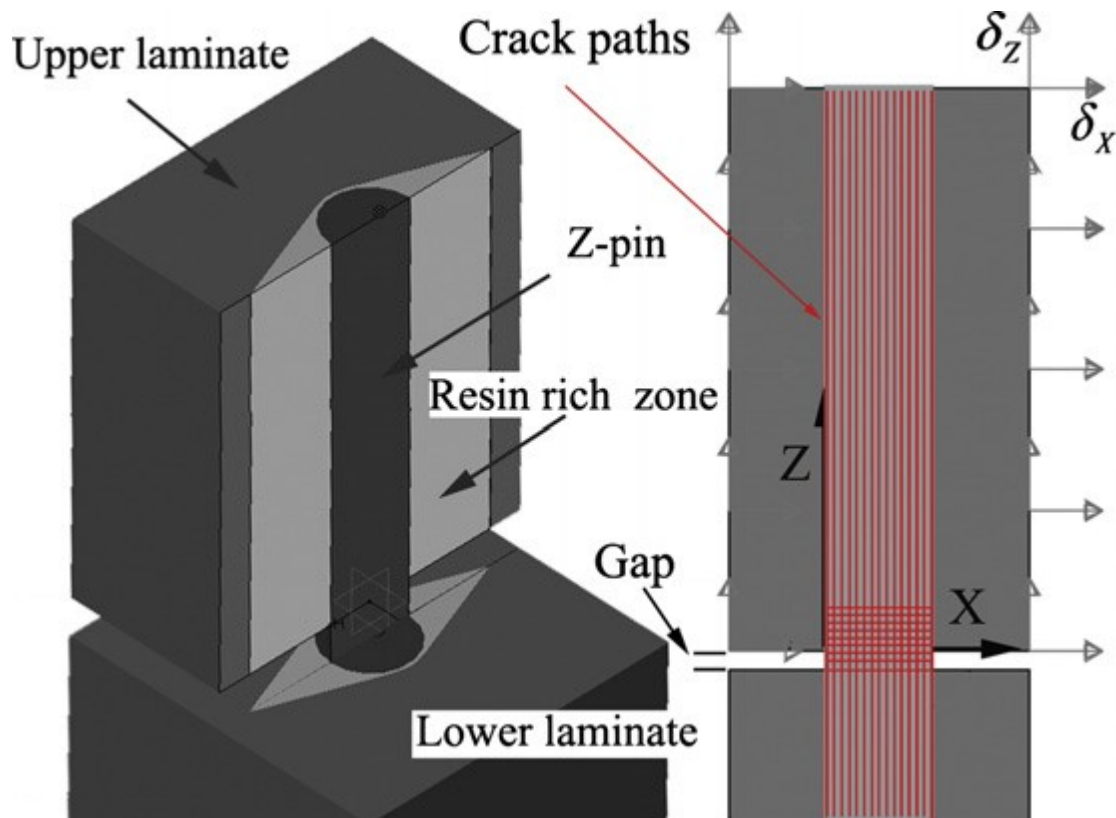


Figure 2.18 Geometry of the model, including the location of coercive elements (red lines), [43]

3D Model – pull-out, shear-out and mixed mode simulation

An advanced, “high fidelity” 3D FE model of a single Z-Pin bridging a gap between two blocks of IM7/8552 composite (**Figure 2.19**) was proposed by Zhang et al [68] in order to investigate the mechanical response of a single Z-Pin, at micro scale, in pull-out (Mode I) and shear-out (Mode II) loading conditions. Abaqus software was used.

This model accounted for the QI stacking sequence $[(90/-45/0/45)_4s]/[(90/-45/0/45)_4s]$ of the laminate and resin pocket in each 1.125 mm thick layer by applying a “star-like” ply mesh approach (**Figure 2.20**), as well as the misalignment of Z-Pin (insertion angle offset, based on experimental results [67]) and in-plane fibre waviness.

The blocks of laminate and the Z-Pin were modelled as linear-elastic orthotropic material and resin was isotropic elasto-plastic material. Zero-thickness cohesive elements following bi-linear cohesive law were applied along the Z-Pin fibres (**Figure 2.20**) in order to model splitting

of the Z-Pin in high longitudinal transverse shear. The cohesive elements featured Coulomb friction with maximum stress of 25 MPa after debonding. Similar cohesive elements modelled contact between the Z-Pin and surrounding laminate, with the maximum Coulomb friction of 40 MPa. The mesh of the laminate close to the Z-Pin was refined in order to closely investigate “snubbing” effect – stress concentrations leading to “friction enhancement” in Mode II (also modelled mathematically in [66]).

The Z-Pin strength was modelled using Weibull distribution with the assumption that only axial tensile stress causes Z-Pin failure.

The calculations were performed in two stages: thermal stage of -160°C cooling, modelling the post-cure contraction applied to all elements, and mechanical stage - movement of one part of the composite block relative to the other, which was constrained.

It was observed that the Z-Pin debonded from the surrounding QI laminate after the cooling stage due to the mismatch of the expansion coefficients of resin and fibre. It initially debonded at the side of the Z-Pin contacting the resin pocket and followed along the Z-Pin in “helix path” due to ply stacking sequence. The cooling also caused damage to the cohesive elements representing splits in the Z-Pin, which in real conditions could decrease the strength of the Z-Pins, especially when subject to bending or shear in in Mode II load conditions.

The results showed load-displacement curves closely following the experimental ones [67,48]. In the Mode I loaded QI laminate the force grew without sharp maximum (**Figure 2.21**), which according to the authors was due to the lack of bond between the Z-Pin and laminate after cooling. The UD laminate results shown in [69] using very similar FE model showed clearly the linear growth of the force, which ended with a sharp maximum when the Z-Pin debonded (**Figure 2.22**). The growth of the pull out force was according to the author due to “enhanced friction”, or “snubbing” which was the result of misalignment of the Z-Pin (and hence mixed mode rather than pure Mode I loading conditions) causing stress concentrations in places where the Z-Pin pushed against the laminate at the mid-plane (**Figure 2.23**). The initial “progressive debonding” of the Z-Pin did not seem to play important role in the pull out process in the QI laminate.

There were no results shown for the 0° insertion angle – the authors assumed that inserting Z-Pin into the laminate without offset was unrealistic. However the shape of load-displacement curves for such case would prove if the offset, and connected to it the “enhanced friction”, was responsible for the growth of the force in the sliding phase.

In Mode II the laminate blocks slid against each other, bending and shearing the Z-Pin until rupture. The splits propagated along the neutral plane of the Z-Pin. The failure of the Z-Pin fibres occurred in parts of the Z-Pin subjected to high tensile stress, on the opposite sides to the enhanced friction zones (**Figure 2.24**). The Mode II results (**Figure 2.25**) corresponded closely with the experiment [67,48].

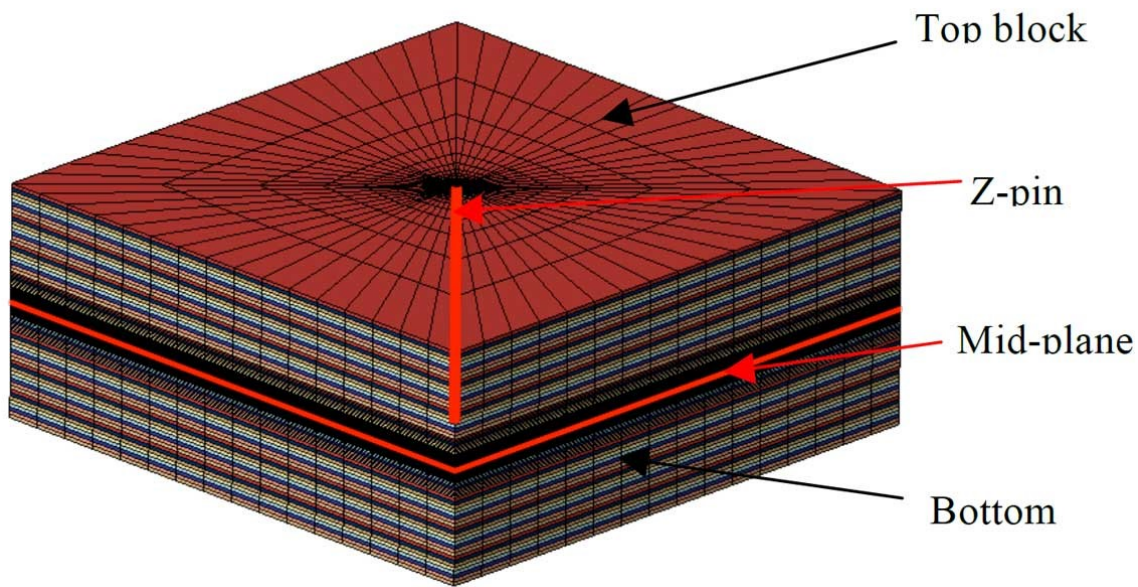


Figure 2.19 Full FE model of z-pinned quasi-isotropic laminates, [68]

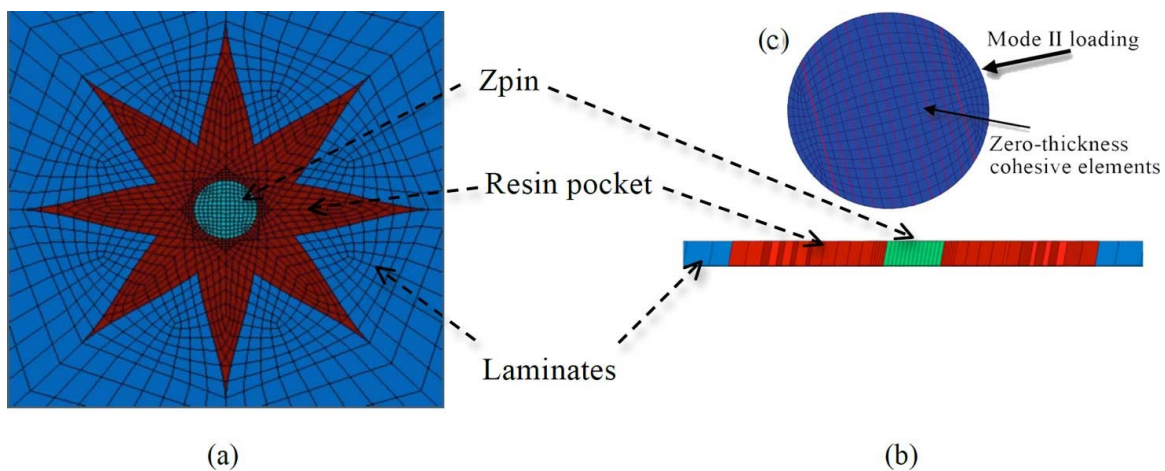


Figure 2.20 Ply level mesh of z-pinned laminates (a), Z-Pin misalignment (b), cohesive elements along the Z-Pin fibres (c), [68]

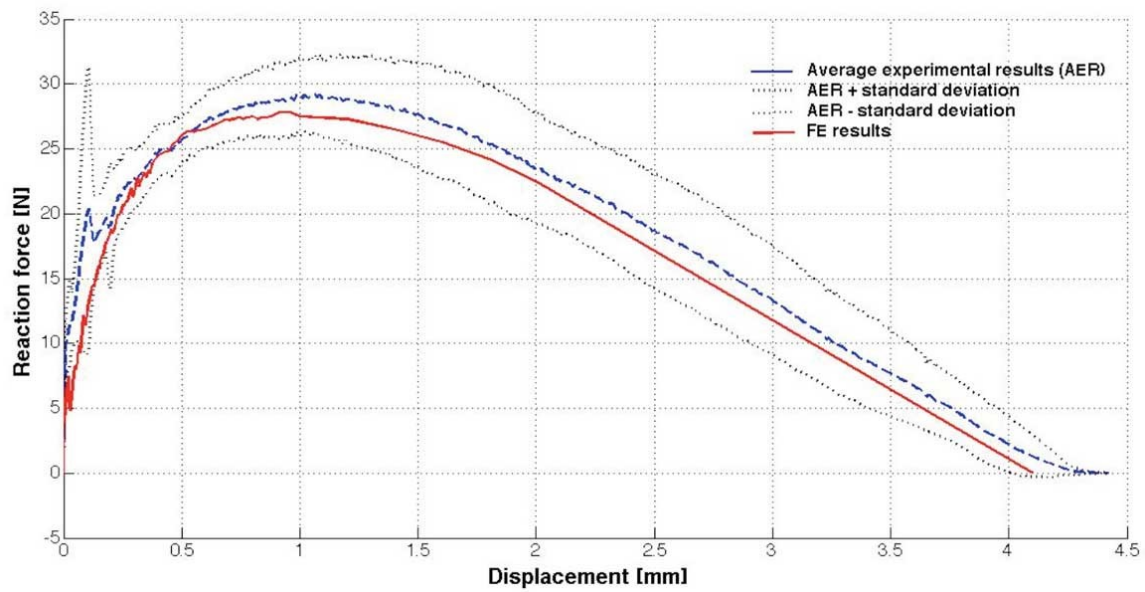
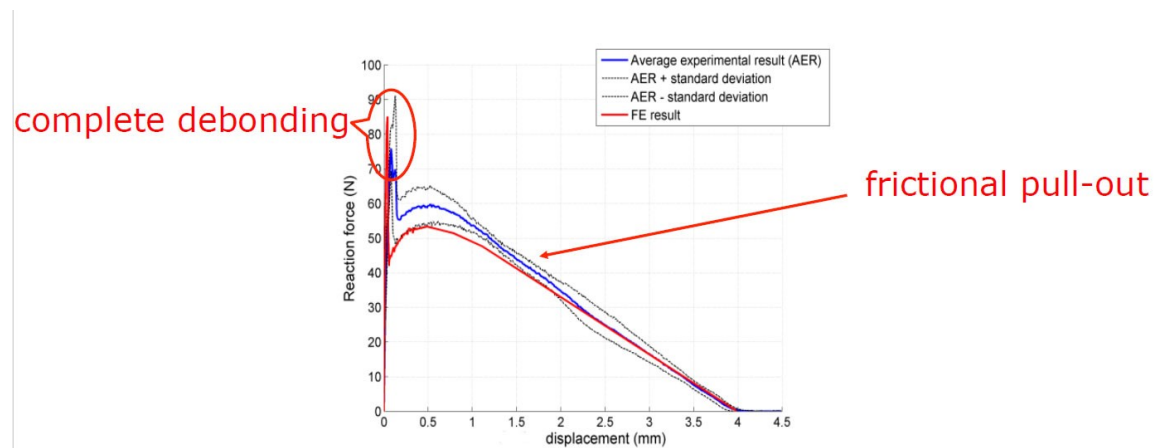


Figure 2.21 Load-displacement curves, Mode I, QI laminate, [68,67]



Reaction force vs. displacement curves of Z-pin pull-out from UD

Figure 2.22 Load-displacement curves, Mode I, UD laminate, [66]

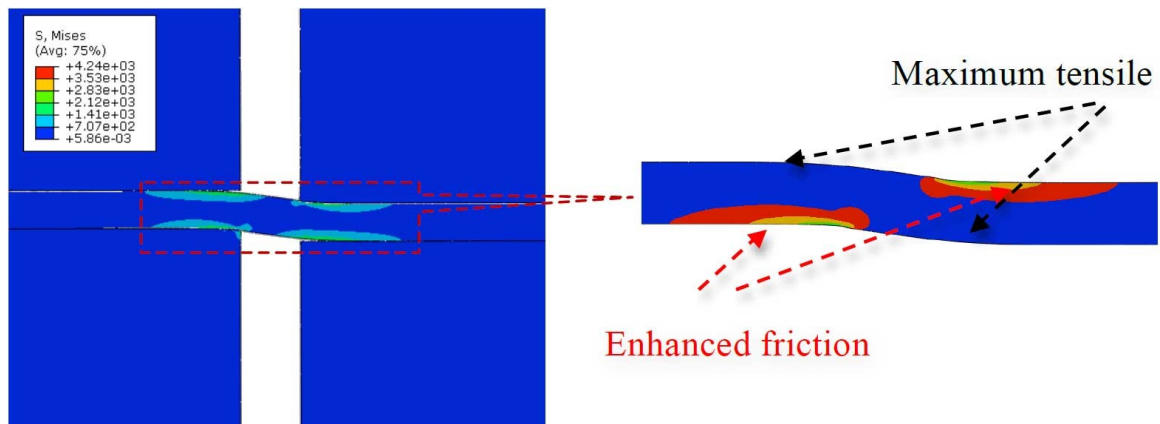


Figure 2.23 Pull-out of Z-Pin and enhanced friction zone

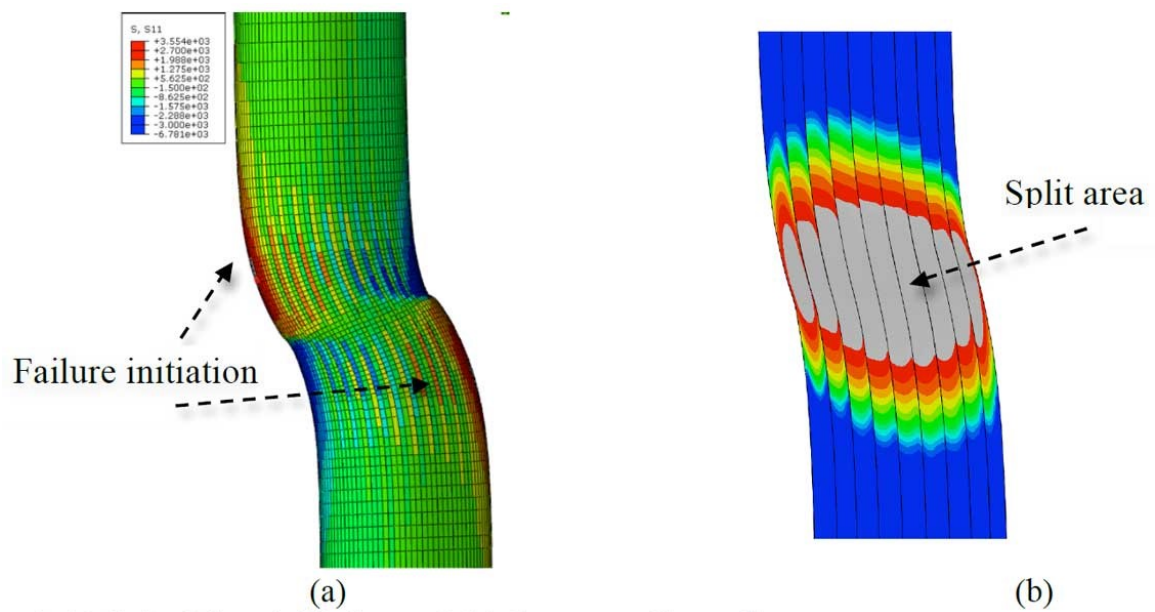


Figure 2.24 Z-Pin failure initiation (a) and corresponding split status (b), [68]

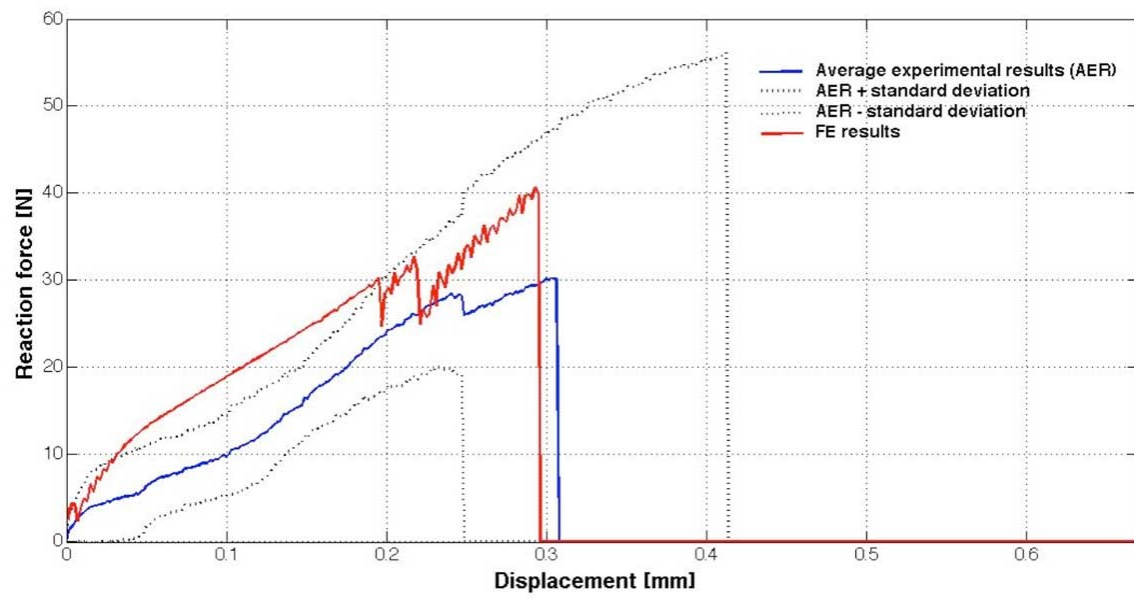


Figure 2.25 Load-displacement curves, Mode II, QI laminate [68,67]

2.5.5 SUMMARY

Majority of the presented models especially the 2D and 3D unit cell, offered simplified approaches. The resin pockets were not modelled at all or were introduced as simple geometrical shapes. The Z-Pin was embedded in a uniform material (resin). These models were used mainly for the purpose of investigating the influence of the z-pinning on the properties of the laminate. It appeared that the z-pinning density of 2% - 4% gave the best results – below 2% the in-plane properties were minimally affected but the full potential of z-pinning is not used, and above 4% density the in-plane properties became greatly affected. The crack propagation models suggested that z-pinning suppressed the delamination propagation but had little effect on the initiation of the delamination.

The only model which offered a fully 3D approach, and included features like lay-up sequence of the laminate, Z-Pin misalignment due to UAZ z-pinning, 3D shape of the resin pocket and allowed for the internal fibre splitting was presented in [68,69], and provided a deep insight into the phenomena taking place during the Z-Pin pull-out and shear-out process.

The Mode I load-displacement curves derived from the model for UD laminates show linear growth until rapid drop of the force, when the Z-Pin debonding occurred. The debonding phase was much less pronounced in QI laminate. This effect was attributed to the post-cure thermal stress, which caused tensile stress at the Z-Pin interface in QI laminate. The growth of the force during the pull-out was attributed to the “snubbing” effect due misalignment of the Z-Pin caused by non-zero insertion angles. The case of zero insertion angle was not considered.

In the Mode II the Z-Pin failure due to bending, without pull out, was observed.

2.6 SINGLE Z-PIN PULL-OUT AND SHEAR-OUT TESTS

2.6.1 INTRODUCTION

Numerous pull-out and shear out tests of a single or groups of Z-Pins of various diameters were undertaken. Majority of the tests utilised two blocks of laminate of various stacking sequences, separated by delamination foil, held together with a Z-Pin or group of Z-Pins, glued between metal coupons and pulled apart. The mutual displacement of the blocks and the reaction force was measured. The tests were performed for a variety of Z-Pin diameters, embedded lengths, at various speeds. The load-displacement curve was used to investigate the phases of the pull-out or shear-out process and measure the peak force and the energy consumed by the pull-out or shear-out, which influenced the ability of the Z-Pins to arrest the propagation of delamination in laminate, or sustain load bearing capacity of the structure after the delamination. The tests were carried out in Mode I (pull-out), mixed mode and Mode II (shear-out) loading conditions and the influence of mode “mixture” on the behaviour of the Z-Pin was also investigated.

2.6.2 PULL OUT TESTS ON GROUPS OF Z-PINS EMBEDDED IN COMPOSITE

Tests of multi-pins specimens in pull-out (Mode I) conditions were reported by Liu et al in [80,81]. The specimens were made of two 1.5 mm thick pieces of IM7/924 laminate pinned together with groups of nine (3 x 3) 0.51 mm or 0.28 mm diameter Z-Pins arranged in a rectangular 3 x 3 array. A “thermal insulation” film was introduced to create an initial crack. The tests were carried on with three different crosshead speeds: 1 mm/min, 10 mm/min and 100 mm/min respectively.

As seen in **Figure 2.26** , three stages of the pull-out process were observed:

- Rapid, linear (or nearly linear) increase in pull-out force until its peak value P_{max} – elastic deformation phase, where the force is smaller than the critical value P_{max} , and the interface between Z-Pin and laminate fully bonded.
- Rapid drop of the force at negligibly small displacement – interfacial debonding phase with rapid, unstable, crack propagation.

- Gradual drop of the force to zero– pull-out phase controlled by interfacial friction. In many cases a slight rise of the force at the beginning of this phase was observed.

An interesting observation was made by the authors for peak force at different crosshead speeds. The peak force $P_{\max}$ was noticeably higher (and peak on the graph visibly sharper) at lower crosshead speeds, becoming lower (and blunter) at higher speeds. The effect was particularly well pronounced by comparing graphs of 1 mm/min and 100 mm/min tests. According to the authors this effect indicates that “the resistance of initial debonding was reduced at higher loading rates”. However, the effect could be a result of relatively coarser sampling at higher rates – the sharp peaks recorded at lower speeds with given sampling rate might become much blunter at higher speeds with the same sampling rates.

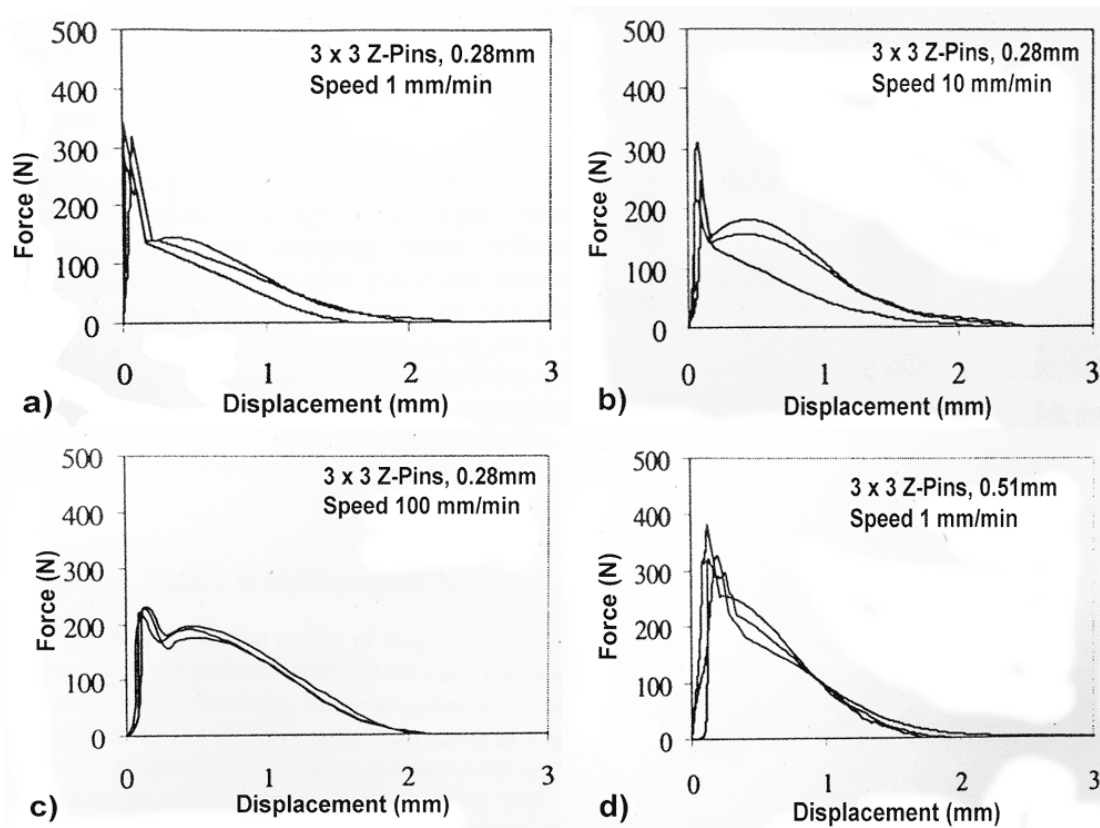


Figure 2.26 Pull-out load-displacement graphs for different crosshead speeds, [80,81]

A multi z-Pin pull-out (Mode I) test was performed by Mouritz et al [47]. Two identical blocks of [0/90]_s T700 carbon–epoxy laminate, divided with PTFE film were bridged by forty nine T300 carbon fibre Z-Pins in a square array 1.75 mm apart. The blocks of 1.2 mm, 2 mm, 4 mm,

6 mm and 8 mm thickness (Z-Pin embedded length) were glued to metal holders and pulled-apart.

For laminate thickness of up to 6 mm the load-displacement curves (**Figure 2.27**) showed rapid linear growth, representing elastic stretch of the Z-Pins, followed by a rapid drop when Z-Pins debonded, and gradual decrease of the force during Z-Pin frictional pull-out. The secondary growth of the force after the first sharp maximum was not observed.

For the 8 mm thick laminate the tensile rupture of the Z-Pins was observed as the frictional pull-out stress was higher than tensile strength of the Z-Pin.

The author also mentioned the irregularities in the internal structure of Z-Pins, including voids/cracks, and debonding cracks along the interface between Z-Pin and laminate. Also a high scatter of insertion angles, ranging from 2° to 30° (median 14°) was reported.

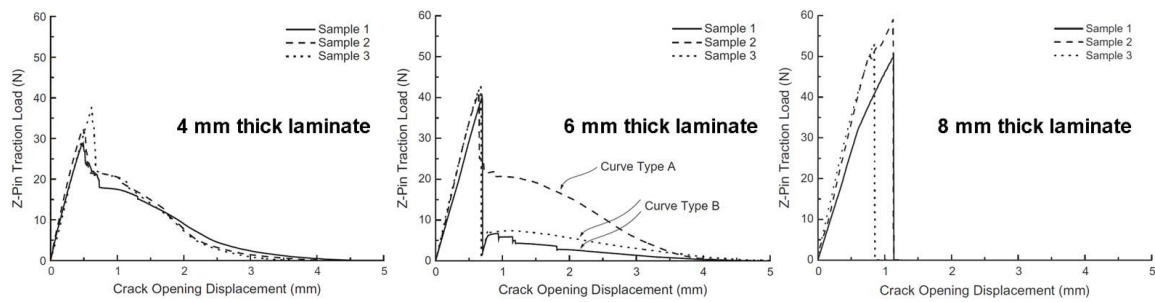


Figure 2.27 Load-displacement curves, [47]

2.6.3 PULL-OUT AND SHEAR-OUT TESTS ON SINGLE Z-PINS EMBEDDED IN COMPOSITE

Single Z-Pin pull-out and shear-out tests were undertaken by Cartié [72] and repeated by Cartié et al [82]. Composite and titanium Z-Pins bridging an existing crack in a fibre/epoxy laminate were tested. For visualization purposes a “pseudo laminate” made of transparent polycarbonate was also used.

Titanium and T300/BMI Z-Fibers of 0.51 mm diameter embedded in 32-ply (4mm thick) unidirectional (UD) IMS/924 laminate were tested in this work. A 20 µm PTFE film was used to introduce a crack in the mid-plane of the laminate. After a standard consolidation procedure the Z-Pins were inserted into the prepreg assembly using a hand-held ultrasonic hammer (UAZ) with spacing about 30 mm between Z-Pins (the excess of Z-Pins had been removed from the Z-Pin pre-form prior to insertion). 12 mm x 20 mm specimens with the Z-Pins in the centre were cut out of the cured laminate. Specimens, glued to the test rig with cyanoacrylate glue were tested with the crosshead speed set at 0.5 mm/min. This method was similar to one of the methods of preparing specimens presented in this thesis. Also “pseudo laminate” specimens were tested, where the composite was replaced by layers of 2 mm polycarbonate sheets. These sheets were “drilled” with a titanium Z-Pin – the heat created by the drilling action enabled the Z-Pin to penetrate and bond to the polycarbonate. Insertion of the carbon Z-Pins into polycarbonate were also attempted but the results were not consistent.

Pull-out tests (Mode I)

In the pull-out tests 12x20x4 mm brick specimens were glued between the T-shaped parts of the rig, see **Figure 2.28**. Swinging and rotation of the grips were restricted.

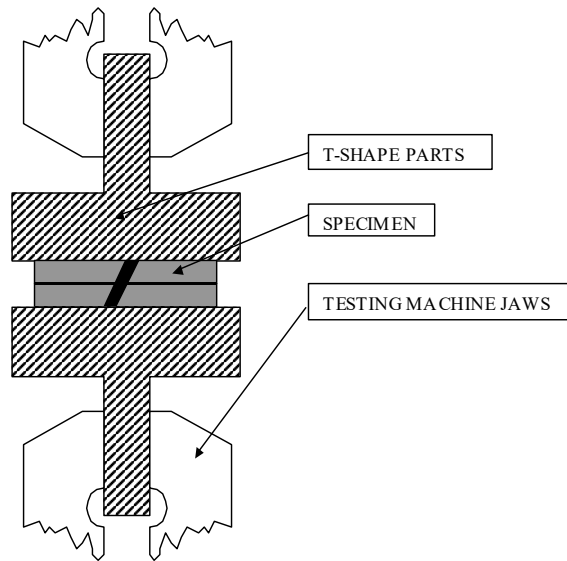


Figure 2.28 Single Z-Pin pull-out test, T-shaped parts of the rig, [72]

The author assumed that the Z-Pin pull out process was “friction controlled”. Two stages of pull-out were identified:

- Elastic stretch and debonding stage
- Frictional slip stage

Typical pull-out curves were shown in **Figure 2.29**.

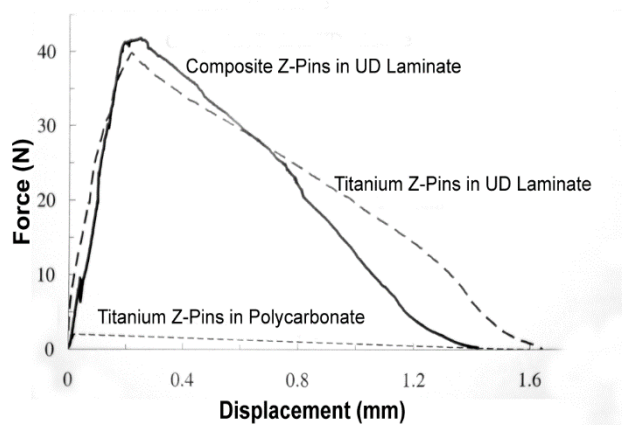


Figure 2.29 Typical experimental pull-out curves, [72]

It was observed that in the first stage the pull-out force grows essentially linearly with displacement as seen on the idealised pull-out curve in **Figure 2.30** representing the pull-out force F versus pull-out displacement u . At the end of this first stage the force reaches a value

F_a which the author reported to be the maximum force during the whole process. The “adhesion stress” τ_a , which was assumed to be uniform over the pin length, was defined as:

$$\tau_a = \frac{F_a}{2\pi r L} \quad \text{where } L - \text{debonded length of the Z-Pin, } r - \text{radius of the Z-Pin.}$$

A similar equation was shown in the work by Nairn et al [60], representing interfacial shear strength τ_{ISS} in single fibre pull-out tests and microbond tests.

$$\tau_{ISS} = \frac{P}{2\pi r l_e}$$

where

P – peak force, required to debond the fibre (function of embedded fibre length),

r – fibre radius

l_e - embedded fibre length

The author observed that the second stage (the frictional slip phase) could begin either with an instant drop in the force, when debonding force F_a was higher than initial friction force (curve a , see **Figure 2.30**) or without the drop (curve b , see **Figure 2.30**). The pull-out force then drops gradually to zero. Because of the variation of the value of “frictional stress” τ_w , the average value of the stress was calculated from the work A of the friction force, see **Figure 2.29**. The value of the smeared frictional stress was calculated using:

$$\tau_w = \frac{2 \cdot A}{\pi \cdot r \cdot L^2}$$

where A was the work of friction force, taken as the area under the frictional part of F - u curve calculated using trapezoidal rule.

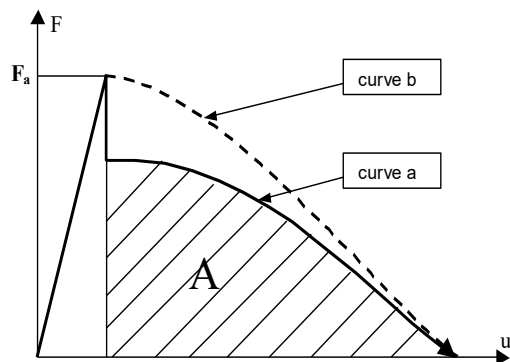


Figure 2.30 Idealised pull-out curve, [72]

The elastic stretch stage of pull-out process was in general linear, however some non-linearity was observed in the titanium Z-Pins cases.

There was only limited number of pull-out curves shown in [72] as the author seemed to focus on shear-out process. No examples of the curves showing the drop of the force at the end of the elastic stretch phase were discussed.

Table 2.10 shows the values of τ_a and τ_w the author determined from his experimental results. Z-Pin material does not seem to affect adhesion stress τ_a . The friction stress τ_w was greater for composite Z-Pins (**Table 2.10**). It was observed that in general the Z-Pin was pulled-out from one side of a specimen only.

Z-Pin material	τ_w [MPa]	τ_a [MPa]
T300/BMI	19.2 ± 4	7.3
Titanium	15.4 ± 3	7.4

Table 2.10 Friction stresses of titanium and composite Z-Pins from pull-out tests on IMS/924 Z-Pins, 2 mm embedded length, [72]

Shear-out tests (Mode II)

The purpose of the shear out tests was to characterize deformations of the Z-Pins during shear-out process. The specimens, 10x10x4 mm, were glued between the loading blocks with the glued surfaces parallel to the direction of the acting force, as shown in **Figure 2.31**. The loading blocks were mounted on pins such that the load line lay in the crack-plane of the specimen for a specimen thickness of 4 mm (the specimens were sanded to 4 mm thickness with the crack exactly in the middle of the thickness). A U-shaped steel block (**Figure 2.31**) was included in the rig to restrict the opening displacement. The specimens were tested in “opening displacement allowed” (with the U-shape piece removed) and “opening displacement restricted” modes. Because of the variation of the Z-Pin insertion angle φ (**Figure 2.31**), the specimens were divided into two groups:

- “Against the nap”, where $\varphi < 0$
- “In the nap”, where $\varphi > 0$

Typical load-displacement curves obtained in the shear-out tests are shown in **Figure 2.32** and **Figure 2.33**. Note that there was no information available about the fibre direction in specimens. The general behaviour of the tests of [72] are summarised in **Table 2.11**. No conclusions about the insertion angles being close to 0° were made.

In the results reported in [82], the effect of “snubbing” [79,47] was noticed. The “snubbing” was described as the growth of friction due to Z-Pin being bent and deflected into the laminate. This effect was believed to be responsible for stability (load increase) of the shear-out process at large displacements. A simple friction model (frictional traction τ_i) was believed to be valid for pull-out and shear-out at small displacements. For higher displacements the effect of “snubbing” and “enhanced friction” τ_e was employed. It was suggested that for the stability of the process the values of both frictional stresses acting on the Z-Pin interface should be: $3 < \tau_e/\tau_i < 10$ and $\tau_e > \tau_i$.

It was also noticed in [82] that pure Mode II could be achieved only in laboratory conditions with restriction of the opening displacement. Interlaminar shear conditions in any other laboratory or real cases were believed to be mixed mode.

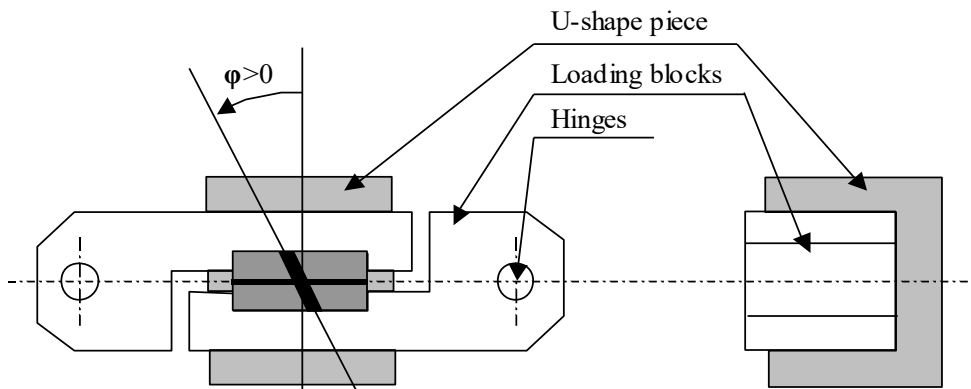


Figure 2.31 Specimen in the testing rig and definition of insertion angle, [82]

Opening displ.	ALLOWED		CONSTRAINED	
Configuration	“in the nap”	“against the nap”	“in the nap”	“against the nap”
Titanium Z-Pins in UD laminate	Z-Pins are pulled-out of the laminate after initial bending and crack opening.	Z-Pins initially bend with a small radius (because of high resistance of the laminate) and Z-Pins break in tension.	After initial debonding Z-Pins are pulled-out with a constant force, higher than in the tests with “opening displacement allowed”.	Z-Pins fail in shear in the crack plane.
Composite Z-Pins in UD laminate	After the debonding phase the opening displacement increases and Z-Pins are pulled-out without a shear failure.	Load was much higher than in the “in the nap” case and leads to shear failure of Z-Pins in the crack plane without a visible opening displacement.	Load reaches high values and Z-Pins fail in shear in the crack plane.	NO RESULTS REPORTED
Titanium Z-Pins in Polycarbonate	The greater the angle “in the nap” the lower the stiffness and high contribution of the pull-out.	Z-Pins “plough” through polycarbonate and then are pulled-out after bending.	NO RESULTS REPORTED	
	Z-Pins are pulled-out from both sides of laminate. Z-Pins bend and after the debonding stage the two halves of the laminate tend to be pushed apart, in the z-direction, by the distorted Z-Pin. The insertion angle ϕ significantly affects the shear-out process. No tensile fracture of the Z-Pins was observed.			
Composite Z-Pins in Polycarbonate	Most of the tested Z-Pins were inserted with angles close to 0°. According to the author, the shear force was highly affected by the friction between Z-Pin and laminate. High insertion angles lead to the failure of Z-Pin; Z-Pins “split” in the crack plane. Z-Pins are damaged in the crack plane while the hole in polycarbonate remains nearly intact.			

Table 2.11 Results of single Z-Pin shear-out tests [72,82]

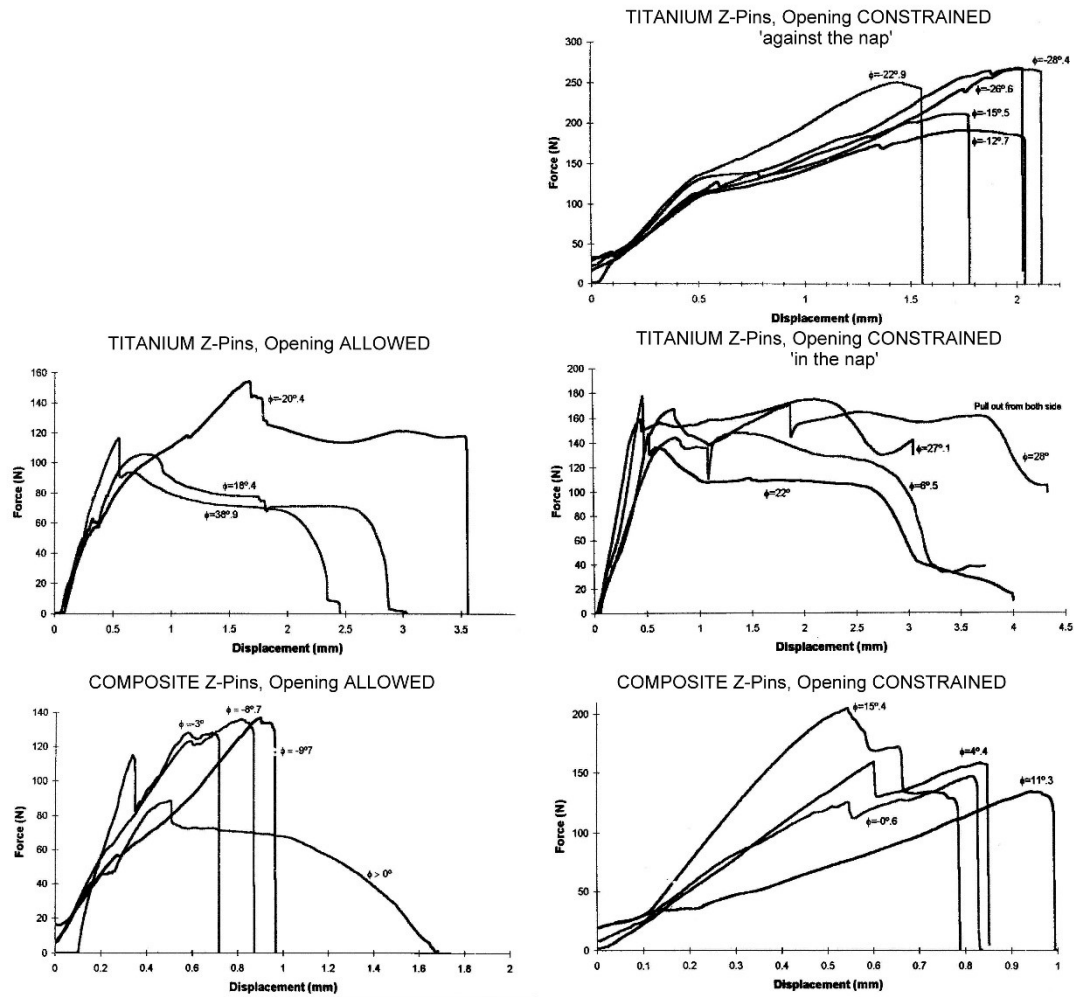


Figure 2.32 Examples of Force vs. displacement plots, [72,82]

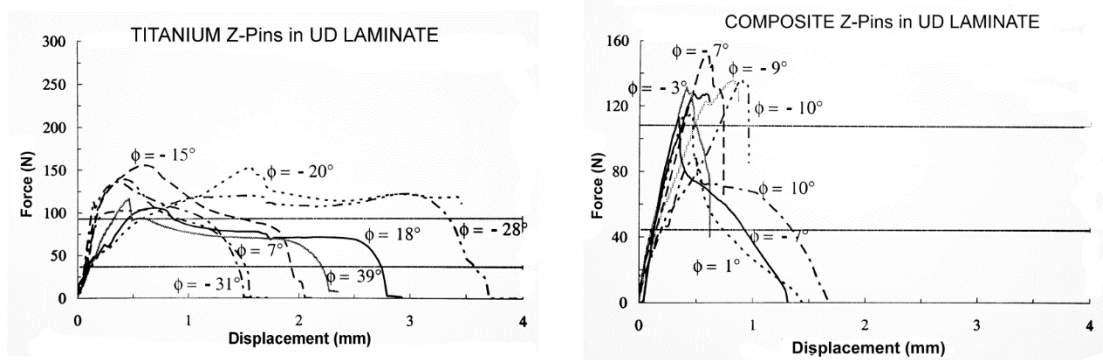


Figure 2.33 Examples of Force vs. Displacement plots, [72,82]

An advanced single Z-Pin (0.28 mm diameter, T300 carbon/BMI) pull-out (Mode I - 0°), shear-out (Mode II - 90°) and mixed mode (Mode I/II - $15^\circ, 30^\circ, 45^\circ$ and 75°) tests were performed by Yasaee [67,48] in order to characterise the bridging mechanisms of a Z-Pin inserted through the thickness of a block of unidirectional (UD) and quasi-isotropic (QI) composite (20 mm x

20 mm x8 mm, 64 plies of IM7/8552) divided at the mid-plane by 16µm PTFE release film (**Figure 2.34**).

The insertion was performed manually by pressing the Z-Pin into warmed (temperature not given) laminate in order to have greater control over the insertion angle (in comparison to standard UAZ insertion). The author assumed that the manual insertion might not be fully representative of the traditional UAZ insertion but the Z-Pins would behave in similar manner regardless of insertion method. However, the offset of insertion angles was still noticeable (mean of $13^\circ \pm 7.5$ for UD and $13.5^\circ \pm 4.5$ for the QI specimens – see **Figure 2.35**). Only specimens of insertion angle below 20° were used. The offset angle was accounted for in calculation of the loading mode “mixity” for each specimen

In the UD laminate $[0_{32}/10//0_{32}]$ an additional ply was added at the mid-plane at 10° , and in QI laminate $[(0/45/90/-45)_{4s}]/[(90/-45/0/45)_{4s}]$ it was ensured that 0° and 90° layers contacted at the mid-plane in order to prevent “nesting” of the fibres.

The pure shear, Mode II testing rig consisted of two parallel sliding sections with the specimen mounted in-between (**Figure 2.36**). Outer guides were used to prevent any opening displacement but an average opening of 0.08 mm was recorded using a non-contact video extensometer. Hence it was not possible to achieve the pure Mode II. If not constrained, the sections could rotate freely. According to the author, the centres of gravity of the blocks were “aligned with the loading line” in order to prevent any damage to the brittle specimens due to mass of the rig.

The mixed mode test rig consisted of upper and lower section with a space for installing the specimens in-between (**Figure 2.37**). The specimens could be mounted to the testing machine axis at 0° to 90° in 15° intervals to achieve various mode “mixities”.

The specimens were glued to the metal sections with cyanoacrylate glue (Loctite), which was applied at the corners of each specimen in order to prevent the glue from contacting the Z-Pin.

The displacement was applied at 0.5 mm/min until failure.

UD specimens in Mode II were loaded in “soft direction” (Z-Pin sheared along the fibres) and “hard direction” (Z-Pin sheared across the fibres). All the mixed mode specimens were loaded in the “soft direction” (Z-Pin sheared along the fibres, through the resin pocket). All the Z-Pins were tested in “with the nap” direction.

The recorded load vs displacement curves (**Figure 2.38, Figure 2.39**) showed high variability, depending on insertion angles, Z-Pin “quality, manufacturing variances and specimen handling” according to the author.

The two stage “bridging traction” was observed (**Figure 2.40**). Strength of the bond between the Z-Pin and the resin was responsible for the linear growth of the force in Stage I. At the end of this stage the Z-Pin was debonded from the resin. Stage II was controlled by the friction between the Z-Pin and matrix.

There was substantial difference between UD and QI specimens. In UD specimens the Stage I was more pronounced, with sharp maximum of 86 N when the Z-Pin debonded, while in QI the Stage I smoothly passed into Stage II without sharp maximum, so the debonding load was difficult to assess. The initial growth of the force was not linear in QI specimens. In both stages the recorded forces were lower in QI than in UD specimens.

According to the author this difference was due to the post-cure thermal constriction of the laminate and the Z-Pins, which is unrestrained in UD laminate and inhibited by the multiple ply orientation in QI laminate due to difference in shrinking along the fibres (lower) and across the fibres (higher). This according to the authors “weakened the pin/matrix interface” and “reduced or eliminated Stage I of the bridging mechanism” in QI specimens.

In the mode “mixities” close to Mode II the UD specimens did not show pull-out, due to the higher strength of the bond between the Z-Pin and resin. Partial pull-out before the rupture was observed in QI specimens, due to their weaker bond.

In Mode I no damage to the pins was reported regardless of the laminate stacking.

In Mode II all the Z-Pins encountered brittle failure, due to bending or shear and no or little pull-out was recorded. No “ploughing” of the Z-Pin through the laminate was observed.

The plots showing Z-Pins pull out energy against the mode angle (representing “mixity” - **Figure 2.41**) revealed three regions: the range of angles at which specimens encountered pull-out (no rupture, high energies), transition region (some specimens ruptured others, scattered energies) and rupture failure region (all specimens rupture, low energies). It was noticed that UD specimens start to rupture at lower angles (11°) than QI specimens (33°).

The absorbed energy seemed to be lower for the specimens loaded in “hard direction” and the author concluded that this might be due to “stiffer response” (Z-Pins rupturing easier over a harder edge), however the amount of specimens was limited.

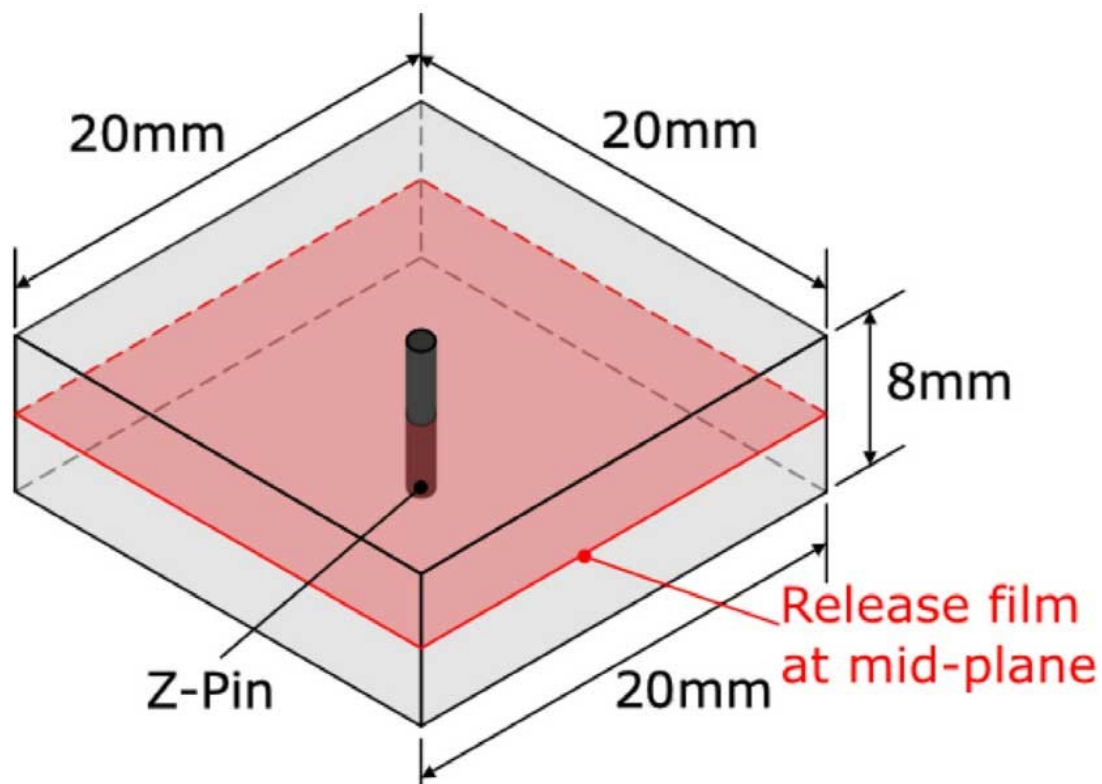


Figure 2.34 Specimen with release film inserts at mid-plane dimensions before testing, [67]

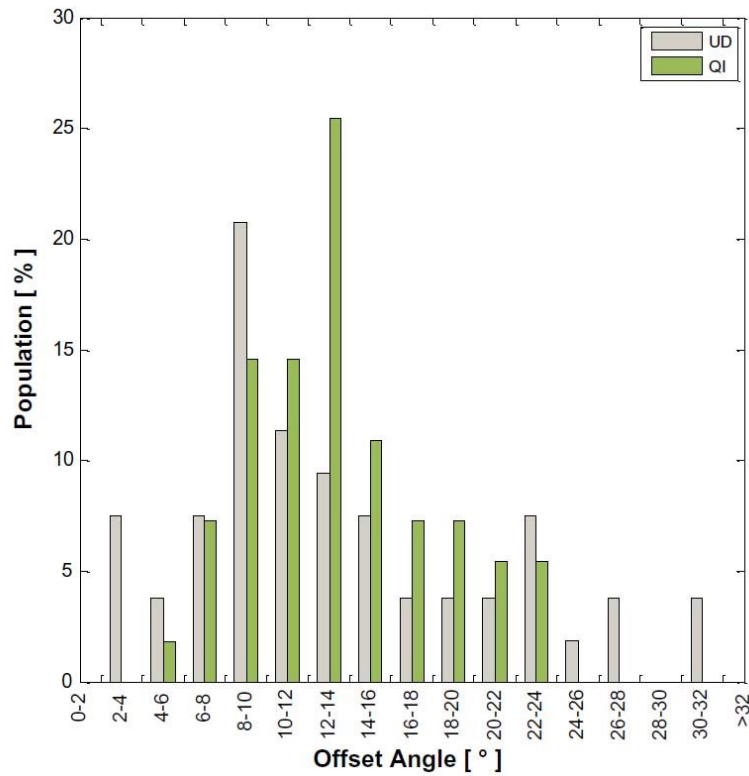


Figure 2.35 Population of pin offset angle after the manufacturing process, [67]

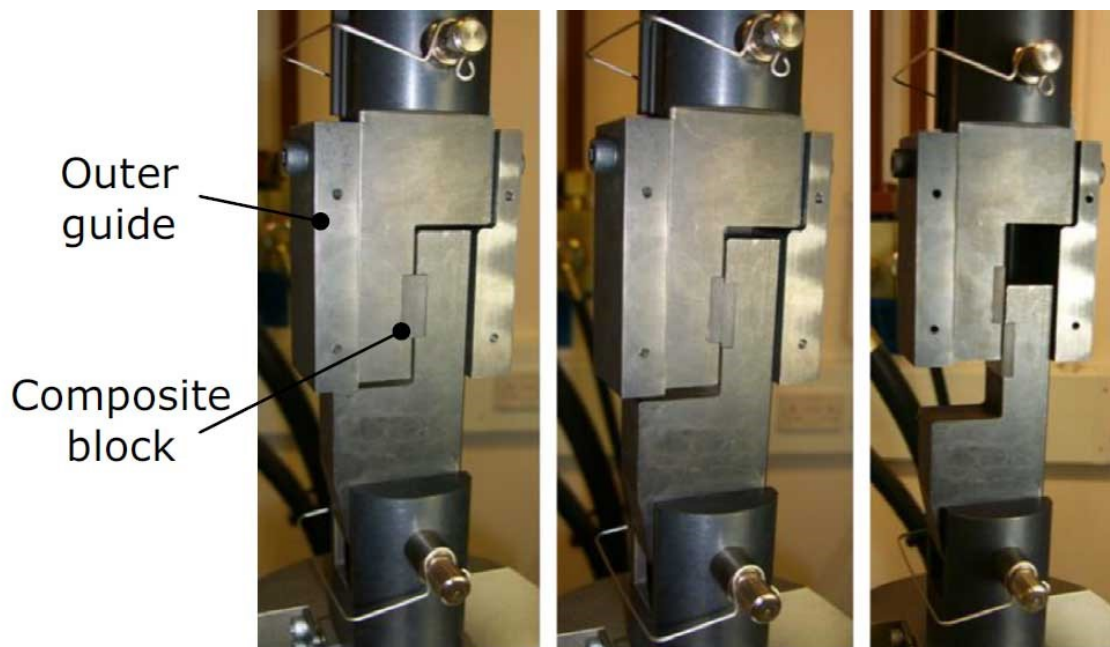


Figure 2.36 Fixture for the Mode II shear testing, highlighting the movement of the loading blocks inside the outer guide and the relative sample position, [67]

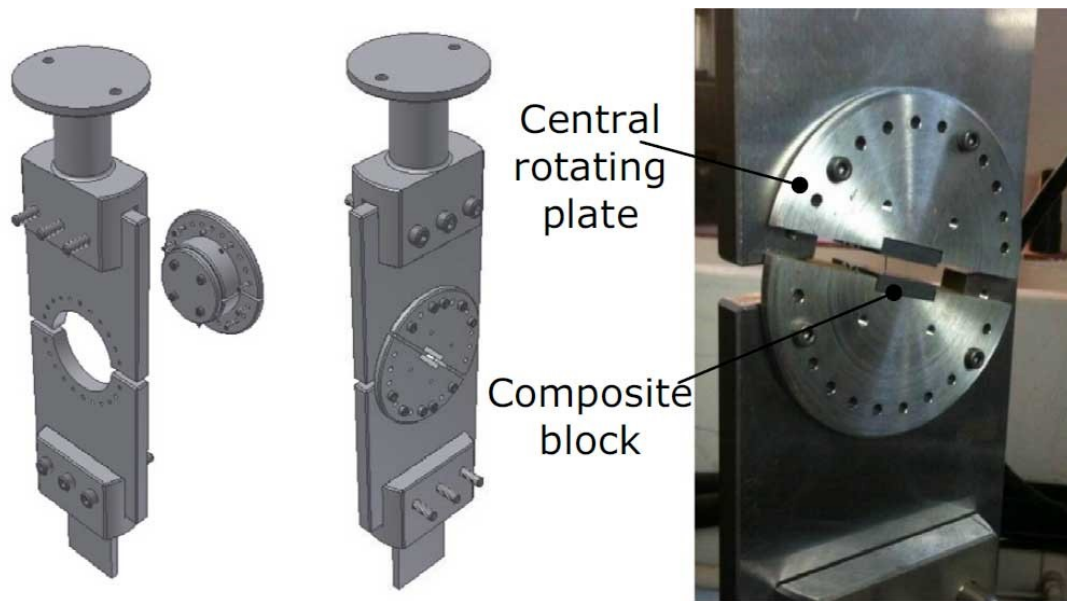


Figure 2.37 Fixture for the mixed mode I/II testing, [67,48]

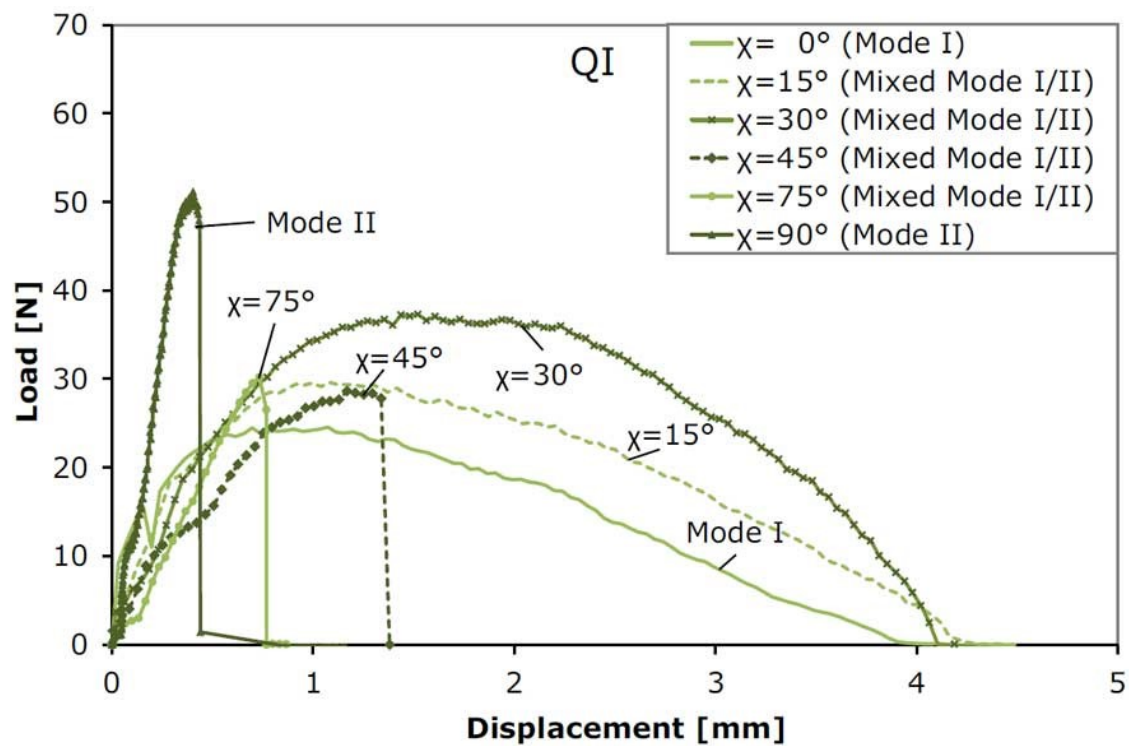


Figure 2.38 Representative QI laminate load vs. displacement results, [67]

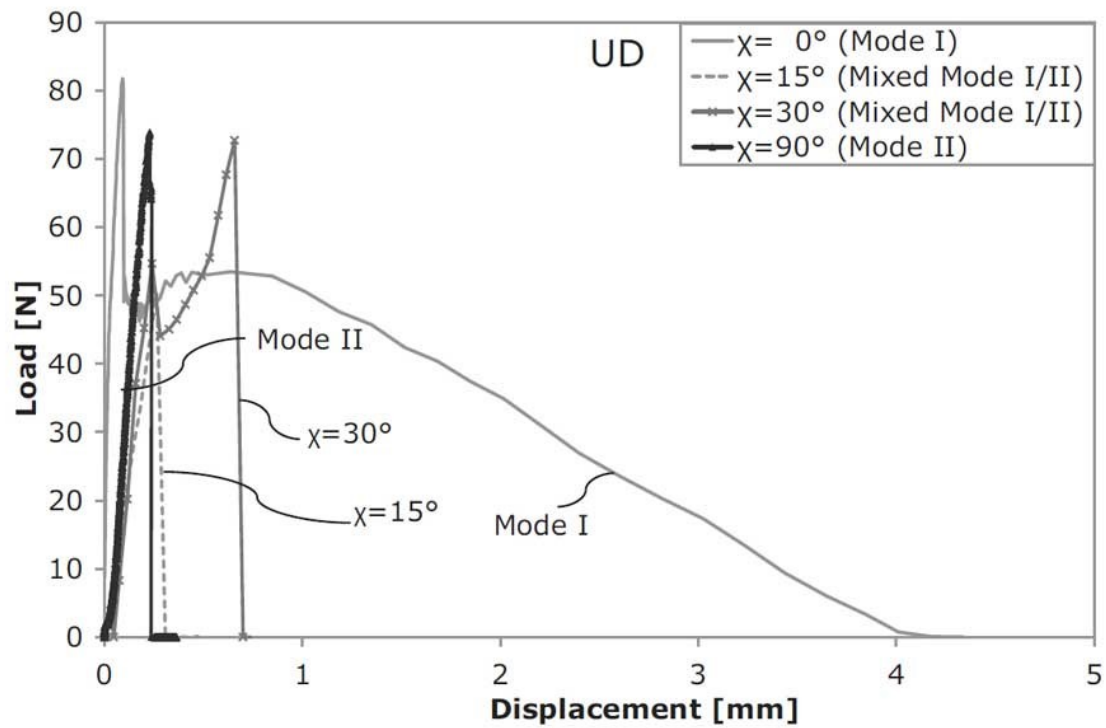


Figure 2.39 Representative UD laminate load vs. displacement results (mixed mode and Mode II curves from sample loaded in “soft” direction) , [67]

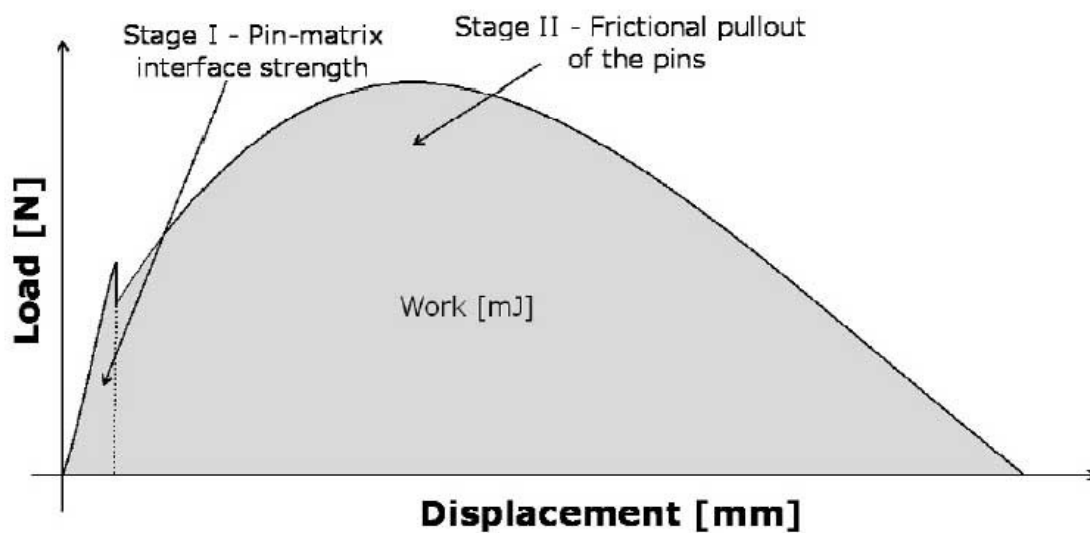


Figure 2.40 Two stage bridging mechanism in mode I and some mixed mode I/II cases, [67]

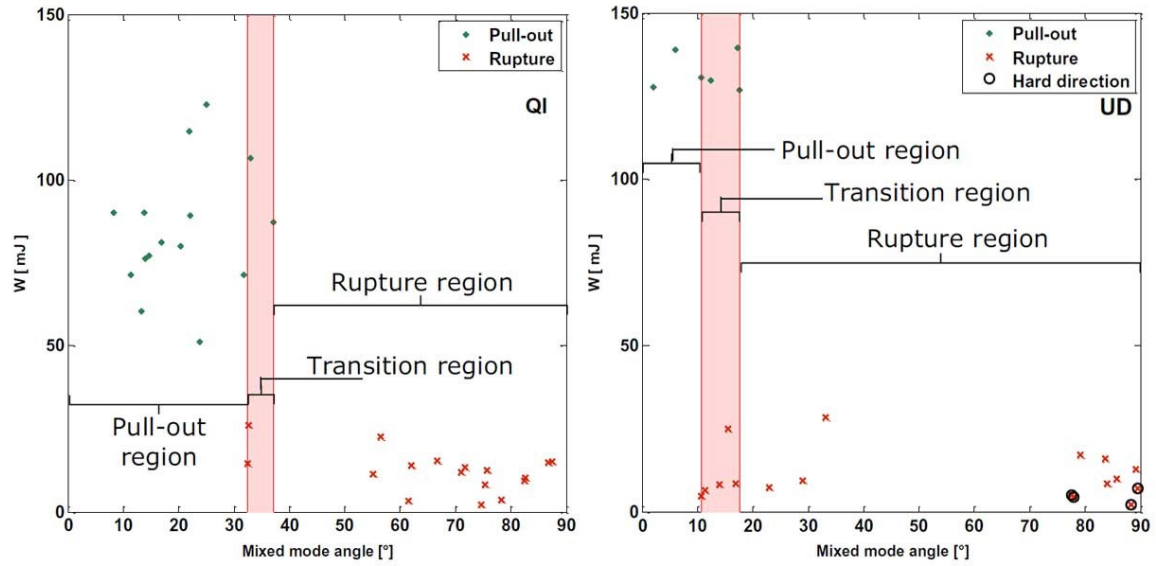


Figure 2.41 Absorbed energy vs. corrected mixed mode angle for failure/pull-out of Z-Pins in QI and UD laminate, [67]

2.6.4 SUMMARY

A variety of the Z-Pin pull-out, shear-out and mixed mode tests have been reported in the literature. The approach of gluing the specimen consisting two parts of QI or UD laminate joined with a Z-Pin (or group of Z-Pins) between the metal coupons was generally adopted. The testing rig based on Arcan et al [83] was utilised in the mixed-mode tests. For the Mode II loading conditions the specimens were held between two metal blocks sliding against each other, with the lateral movement (opening displacement) constricted or allowed.

In case of pull-out tests, the results of early experiments [72,82] seemed different than the recent ones [67,48]. The early experiments results show linear or nearly linear growth of the force to a maximum during the first phase, followed by a gradual decrease of the force during the second phase. The growth of the force was attributed to the elastic stretch combined with debonding, which seemed to occur during the entire initial phase.

The recent pull-out results show linear growth finished with a sharp maximum. Contrary to the previous observations, it was assumed that the Z-Pin was fully bonded with the laminate during this first phase of linear stretch, and debonding occurred rapidly at the end causing an instant drop of the force [81,80,48,67]. Also, the later tests show a substantial growth of the force after the first sharp maximum (in many cases to the higher values than the first maximum). This

secondary growth was attributed to the “snubbing effect” causing “enhanced friction” between the edge of the laminate at the delamination and the bent Z-Pin sliding along. This effect was confirmed by the latest FE modeling [68])

The bending of the Z-Pin during pull-out was assumed to be due unavoidable scatter in Z-Pin insertion angles, reported by all the authors. The insertion angles caused by commonly used UAZ insertion method were reported to vary from 2° to 30° averaging at 13° - 14°.

In the latest test results the difference between pull-out from UD and QI laminate was noticed and attributed to the different stress surrounding Z-Pin caused by the post-cure thermal contraction: unconstrained compression in UD laminate and tensile stress in QI laminate, caused by the mismatch in thermal expansion coefficients along and across fibres in subsequent layers of laminate.

In case of shear-out tests the results were more consistent and showed the failure of the Z-Pin due to shear and bending at or close to the delamination surface. No or little pull-out was reported. In the early tests the effect of the Z-Pins ”ploughing” through the laminate was observed in case of the Z-Pins being sheared “in the nap”, but such effect was not observed in the more recent tests. It was also reported that the specimens, in which the Z-Pin was sheared along the laminate fibres (through the resin pocket) failed at slightly higher displacements than the ones sheared across the fibres. This was attributed to the softness of the resin dominated edge.

The mixed mode tests results, show a range of mode “mixities” for which the Z-Pins encountered full pull-out (no rupture), the transition range, where Z-Pins showed shear- or pull-out behaviour randomly, and the high angles range, where Z-Pins ruptured, as in shear-out.

2.7 OVERALL SUMMARY OF LITERATUR REVIEW

Among the many methods of improving interlaminar toughness, z-pinning seems to be the most promising, offering significant increase of the delamination resistance, at relatively low cost, with the ability to be used with prepreg based laminates.

Tests and FE analysis seemed to agree that the z-pinning has little influence of the crack initiation, however offers a considerable capability for inhibiting the crack propagation and enhancing the load carrying capacity of the structure after the delamination.

Physical tests and FE models also seem to agree on the negative influence of the Z-Pins on the in-plane mechanical properties, due to the fibre waviness, crimp, resin rich pockets or fibre breakage. Increase in both the Z-Pin diameter and z-pinning density have a detrimental effect on the in-plane properties. Best effects were achieved using Z-Pins of small diameters at a z-pinning density not exceeding 4%.

The reported damage of the internal microstructure of the laminate was attributed to the commonly used insertion method (UAZ), based on pushing a rather blunt Z-Pin into the laminate aided with ultrasonic vibrations, which locally heat the laminate. Worth noticing was the scatter in z-Pin insertion angles of Z-Pins, ranging from 2° to 30° (averaging at 13° - 14°). Also, the UAZ insertion method depends on using pre-forms, which greatly increase the price of z-pinning. An alternative method of Z-Pin insertion is presented later in this thesis. Any losses in the in-plane properties were, however, greatly compensated by the increase in the delamination resistance.

In the recent publications, the load-displacement curves, representing the “bridging law”, derived for Mode I, mixed mode and Mode II loading conditions during physical tests seemed to agree with the results of the FE modelling. A substantial difference in the behaviour was observed between the UD and QI laminates.

In case of the Mode I (or mode “mixities” close to pull-out) the initial growth, controlled by the strength of the Z-Pin interface, was followed by a rapid drop, when the Z-Pin debonded. While in UD laminates the growth was linear and culminating in a sharp maximum, in case of

the QI laminate the growth was less steep and the maximum not as sharp. This phenomenon was attributed to the difference in post-cure stress around the Z-Pin: compressive in case of UD laminate, and tensile in QI, due to the mismatch in thermal coefficient of fibre and resin.

This initial phase was followed by the friction controlled second phase, characterised by either the gradual decrease in bridging force, or secondary growth and then gradual decrease. Most authors attributed this secondary growth to the “enhanced friction” or “snubbing” of the slightly bend Z-Pin (it was noticed that due to scatter of insertion angles the pure Mode I was practically never observed).

Mode II was controlled by the failure of the Z-Pin due to shear or bending and showed gradual growth of the force ending with a rapid drop, when Z-Pin ruptured.

For the range of low mode “mixities” the Z-Pins showed the character similar to the Mode I, and for high mode “mixities” the curves showed Mode II character. A range of transitional “mixities” were characterised by a high scatter in results, due to part of the curves showing pull-out and part shear-out character.

The analysis of the energy consumed across the loading modes shows that high energy was observed for the Mode I and low mode “mixities”, characterised by full pull-out of the Z-Pin. High “mixities” and Mode II, where the Z-Pin ruptures due to shear or bending, were characterised by much lower energy. In the transitional “mixities” a slight increase of the energy was observed, which was attributed to part of the Z-Pins encountering simultaneous pull-out and internal splitting of the fibres due to shear, which consumed additional energy. The internal splitting of the fibres along the Z-Pin without the rupture led to formation of a “brush shape”.

3 EXPERIMENTAL DETAILS

3.1 OVERVIEW

In order to investigate the behaviour of Z-Pins bridging a delamination, single Z-Pin pull-out, shear-out and mixed mode tests were designed. Initially the Z-Pin pull-out tests based on [72] were performed. For shear-out and a range of mode “mixities” a new multi mode testing rig was designed, similar to the one used in [67] with additional features allowing for control of the opening displacement in shear-out tests with springs.

The standard UAZ Z-Pin insertion method was initially used. However after observation of unacceptable quality of the produced specimens, mainly acute and unpredictable Z-Pin insertion angles or lack of though the thickness penetration of the laminate, an alternative manual, needle assisted, insertion method has been developed and later used in the majority of the tests.

Over 400 specimens were produced and tested for the purpose of this project. Four different panels, of quasi-isotropic (QI) or unidirectional (UD) layup containing a delamination film, were manufactured and Z-Pinned using the UAZ and manual insertion methods.

The specimens prepared from QI and UD laminates, containing a single Z-Pin or group of four Z-Pins of two different diameters (0.28 mm and 0.51 mm), with a range of embedded lengths (1 mm, 1.5 mm, 2 mm, 2.5 mm or 3 mm) were tested in pull-out, shear-out and mixed mode (30°, 45°, 60°, 70° and 80°).

In the case of shear-out, the opening displacement (in the direction perpendicular to the applied force) was controlled with springs of three different stiffnesses.

Four different preparation methods were used for the manufacture of Z-Pinned laminate specimens:

- Method A - UAZ Insertion - Excess Z-Pins removed from pre-form before Z-Pinning
- Method B - UAZ Insertion - Excess Z-Pins removed from prepreg panel before preconsolidation
- Method C - Manual Insertion - Z-Pinned after preconsolidation (panel heated up to 50°C)
- Method D - Manual insertion - Z-Pinned directly after laying up

3.2 MATERIALS

For the experiments reported in this project the prepreg was IM7/8552 unidirectional carbon-epoxy and the Z-Pins were T300/9310 in diameters of 0.28 mm and 0.51 mm.

The material properties for the Z-Pin (based on data from Aztex, the manufacturer) and for the carbon-epoxy laminate are shown in **Table 3.1**. Three different types of Z-Pin pre-form were utilized:

- 0.28 mm Z-Pin diameter, 0.6% areal density
- 0.51 mm Z-Pin diameter, 2.0% areal density (“grey” Z-Pins)
- 0.51 mm Z-Pin diameter, 6.7% areal density (“brown” Z-Pins)

	Z-PIN T300/9310	COMPOSITE IM7/8552		
	Z-PIN	COMP.	FIBER	RESIN
E_{11} [GPa]	141.3	164.1	276	4.67
E_{22} [GPa]	7.17	11.7	-----	4.67
E_{33} [GPa]	7.17	11.7	-----	4.67
G_{12} [GPa]	4.37	5.1		
G_{23} [GPa]	2.60			
G_{31} [GPa]	4.37			
ν_{12}		0.34		
ν_{23}				
ν_{13}		0.34		
Strength 11 [GPa]		2.72	5.15	
Strength 22 [GPa]		0.111		
Elongation		1.62%	1.81%	
Density [kg/m ³]		-----	1780	1301

Table 3.1 Material properties of the composite and Z-Pins used in this project (according to [43, 76] and manufacturer’s internet resources).

3.3 Z-PIN INSERTION METHODS

3.3.1 OVERVIEW

The two most commonly used manufacturing processes for inserting Z-Pins into most types of polymer matrix composites are

- Ultrasonically Assisted Z-Pin insertion (UAZ)
- Autoclave insertion

For the research described in this thesis, a unique insertion method was also applied. It was based on manual insertion of Z-Pins into holes made in the laminate before cure or after pre-cure with a sharp steel needle. This process will be called “Manual insertion” in this thesis.

Also another method, based on shooting Z-Pins into a prepreg panel with an air gun was briefly investigated. This method will be referred to as “Air gun insertion”.

3.3.2 UAZ INSERTION

In the case of UAZ insertion (**Figure 3.1**) the pins can be inserted into a laminate:

- before cure (in the case of prepreps or RFI process)
- before resin injection (in the case of RTM moulding)

An extra pre-curing consolidation process is recommended before inserting the pins in the case of prepreps. The aims of this process are:

- to debulk the freshly laid-up laminate
- to consolidate the prepreg assembly close to the intended thickness of the laminate
- to make the prepreg assembly stiff enough to minimize the fibre/ply damage (waviness) during insertion process

The ultrasonic pinning device, called an ultrasonic hammer (**Figure 3.1**), is composed of a power supply, a transducer, a signal booster, a compressed air system and an insertion horn. Ultrasonic vibrations increase the temperature of the pins, soften the resin of the prepreg assembly and so facilitate insertion. Normally 20kHz transducers with the amplitudes of 25 to

50 μ m (for insertion of composite Z-Pins) or 25 to 90 μ m (for metal Z-Pins) are used. The horn is the part of the hammer which is in contact with pins during the pinning process. The footprint of the horn used in this project was 15x40 mm, but horns in different shapes are available for pinning of areas which are difficult to access. The booster and the transducer allow the amplitude of the vibration of the horn to be changed. The compressed air system drives the whole assembly down and presses against the pre-form for insertion. The pressure can be applied in two stages (each stage started manually by pressing the button). The entire device is mounted on a gantry. The gantry allows positioning the hammer above the flat, steel surface of the support table where the panel to be reinforced is laid.

Before the insertion the pieces of pre-form are cut to the shape of the area to be reinforced. The prepreg assembly to be reinforced is laid on the surface of the support table. The pieces of the pre-form are put on the surface of the panel, base foam down. Because of the vibration of the ultrasonic horn there is a problem of Z-Pins being pushed out of the pre-form in the area surrounded the horn position. Hence, the pre-form upper surface should be covered by an adhesive tape to prevent this effect. Patches, slightly smaller than the footprint area of the horn, should be left uncovered in order to provide direct contact between the horn and the Z-Pins being inserted.

Once the laminate stack is prepared, the insertion starts by locating the horn footprint on the top of the pre-form (support foam) on the first area to be reinforced. The ultrasonic vibration is then activated, the first stage pressure (lower) is applied, the support foam collapses and Z-Pins are driven into the laminate. When the movement of the horn stops (support foam is collapsed, base foam is intact) the second stage pressure (higher than the first) is applied, the base foam collapses and the Z-Pins are driven further into the laminate until the process stops completely (both foams are fully compacted). Insertion is carried on over small areas corresponding to the patches not covered by the tape. Because of the thickness of the compressed foam, which remains after the insertion, the full length of the Z-Pins cannot be inserted. The compressed foam is removed and the excess pin length is cut with specially designed sharp tool. If the desired depth is not achieved then the remaining foam may be removed and the pins (the ends of the pins, sticking out of the laminate, unsupported) may be inserted deeper in the last stage. The criteria for the process completion may be:

- Visible marks on the bottom face of the laminate (requires removal of the laminate from the support table)
- Complete collapse of the foam
- Complete insertion of the pins (whole length)
- Crushing of the ends of the pins

An areal density of up to 5% and an insertion depth of up to 25 mm (Cartié, [72]) may be achieved. However, the process of pinning of large areas may be laborious due to small area of the horn footprint. Many parameters affect the insertion process:

- Temperature
- Pressure applied in the first and the second stages of insertion
- Quality of the pre-forms
- Thickness of the reinforced laminate

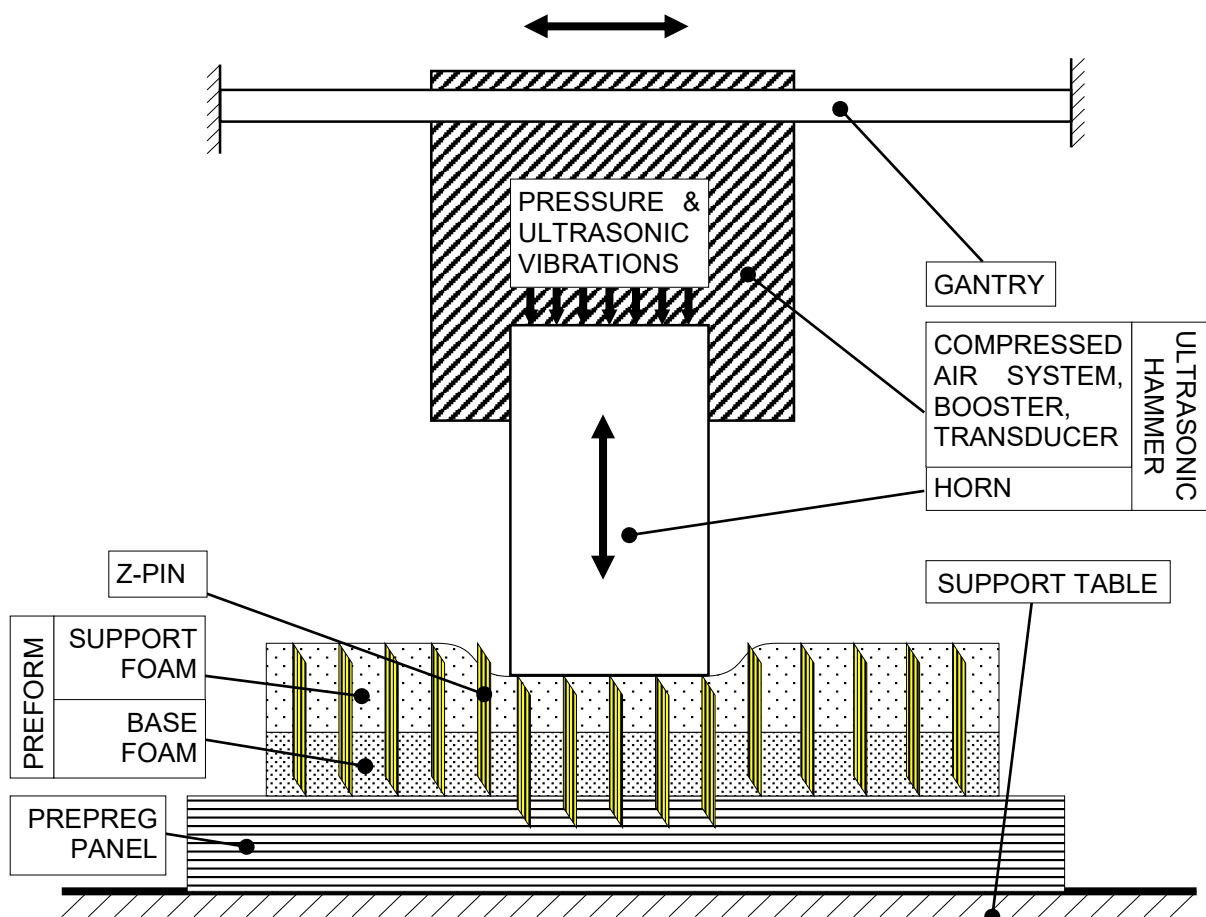


Figure 3.1 Z-Pinning process (UAZ machine) – drawing based on the machine used in QinetiQ, Farnborough

The main drawback of this method seems to be high dependence of the pinning quality on the skills of an operator (high human factor). The pinning depth, pinning angle or even the percent of Z-Pins being fully inserted depended strongly on the combination of factors like applied pressure, the way in which the pressure was applied (sharp or gradual increase), the hammer's footprint areal density and diameter of the Z-Pins. Achieving the perfect combination of those factors can be rather difficult - even for a highly skilled operator.

Also, regardless of the pinning quality, Z-Pins being pushed into the laminate caused significant in-plane and also out-of-plane fibre distortion in the laminate. During the insertion process fibres of the laminate are being pushed aside and also downwards by the rather blunt tips of the Z-Pins. This effect seems to be unavoidable during UAZ insertion.

Due to the extremely low areal density of Z-Pins in the pre-form used in these experiments (approximately 1 Z-Pin per 3cm^2 of the pre-form, see **Chapter 3.3**) the pre-forms were particularly soft and collapsed rapidly under the pressure. This caused most of Z-Pins to be broken before they had fully penetrated the prepreg assembly, causing vast loss in specimens and material. Because of this problem a unique manual insertion method described in the next section, was developed and applied for the purposes of the experiments conducted for this thesis.

For the purpose of this thesis the UAZ device located at QinetiQ (in Farnborough, UK) was used. Only part of the specimens (an initial attempt) were made of the panels z-pinned using this UAZ device. Most of the specimens tested, were created using manual insertion method.

3.3.3 MANUAL INSERTION

The general idea of this method was direct insertion of the Z-Pins into the laminate, without using pre-forms or sophisticated and hardly accessible UAZ machine, in simple laboratory conditions.

A stainless steel polished sewing machine needle, approximately 0.8 mm in diameter at its thickest point, was used to perforate the prepreg assembly. Because of its sharp point (much sharper than tapered tip of a Z-Pin), gradually increasing thickness and smooth polished surface

the needle easily slides into the laminate, gently pushing fibres apart, and causing negligible out-of-plane fibre misalignment. For perfect alignment of the perforation (perpendicular to the laminate surface) the needle was locked in a chuck of a table-mounted drill press (via a smaller chuck, more suitable for a small diameter needle, see **Figure 3.2**). Also, as the needle was axially symmetrical, it did not encounter a change in direction during insertion. The sharp end of a Z-Pin made by cutting it at an angle caused a tendency to offset z-pinning angle, when using UAZ insertion or any type of insertion based on pushing a Z-Pin directly into the laminate. This problem was reported and partially addressed by careful manual insertion of each Z-Pin into the laminate by Yasaee et al [67], however a substantial z-pinning angle offset was still measured.

The prepreg assembly was placed on an approximately 10 mm thick soft wood panel on the working table of the drill. The needle was driven through the thickness of the laminate and into the chip wood panel, and back, using the drill handle.

Z-Pins, taken out of their pre-forms, were placed into the holes, which were large enough to enable manual insertion of the Z-Pins, without any pushing force. The ends of the Z-Pins sticking out of the surface of the laminate were cut off with a precision wire cutter (see **Figure 3.2**).

It was observed that the perforation holes stayed open for some time (depending on the temperature) and then gradually closed, tightening the fibres of the laminate around embedded Z-Pins.

To avoid any possibility of damage of the Z-Pins tips by the aluminium plates used in autoclave, sheets of soft rubber, approximately 2 mm thick, were placed on the both surfaces of the prepreg panel prior to the curing procedure.

This method proved to be extremely easy and cost effective. Only small pieces of pre-form were used as a source of Z-Pins. Specimens made by manual insertion seemed to be of the highest quality for the insertion angle and insertion depth (100% of the Z-Pins were fully embedded). Also the lowest out-of-plane fibre distortion was observed (see **Chapter 4.2** for microscopic observations).

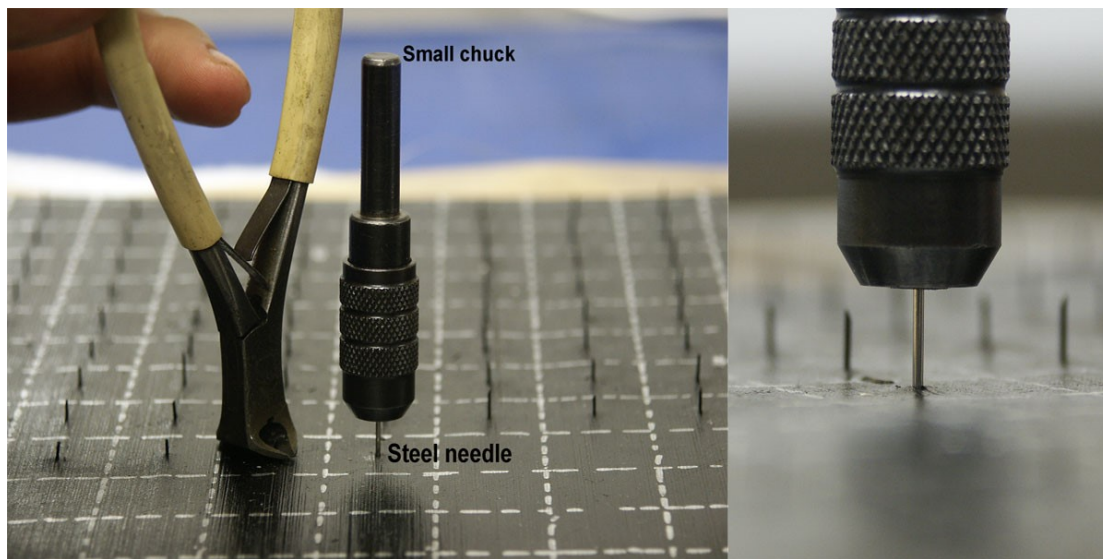


Figure 3.2 Manual Z-Pin insertion – the actual needle, chuck and Z-Pinned panel made at the Imperial College London for the sole purpose of this thesis.

Most of the specimens tested were created using manual insertion method in the workshop at Imperial College London, using prepregs and Z-Pin rodstock supplied by Aztex and equipment available in house.

3.3.4 AUTOCLAVE INSERTION

In the case of autoclave insertion, also called pressure insertion, the pre-form is placed on top of the uncured laminate, with a release film between the laminate and the pre-form and a backing plate on the top of the preform. A combination of pressure and heat makes the pre-form collapse and pushes the pins in. The remaining foam is then removed at the end of the curing process.

This autoclave process is preferable for large area reinforcements. However, because of the high pressure required, only relatively low pinning densities can be used (usually less than 1%). The method is now rarely used - the UAZ insertion has become preferred option.

This method of insertion was not used in the experiments performed for this thesis.

3.3.5 AIR GUN INSERTION

This method was used only for trial purposes.

Z-Pins were shot into the laminate using 4.5 mm calibre air pistol. The air gun used in the experiment was UMAREX hand held, CO₂ cartridge driven pistol. A standard lead pellet being shot with this gun was supposed to leave the nozzle at approximately 110m/s.

The experiments were conducted with composite Z-Pins (T300/9310) and also with mild steel needles, used in place of Z-Pins. These Z-Pins were embedded into 4.5 mm diameter rubber or plastic cylinders, as shown in **Figure 3.3**. The pins were shot into a 3 mm prepreg panel (IM7/8552).

In order to find out the best shooting method, the nozzle of the gun was held at various distances from the surface of the uncured prepreg panel. The experiment was carried out with a panel at room temperature as well as heated up to approximately 50°C.

Using this experimental method none of the Z-Pins were fully embedded into the laminate. The composite Z-Pins were crushed on contact with laminate. The steel pins were either inserted only partially or were bent and even twisted (especially when stiff plastic cylinders were used). The temperature of the panel did not seem to have any influence. No damage was observed on the surface of the laminate.

It is possible that the pressure in the barrel, and hence the speed, was not high enough for the Z-Pin insertion. However, considering the high viscosity of the resin (and laminate) it may be that Z-Pins should be driven slowly into the laminate rather than shot in at high speed.

Regardless of the negative results of this trial, it might be worth repeating the experiment with a gun of much higher energy (and so higher nozzle speed).



Figure 3.3 A pistol and a Z-Pin in rubber cylinder used in air gun insertion method.

3.3.6 SUMMARY

The initial set of the specimens were prepared using standard UAZ insertion and tested, in order to make the tests comparable with the tests reported in the literature. However, due to exceptionally poor specimen quality (acute insertion angles, partial penetration of the laminate) an alternative manual insertion was used for most of the specimens tested for the purpose of this thesis. The methods of specimen manufacture used in this thesis are explained in the following section.

3.4 SPECIMEN MANUFACTURE AND PREPARATION

3.4.1 INTRODUCTION

Specimens consisting of two parts of the laminate, divided by the delamination foil and connected with a Z-Pin or a group of Z-Pins were used in this thesis. Initially the standard UAZ insertion method was used but, as noted earlier, due to low quality of z-pinning achieved using this method, alternative methods of z-pinning, especially for the purpose of this thesis, were tested.

3.4.2 METHOD A – PULL-OUT

All the specimens produced using Method A were used in pull-out tests. A panel of 56-ply (7 mm thick) laminate were laid-up manually:

- Unidirectional (UD) - $[0^\circ]_{56}$ 150 mm x 200 mm x 7 mm
- Quasi-isotropic (QI) - $[[0^\circ/\pm 45^\circ/90^\circ]_s]_7$ 150 mm x 200 mm x 7 mm

A 20 μm PTFE release film was located at the depth of 16 plies (2 mm) - in one part of the panel, and 24 plies (3 mm) - in another part, from the pinning surface in order to introduce a crack. After laying up every four layers, the prepreg stack was de-bulked using a mangle. The next stages of the process to produce a cured, Z-Pinned panel are summarised in **Table 3.2**.

1.	EXCESS Z-PINS REMOVAL FROM THE PRE-FORM	
2.	PRECONSOLIDATION	30 mins dwelling: Vacuum ~90 kPa No pressure Temperature 70°C
		Cooling to room temperature
3.	Z-PINS INSERTION - UAZ	
4.	FINAL CURING	20 mins dwelling: Vacuum 90 kPa Pressure 606.7 kPa Temperature 180°C
		Cooling to room temperature

Table 3.2 Manufacturing process of a laminate with Z-Pins – Method A.

Prior to the pinning process the excess Z-Pins were removed from the pre-form with pincers. A single Z-Pin or four closest Z-Pins were left in the pre-form in such a pattern that 14 mm square specimens would be cut from the cured panel with a single Z-Pin or group of four Z-Pins in the middle. The pattern of Z-Pins removed and remaining in the pre-form is shown in **Figure 3.4**. Such prepared pre-forms were cut into appropriate pieces to cover the working area of the prepreg panel.

The Z-Pins were inserted into the prepreg using the UAZ insertion method described earlier, using the UAZ device available at QinetiQ. The prepreg laminate, covered with non-stick peel-ply separation material on both sides (the same material as used during autoclave curing process), was put directly on the support table of the UAZ machine.

The pieces of pre-form containing pins of different diameters and spacing were held in place with Sellotape. Due to the vibration, the Z-Pins around the footprint of the ultrasonic horn tend to work their way out of a pre-form. To avoid this occurring an additional layer of Sellotape was used to cover the whole upper surface of the pre-form. An ultrasonic horn of dimensions 2in x 1in was used, so the Sellotape covering the pre-form was cut in 2in x 1in rectangular patches. Prior to pinning the Sellotape was removed from the patch to be pinned so that the working surface of the horn was in direct contact with the tips of Z-Pins.

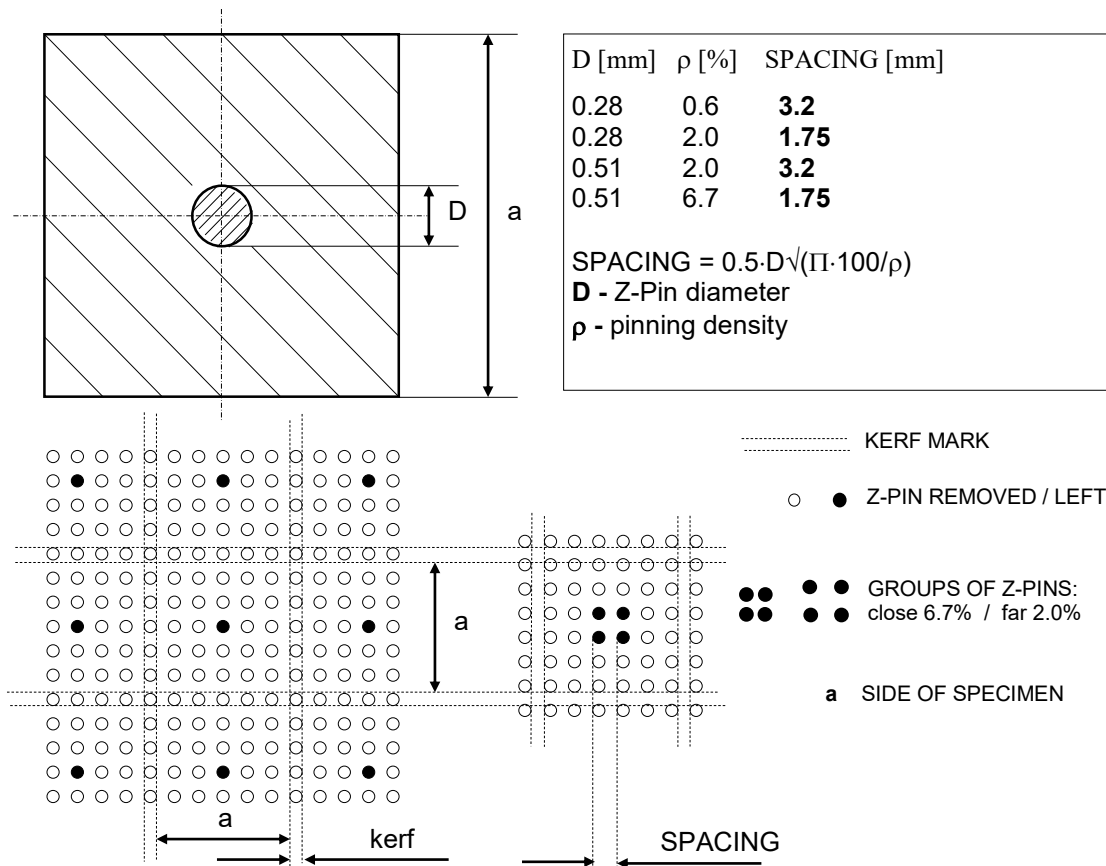


Figure 3.4 Geometry of the Z-Pinning pattern - the way of cutting single and four Z-Pins specimens out of the panel (similar for all methods).

The Z-Pins were inserted in three-stage process:

- Low pressure pinning to initiate the insertion process. The pressure was set at ~310 kPa with the ultrasonic action turned on. The process was carried out until there was no visible further movement of the horn.
- High pressure pinning to drive the Z-Pins fully into the laminate. The pressure was set at ~620 kPa and again the ultrasonic action was on. The process was continued until the horn no longer moved.
- Inserting the remaining ends of the Z-Pins (after removal of the compressed foam). The ends of Z-Pins not supported by the foam were driven into the laminate with lower pressure ~310 kPa with the help of the ultrasonic action. The process was continued until the horn rested on the surface of the laminate. At this point the Z-Pins were either fully driven in or broken.

There is a possibility of the formation of the chamfer (see **Figure 3.5**) at the upper tip of the Z-Pins in contact with the horn. In this project the Z-Pins pins, over 10 mm long in the pre-forms, were fully inserted. At the end of the process the horn rested on the surface of the composite. Because the Z-Pins were pushed all the way through the thickness of the panel, there was also possibility of chamfer formation on the other ends of the Z-Pins, in contact with the support table.

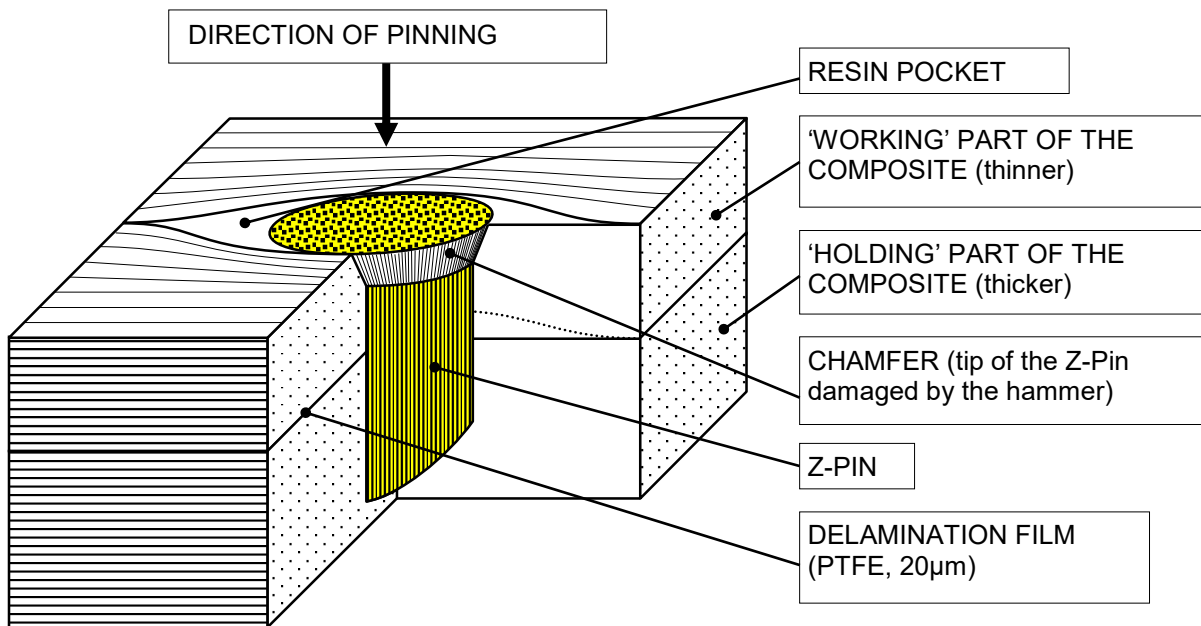


Figure 3.5 Single Z-Pin specimen with visible chamfer, fibre waviness caused by the insertion of Z-Pin, working and holding part – Method A.

Due to a large amount of the Z-Pins being removed from the pre-form, the support foam tended to collapse rapidly under the horn after the pressure had reached a particular value. This might be the reason for the bad pinning quality, e.g. odd insertion angles or breakage of Z-Pins prior to the full insertion. Also, the contact surface of the horn was smooth, hence slippery for the tips of inserted pins. Together with the weakness of the support foam, it made the pins tilt at the very beginning of the insertion process. Besides the recommended standard insertion pressure (310 Kpa / 620 kPa – as indicted on the installed pressure meter), variations in the insertion pressure (+/- 50% of the recommended value) were tried but it was found very difficult to achieve a suitable pressure: too high a pressure caused rapid collapse of the foam and breakage of the Z-Pins; too low pressure resulted in lack of movement of the horn.

After the pinning process the laminate was finally cured using standard procedure for this material – see **Table 3.2** for the details of the curing procedure.

The cured panels were cut into 14x14 mm specimens with a circular saw 2 mm thick, along previously marked lines (kerf marks), see **Figure 3.4**. There was a single Z-Pin or group of four Z-Pins positioned close to the centre of each specimen.

The PTFE release film divided each specimen into two parts of different thicknesses:

- **Working part** – from which the Z-Pin was intended to be pulled out (2 mm or 3 mm thick)
- **Holding part** –which was expected to hold the Z-Pin during the pull-out process (5 mm or 4 mm thick)

It was found that great number of specimens were unavailable due to imperfections produced during the pinning process. Nearly all the 0.28 mm diameter Z-Pins specimens (except for two) were lost because the Z-Pins were not inserted to the proper depth (most of them did not get to the depth of the delamination film). In most of the 0.51 mm diameter Z-Pin specimens, the Z-Pins went through the delamination film, however in a number of cases the insertion depth was not sufficient to carry out valid tests. The “lost” and valid specimens can be seen at **Figure 3.6**. Out of 108 planned specimens approximately 70 were lost due to pinning imperfections and insufficient pinning depth.

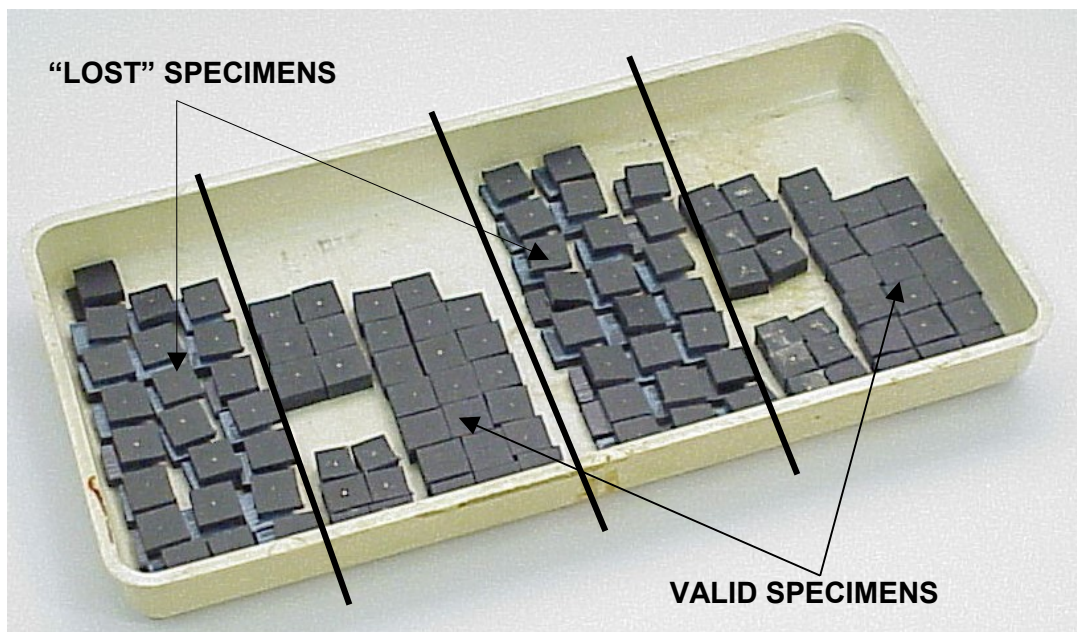


Figure 3.6 Lost and proper specimens prepared using Method A, before the tests.

Only pull-out tests of 0.28 mm and 0.51 mm single and four pin (close and far) specimens, 2 mm or 3 mm pinning depth, using a simple testing rig were performed with this panel.

Quantities of specimens of each type and types of tests performed are summarised later.

3.4.3 METHOD B – SHEAR-OUT

All the specimens produced using Method B were used in shear out tests. Two panels of 48-ply (6 mm thick) laminate were laid-up manually:

- Unidirectional (UD) - $[0^\circ]_{48}$ 150 mm x 200 mm x 6 mm
- Quasi-isotropic (QI) - $[[0^\circ/\pm 45^\circ/90^\circ]_s]_6$ 150 mm x 200 mm x 6 mm

As in Method A, during the layup of the panels the prepreg assembly was de-bulked using a mangle every four plies. A 20 μ m PTFE release film was located in the mid-plane of the assembly in order to introduce a crack. The next stages to produce a cured, Z-Pinned panel are described in **Table 3.3**.

1.	PRECONSOLIDATION	30 mins dwelling: Vacuum ~90 kPa No pressure Temperature 70°C
		Cooling to room temperature
2.	Z-PINS INSERTION - UAZ	
3.	EXCESS Z-PINS REMOVAL FROM PREPREG PANEL	
4.	FINAL CURING	20 mins dwelling: Vacuum 90 kPa Pressure 606.7 kPa Temperature 180°C
		Cooling to room temperature

Table 3.3 Manufacturing process of a laminate with Z-Pins – Method B.

In contrast to the pinning procedure of Method A, the pre-forms were used as supplied by the factory, with no Z-Pins being removed.

The Z-Pins were inserted into prepreg laminate using UAZ insertion method. To avoid formation of chamfers or/and crushing at the tips of Z-Pins on the hard surface of the support table, the panel was laid on a layer of dry glass fibre fabric (about 5 mm thick). The fabric was soft enough for the Z-Pins to penetrate without crushing and hard enough to provide support for the panel and avoid bending of the panel under the UAZ horn compression. An additional layer of the peel-ply was laid on the pinning surface to facilitate the removal of the compressed foam after pinning process.

Similar to the procedure used in Method A, the Sellotape was applied to immobilise the pre-form and to avoid Z-Pins working their way out due to the vibrations. The patches of the Sellotape though, were not removed from the surface during pinning process, which was assumed not to have any influence on the pinning quality, and could help prevent slipping of the Z-Pins on the surface of the horn.

The Z-Pins were inserted in two-stage process:

- Low pressure pinning to seat the Z-Pins. The pressure was set at ~310 kPa with the ultrasonic action turned on. The process was carried out until there was no visible further movement of the horn.
- High pressure pinning to drive the Z-Pins fully into the laminate. The pressure was set at ~620 kPa and again the ultrasonic action was enabled. The process was continued the horn no longer moved.

At the end of the last stage the foot of the horn rested on the surface of the compressed foam – no further pushing was performed.

With all the Z-Pins left intact and the functionality of the pre-form unaffected, the pinning process was much less problematic than in Method A and most of Z-Pins went through the thickness of the prepreg panel without buckling or breakage.

The excess Z-Pins were removed from the prepreg panel, leaving only a single or a group of four Z-Pins in every 19.2 x 19.2 mm square of the panel, (see **Figure 3.4**). This process proved to be extremely difficult and time consuming, as hundreds of Z-Pins had to be removed from

the prepreg manually. The parts of the remaining Z-Pins protruding from the prepreg were cut off with pliers close to the lower and upper surface.

After the pinning process the laminate was finally cured using standard procedure for this material - see **Table 3.3** for the details of the curing procedure.

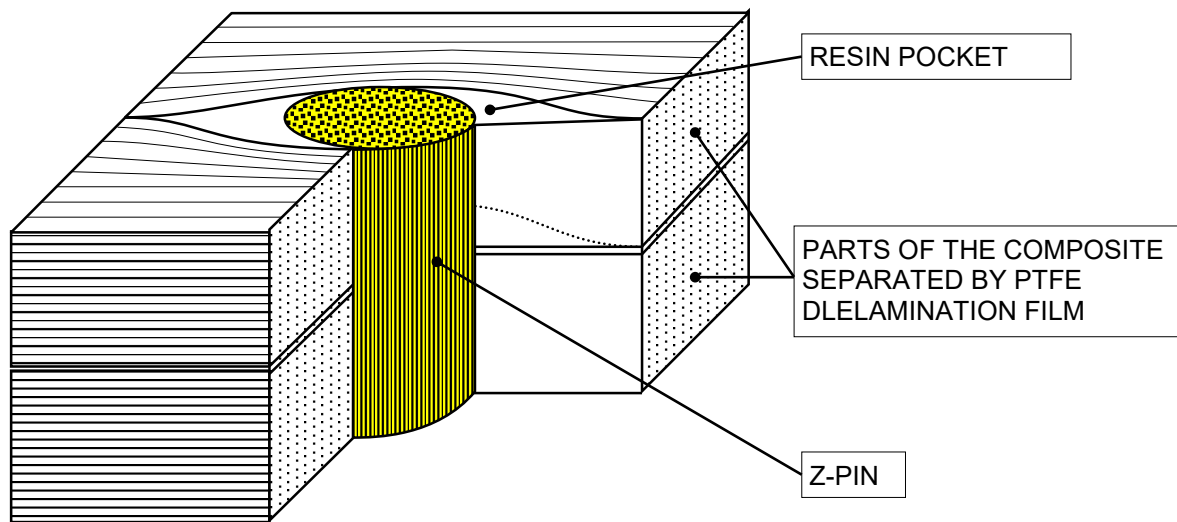


Figure 3.7 Single Z-Pin specimen – Method B, C and D.

There was low probability of the chamfer formation (see **Figure 3.7**) on either side of the prepreg panel due to use of the soft fabric under the panel and the fact that the Z-Pins were not driven to the very surface of the panel. Any possible damage to the upper end of the Z-Pins could be therefore caused when the pin material was trimmed off.

Similar to the Method A case, the cured panels were cut into single, 16 x 16 mm (due to problems with gluing encountered during the Method A tests, the specimens in Methods B, C and D were made slightly bigger) specimens with a circular saw 2 mm thick, along previously marked lines (kerf marks), see **Figure 3.4**. There was a single Z-Pin or a group of four Z-Pins positioned close to the centre of each specimen.

In order to achieve various pinning depths, the specimens were drilled from one side only with a flat-bottomed drill to the desired depth at the Z-Pin position, see **Figure 3.8**. Specimens of four different pinning depths were created: 1.5 mm, 2.0 mm, 2.5 mm and the baseline of 3.0 mm.

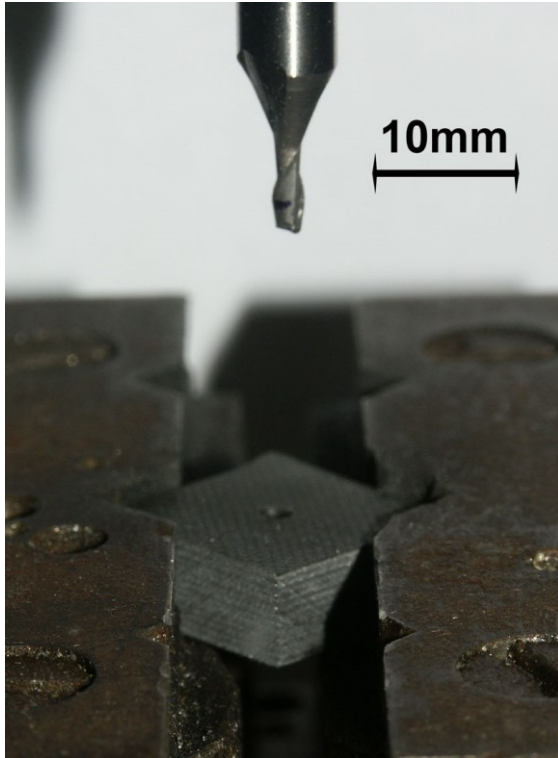


Figure 3.8 Drilling the specimens in order to change pinning depth

The surfaces of each specimen to be bonded to the test rig were abraded with sand paper and cleaned with solvent before gluing to the test rig.

Quantities of specimens of each type and types of tests are summarised later in **Table 5.6**.

3.4.4 METHOD C AND D - PULL-OUT, SHEAR-OUT AND MIXED MODE

The specimens produced using Methods C and D were tested in pull-out, shear-out or mixed mode. Two panels of 48-ply (6 mm thick) laminate were laid-up manually, using the same procedure as in Methods A and B:

- Unidirectional (UD) - $[0^\circ]_{48}$ 150 mm x 200 mm x 6 mm
- Quasi-isotropic (QI) - $[[0^\circ/\pm 45^\circ/90^\circ]_s]_6$ 150 mm x 200 mm x 6 mm

As in Method A, during the layup of the panels the prepreg assembly was de-bulked using a mangle every four plies. A 20 μ m PTFE release film was located in the mid-plane of the assembly in order to introduce a crack.

Instead of standard UAZ insertion method, Z-Pins were inserted manually, using method described earlier.

In Method C the Z-Pins were inserted after preconsolidation (see **Table 3.4**). Z-Pinning (and perforating with a needle) at this stage was believed to cause less damage to the internal structure of the panel than in case of newly laid up prepreg. Also, to make the needle perforation of the pre-consolidated panels easier, the panels were heated up to slightly below 50°C.

In case of Method D, newly laid up prepreg panel was perforated and Z-Pinned, prior to preconsolidation (see **Table 3.5**). Also perforation and Z-Pin insertion was continued at elevated temperature.

There was no particular difference in the results achieved in these two methods. Needle perforation of newly laid up prepreg in Method D seemed to be easier – a slightly lower force was needed to drive the needle into the material.

Because Z-Pins were put manually into the perforations made with a needle, without using any pushing force, there was no damage to the Z-Pins during the insertion process. To prevent any damage during autoclave curing process, sheets of soft rubber were applied to the both sides of the panel, preventing ends of Z-Pins being crushed. Chamfer formation (or any other means of Z-Pin damage) was thus completely excluded.

The panels were cured in the autoclave using the standard conditions for these materials – summarised in **Table 3.4** and **Table 3.5**.

1.	PRECONSOLIDATION	30mins dwelling: Vacuum ~90 kPa No pressure Temperature 70°C
		Cooling to room temperature
2.	Z-PIN INSERTION - MANUAL	Temperature approx 50°C
3.	FINAL CURING (Rubber sheets used)	20mins dwelling: Vacuum 90 kPa Pressure 606.7 kPa Temperature 180°C
		Cooling to room temperature

Table 3.4 Manufacturing process of a laminate with Z-Pins – Method C.

1.	Z-PIN INSERTION - MANUAL	Room temperature
2.	PRECONSOLIDATION	30mins dwelling: Vacuum ~90 kPa No pressure Temperature 70°C
		Cooling to room temperature
3.	FINAL CURING (Rubber sheets used)	20mins dwelling: Vacuum 90 kPa Pressure 606.7 kPa Temperature 180°C
		Cooling to room temperature

Table 3.5 Manufacturing process of a laminate with Z-Pins – Method D.

As in previous cases the cured panels were cut into single square specimens, 16 x 16 mm with a circular saw 2 mm thick, along the marked lines (kerf marks), see **Figure 3.4** earlier. As before the specimens contained a single Z-Pin or a group of four Z-Pins positioned close to the centre.

As for Method B, some specimens containing Z-Pins were drilled out with a flat-bottomed drill in order to achieve a range of pinning depths: 1 mm, 2 mm and 3 mm in this case.

3.4.5 SUMMARY

The specimens for the purpose of this thesis were prepared using four methods. Initially the preparation of the specimens was based on the standard approach – the UAZ insertion (Method A and B). However, due to poor z-pinning quality, high loss of specimens and low quality of the specimens, alternative, needle assisted, manual insertion method, without the necessity of preforms (Method C and D), was developed and used for most of the tests.

- Method A specimens – used for Mode I tests only
- Method B specimens – used for Mode II tests only
- Method C specimens – used for Mode I, Mode II and mixed mode tests
- Method D specimens – used for the mixed mode tests with lateral displacement measurement.

The types and quantities of specimens, as well as types of tests performed are summarised in **Table 5.6**.

QUANTITIES OF SPECIMENS																
METHOD A (specimens 14 x 14 mm)																
	Made	Tested	1 x 0.51 mm	1 x 0.28 mm	4 x 0.51 mm far	4 x 0.51 mm close	Working part 2 mm				Working part 3 mm			UD	QI	
PULL-OUT	9	0	✓				✓							✓		
	9	1		✓			✓							✓		
	12	6	✓								✓			✓		
	12	0		✓							✓			✓		
	6	4			✓						✓			✓		
	6	5				✓					✓			✓		
	9	7	✓				✓								✓	
	9	0		✓			✓								✓	
	12	8	✓								✓				✓	
	12	0		✓							✓				✓	
	6	2			✓						✓				✓	
	6	5				✓					✓				✓	
METHOD B (specimens 16 x 16 mm)																
	Made	Tested	1 x 0.51 mm	1 x 0.28 mm	4 x 0.51 mm far	4 x 0.51 mm close	1.5 mm deep	2.0 mm deep	2.5 mm deep	3.0 mm deep	Low st.spring	Med. st.spring	High st.spring	UD	QI	
SHEAR-OUT	16	9		✓						✓		✓			✓	
	16	10		✓						✓		✓		✓		
	8	5		✓					✓		✓				✓	
	8	4		✓				✓			✓				✓	
	8	3		✓			✓				✓				✓	
	16	12	✓							✓		✓			✓	
	16	12	✓							✓		✓		✓		
	8	5	✓				✓				✓				✓	
	16	4	✓				✓				✓			✓		
	8	4	✓					✓			✓					✓
	8	2	✓						✓		✓					✓
	8	5				✓				✓		✓			✓	
	8	7				✓				✓		✓		✓		
	8	7			✓					✓		✓			✓	
	8	8			✓					✓		✓		✓		
Continued on next page...																

METHOD C (specimens 16 x 16 mm)																	
	Made	Tested	1 x 0.51 mm	1 x 0.28 mm	4 x 0.51 mm far	4 x 0.51 mm close	1 mm deep	2 mm deep	3 mm deep	Low st.spring	Med. st.spring	High st.spring	0.05 mm/min	0.5 mm/min	5 mm/min	UD	QI
PULL-OUT	8	8		✓					✓					✓		✓	
	8	7		✓					✓					✓			✓
	8	7	✓						✓					✓		✓	
	8	7	✓						✓					✓			✓
	8	5	✓					✓						✓			✓
	8	7	✓				✓							✓			✓
	8	6	✓						✓						✓		✓
	8	6	✓						✓				✓				✓
	8	7			✓	✓			✓				✓	✓		✓	
	8	7			✓	✓			✓					✓		✓	
	8	7			✓	✓			✓					✓			✓
	8	7			✓	✓			✓					✓			✓
SHEAR-OUT	8	6		✓								✓				✓	✓
	8	5		✓								✓				✓	
	8	5		✓							✓						✓
	8	5		✓						✓							✓
	8	5		✓						✓						✓	
	8	7	✓						✓			✓					✓
	16	12	✓						✓			✓				✓	
	8	5	✓				✓					✓					✓
	8	5	✓					✓				✓					✓
	8	6	✓						✓		✓						✓
	16	11	✓						✓		✓					✓	
	8	7	✓						✓	✓							✓
	16	14	✓						✓	✓						✓	
	8	5			✓				✓	✓							✓
	8	6				✓			✓	✓							✓
	8	6				✓			✓	✓					✓		✓
	8	5			✓				✓			✓					✓
	8	6				✓			✓			✓					✓
	8	6				✓			✓			✓				✓	
MIXED MODE										30°	45°	60°	70°	80°	Free fig		
	8	7		✓					✓		✓						✓
	16	12		✓					✓		✓					✓	
	16	13	✓						✓		✓					✓	
	8	8	✓						✓								✓
	8	5	✓						✓		✓						✓
	8	8	✓						✓			✓					✓
	8	7	✓						✓				✓				✓
	8	7	✓						✓					✓			✓
	8	5	✓						✓		✓			✓			✓
	8	7	✓				✓				✓				✓		✓
	8	7	✓					✓			✓						✓

Table 3.6 Quantities of specimens used in various tests (There were only a few specimens of the Method D tested).

3.5 TESTING RIGS

3.5.1 OVERVIEW

Initially a simple testing rig, based on [72], was used to perform trial Z-Pin pull-out tests. The specimens prepared using Method A were tested. For the further tests, a multi mode testing rig, based on the model developed by Arcan et al [83], was designed in order to carry on tests under various mode “mixities”, including Mode I and II. This rig was equipped with the facility to control the opening displacement in Mode II conditions with springs of various stiffnesses. A facility to install a laser gauge to measure the opening displacement in any mode was also added. Additionally, a testing rig for pure shear and shear with bending of a single Z-Pin was developed.

3.5.2 SIMPLE TESTING RIG

This simple rig was manufactured for pull-out testing only. Its construction was based on a similar rig used by Cartié [72]. The composite parts of the delicate specimen needed to be pulled apart in the direction of the Z-Pin with the possibility to measure the gap, control the speed of the movement and measure the force caused by the Z-Pin holding the parts together. The size and material used for the parts of the rig was chosen to minimise the influence of the compliance of the rig on the measurement. The way the specimen was mounted in the rig had to ensure that the brittle specimen was not damaged before the onset of the test. The main parts of the rig were two mild steel holding cylinders, between which the Z-Pinned, composite specimens were glued. The cylinders were connected rigidly with the support table and moving cross-head of the Instron test machine, respectively. The pull-out force was measured with a load cell installed between one of the cylinders and the moving cross-head of the machine.

The expected load amplitude was less than 200 N (this expectation was based on earlier simple manual tests as well as on the work of Cartié [72] and so a 500 N load cell was chosen.

The displacement was measured with an external LVDT gauge (see **Figure 3.9**).

The specimens were glued with an instant cyanoacrylate adhesive (Loctite 454,Gel). In each single case both surfaces of the specimen as well as the surfaces of the cylinders were sanded with 500 grade sand paper. (The sand paper was laid on the flat hard surface and the object to

be sanded was moved smoothly in random directions.) The applied adhesive was expected to fill possible small gaps between the surfaces of the specimen and the holding block. However the behaviour of the glue was highly unpredictable, which often resulted in breakage of the glue joint at the beginning of the pull-out process and, hence, the loss of the specimen.

Due to the high fragility of the specimens, the process of gluing them to the cylinders was carried out in-situ. With the rig installed in the machine, a small droplet of the glue was placed on both sides of the specimen. The specimen was located between the cylinders. The moving cross-head of the Instron was then slowly lowered down, compressing the specimen between the cylinders up to a maximum of 100 N.

A number of specimens were lost due to imperfection of the glue joint. This was particularly the case during the four pin specimens tests. As the test progressed a special treatment was applied to the glued surfaces - in addition to sanding and treating with solvent, the surface of the specimen was slightly dampened to improve bonding of cyanoacrylate glue. This treatment noticeably improved the strength of glued joint.

The load cell and a displacement gauge were connected to the computer equipped with software to monitor and store the load-displacement data. The data collected was processed with MS Excel software after the tests.

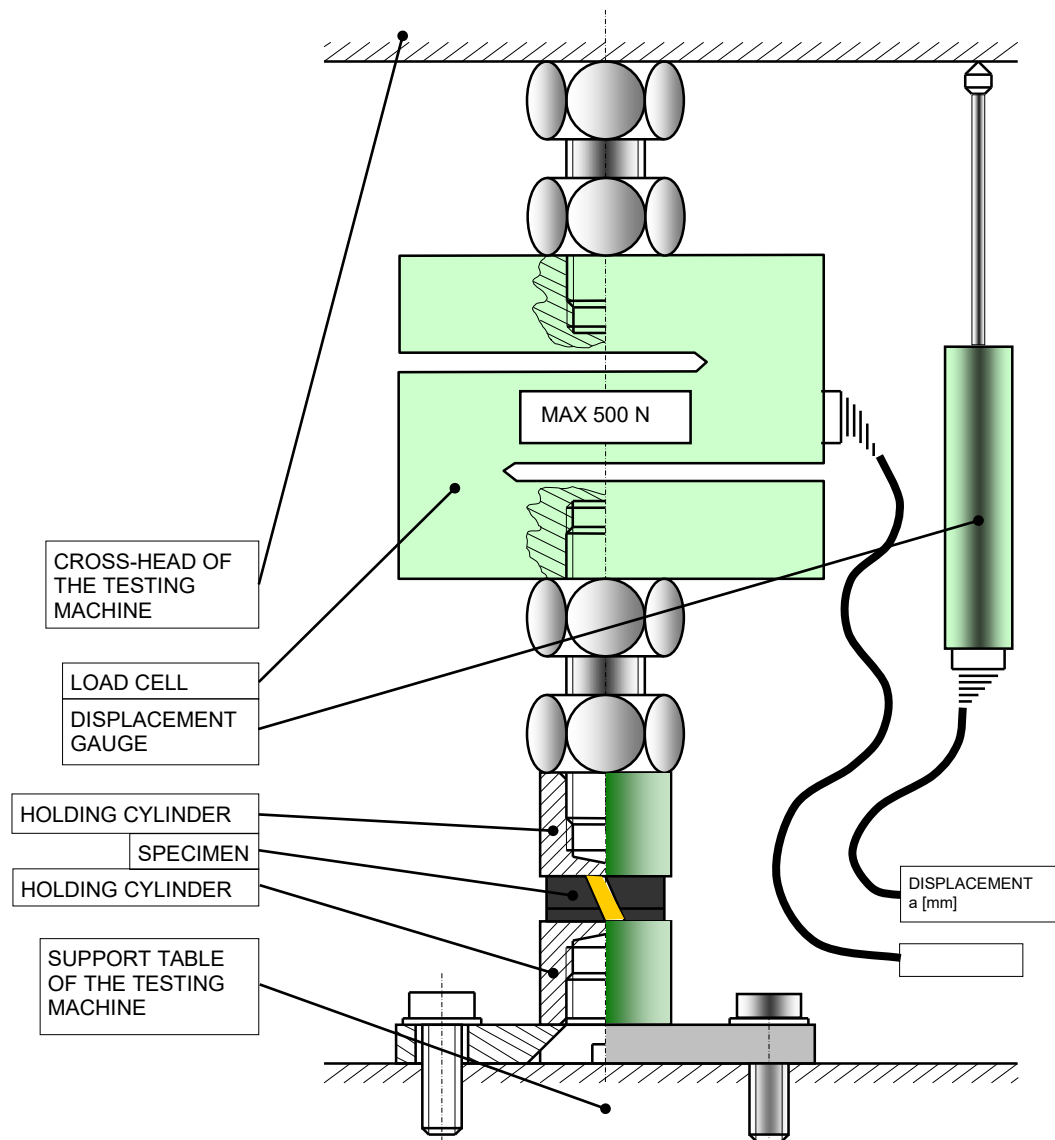


Figure 3.9 The specimen set in the testing rig (pull-out test)

3.5.3 MULTI MODE TESTING RIG

A multi mode testing rig was designed and manufactured to perform pull-out, shear-out and mixed mode tests of specimens containing single or multiple Z-Pins. The design was based on the concept presented by Arcan et al [83] (see **Figure 3.10**) with a modified specimen holder and a feature allowing for installation of springs to control the opening displacement. The test rig set up for the pure shear-out tests is shown in **Figure 3.11**.

The body of the test rig consisted of two main parts machined out of the 22 mm thick plate of rolled steel and then hardened. The parts were connected to the moving cross-head of the testing machine, and to the support table, respectively, through the fork-end fittings. The main parts and the fork-end fittings are connected with a system of pins, which allows a rigid connection or a free, swivelling set up.

The pinned specimens were glued with an instant cyanoacrylate adhesive (Loctite 454, Gel) between the two mild steel dovetail-shaped specimen holders. Rectangular slots in each holder helped to position and hold the specimens. The specimens were first glued to the two dovetail-shaped specimen holders outside of the rig and then the bonded assembly was slid into the dovetail slots in the two main parts of the rig. In order to allow easy mounting of the specimen, and to avoid breakage of delicate specimens, the specimen holders were only a loose fit to the dovetail slots in the main body of the rig. To fix the position of the specimen in the rig the locking pins were provided (as seen on **Figure 3.11**).

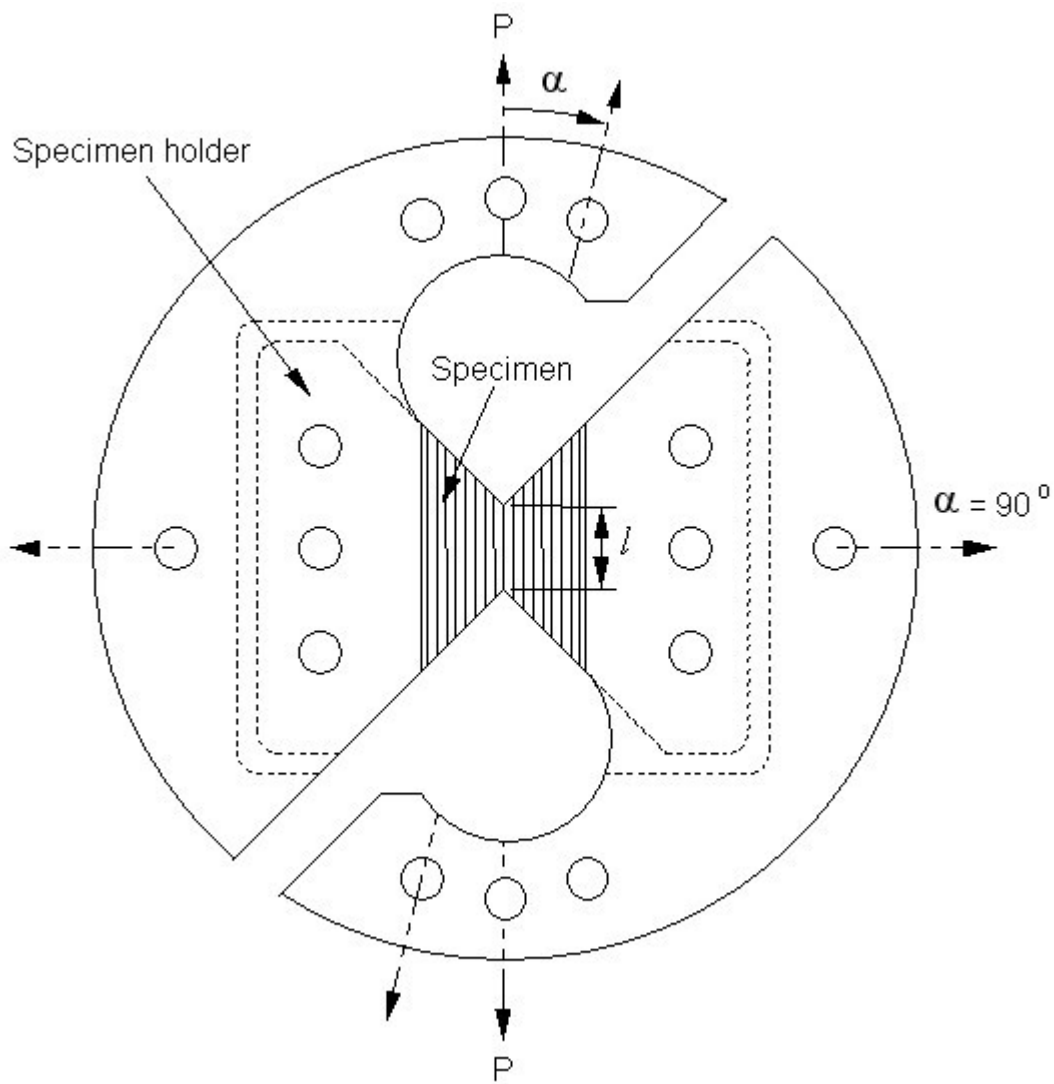


Figure 3.10 The original test rig developed by Arcan, [83]

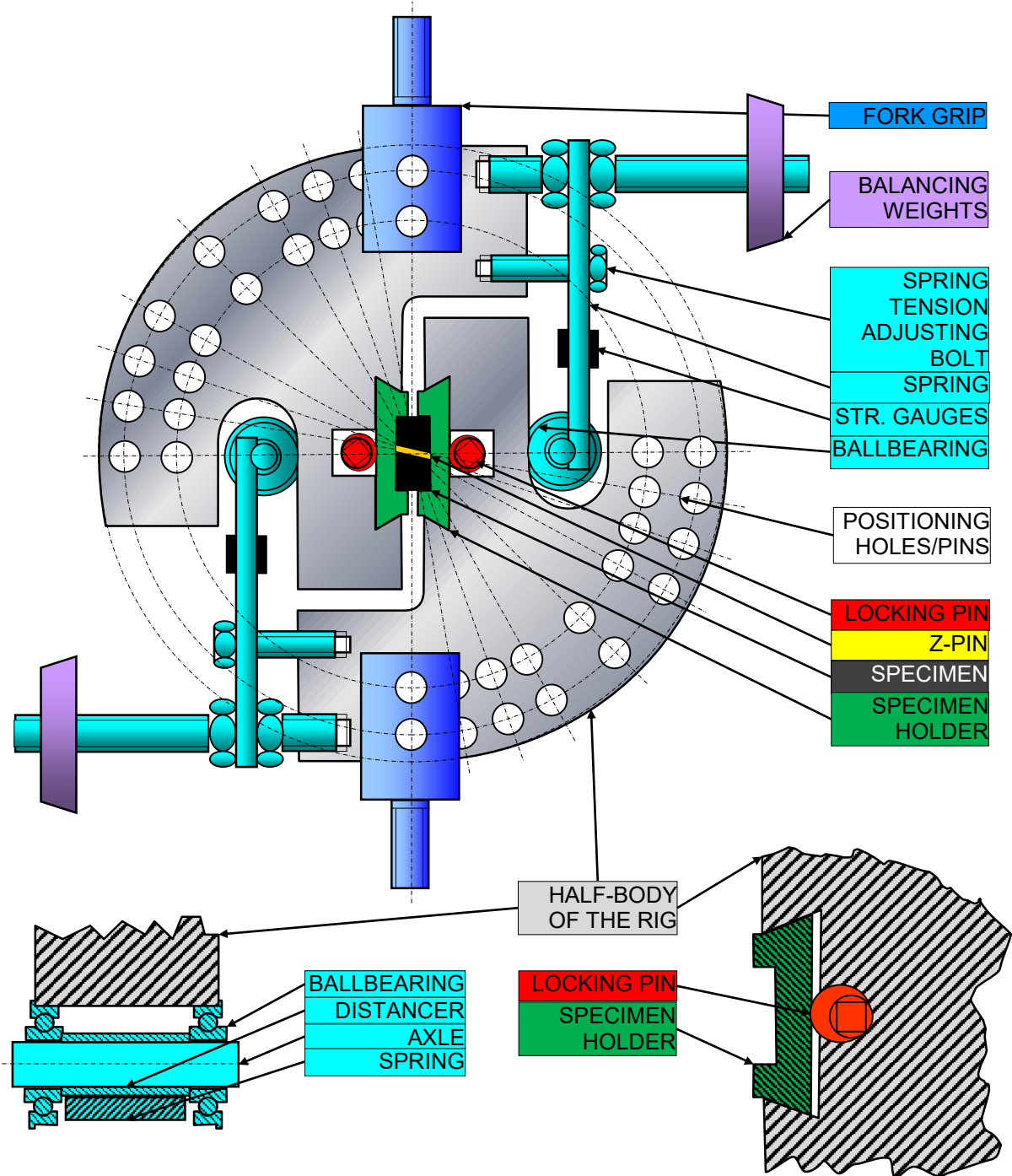


Figure 3.11 Multi mode testing rig: assembly view of the rig in shear-out position, with springs and weights attached.

As noted earlier, two types of set-up are available:

- Rigid set-up – using two fixing pins per fork-end fitting
- Free set-up – using one fixing pin per fork-end fitting

The pin holes are situated along the circular edge of the parts of rig. Using different holes one can attach the rig in nine different angular positions, allowing different test modes:

- 0° – standard pull-out test
- 90° – standard shear out test
- 10°, 20°, 30°, 45°, 60°, 70° and 80° mixed mode tests

3.5.4 OPENING DISPLACEMENT MEASUREMENT AND CONTROL FOR THE SHEAR-OUT TESTS

Multi mode testing rig, in the case of shear-out tests, might be equipped with a pair of springs (see **Figure 3.11** and **Figure 3.12**) in order to measure and/or control the opening displacement and the associated force. The springs, situated symmetrically in relation to the specimen and the rig, provide controlled stiffness in the direction perpendicular to the crack surface of the specimen during shear-out tests. The springs are equipped with ball bearings rolling over the hardened surface of the corresponding parts of the rig, which minimises any possible drag forces. The deflection of the springs, caused by any opening of the specimen during the test, was collected with a system of strain gauges installed on both sides of each spring and connected into a balanced Wheatstone bridge (see **Figure 3.13**).

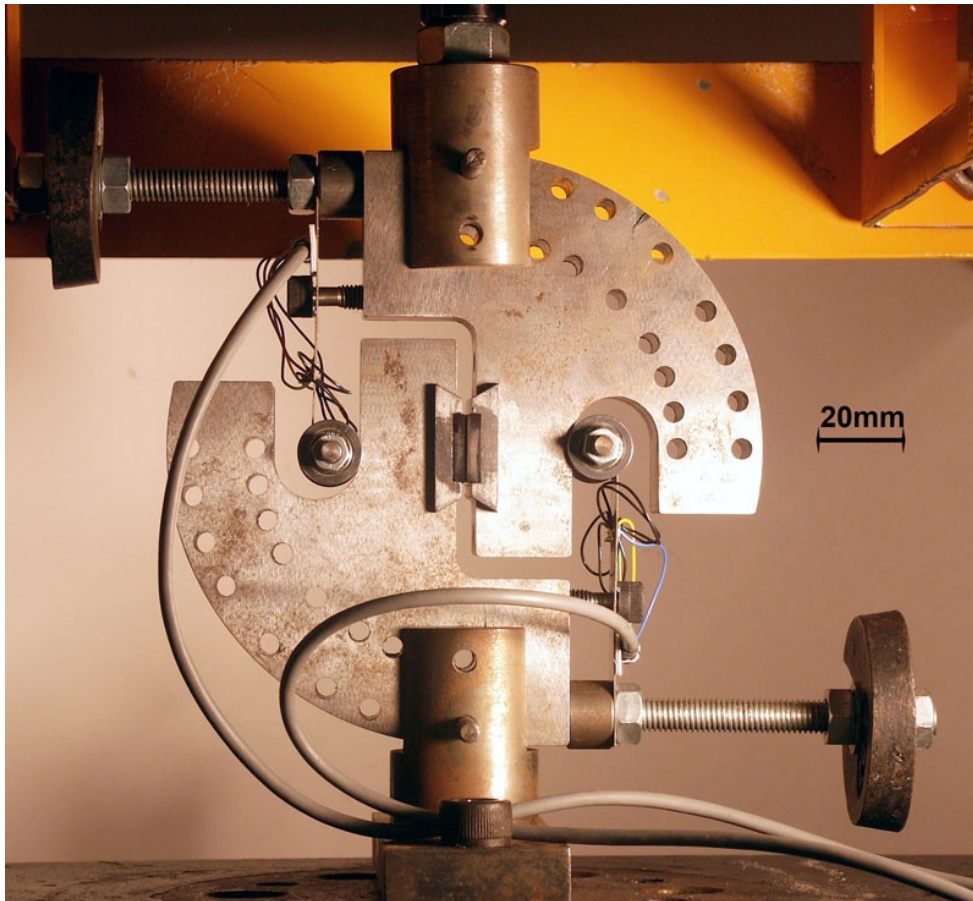


Figure 3.12 Multi mode rig with opening displacement controlling springs and weights attached.

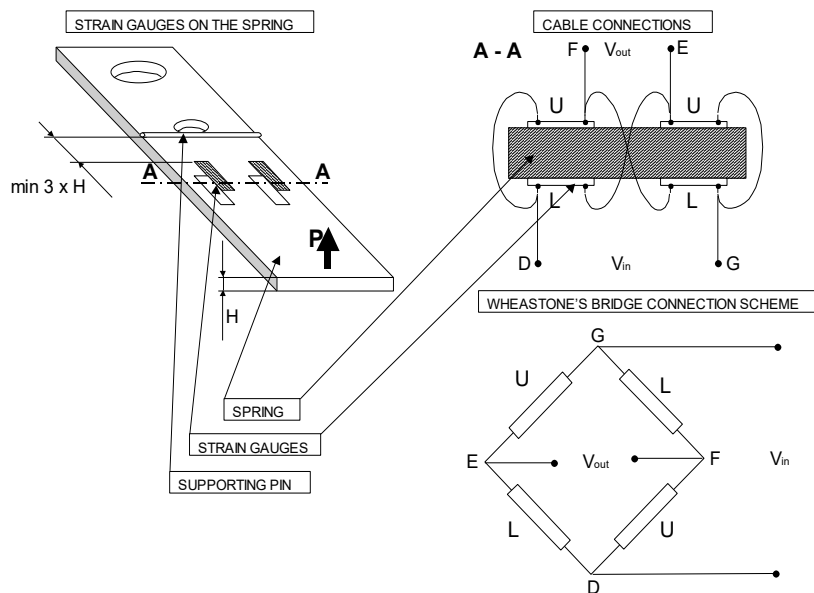


Figure 3.13 Scheme of strain gauge set for opening displacement and force measurement in shear-out tests.

There were three sets of springs used for the tests purpose. The springs were calibrated using the multi mode rig and the Instron machine, each spring separately. Each spring was deflected

and released at the rate of 0.5 mm/min (a few times), in exactly the same manner as it had been during a test. The signals from the strain gauges and the readings of force and displacement from the Instron internal gauges, were recorded. The results of the calibrations were collected in **Table 3.7**. The measured stiffnesses were as follows:

- Low stiffness (soft) spring (W) 0.5 N/mm
- Medium stiffness (medium) spring (H) 38 N/mm
- High stiffness (hard) spring (V) 121 N/mm

SPRINGS CALLIBRATION - FREE REGRESSION LINE $y=mx + b$		
HIGH STIFFNESS SPRING	V1/V2 LOAD vs DISPL	
	m [N/mm]	b [N]
Average	121.2161	-8.86261
MEDIUM STIFFNESS SPRING	H1/H2 LOAD vs DISPL	
	m [N/mm]	b[N]
Average	38.11462	-1.08861
LOW STIFFNESS SPRING	W1/W2 LOAD vs DISPL	
	m [N/mm]	b[N]
Average	0.515792	-0.0392

Table 3.7 Spring calibration and stiffness measurement results.

3.5.5 OPENING DISPLACEMENT MEASUREMENT WITH LASER GAUGE FOR MIXED MODE TESTS

In case of mixed mode tests, the multi mode rig could be equipped with a laser gauge system in order to record the movement of the specimen in the direction perpendicular to the line of action of the applied force. (Note, that the displacement was measured at an angle to the specimen crack surface, related to the angle of the mixed mode test.)

The laser gauge, calibrated to show readings in mm, was attached rigidly to one of the main body parts of the rig. A reflector, made of a piece of aluminium L-shape profile, was attached to the other body part of the rig. The gauge and the reflector were positioned in such a way that the laser beam went in the direction perpendicular to the acting force at the level of the centre of the specimen. It was assumed that during the tests, once the crack between two halves of a specimen started to open, the distance between the gauge and the reflector would change at the same rate. It was noticed, however, that the body parts of the rig do not necessarily turn at the same rate, which might cause false readings. Ideally there should be two laser gauges, one on each part of the rig, and a set of counter-facing reflectors. The average reading taken from both

gauges would give more realistic results. However, the tests performed on 45° mixed mode, single 0.51 mm Z-Pin QI specimens proved the laser gauge attachment worked properly.

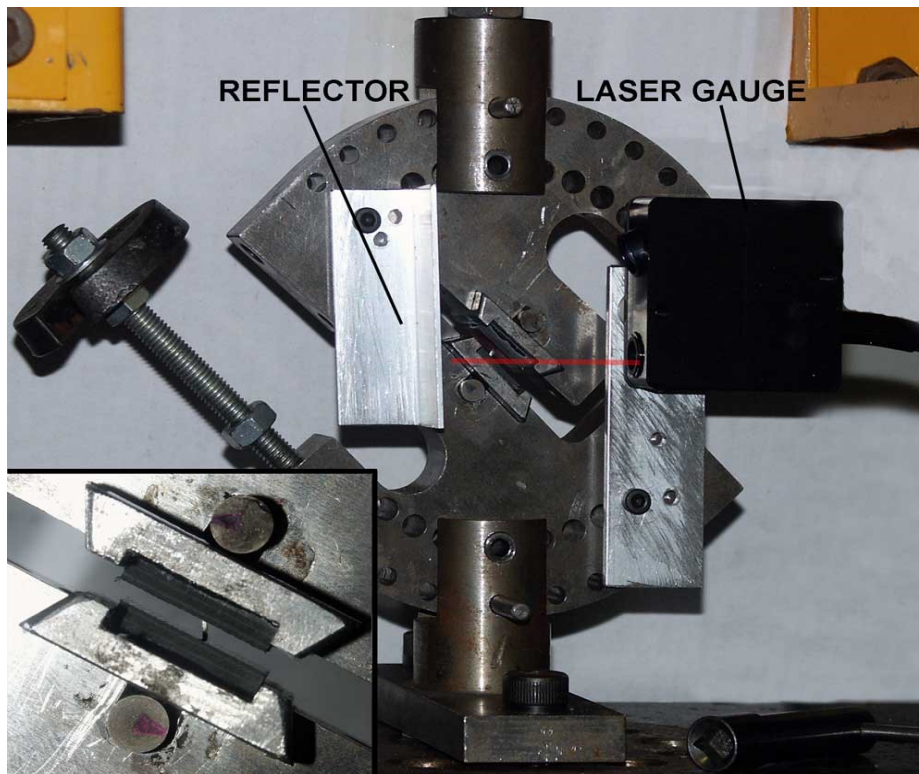


Figure 3.14 Multi mode rig in 45° mixed mode configuration, with laser gauge attached.

3.5.6 Z-PIN IN PURE SHEAR AND SHEAR WITH BENDING CONDITIONS

In order to investigate the behaviour of a Z-Pin in pure shear and shear with bending conditions a simple testing rig, consisting of four aluminium bars, was manufactured to carry out shear-tests using the Instron screw driven testing machine (**Figure 3.15**). Three of the bars, connected together rigidly and forming a fork-shaped structure, were clamped in the one jaw of testing machine. The third bar, the cutting bar, was positioned between the forks and clamped in moving clamp of the testing machine. The pin specimen was inserted into a sliding fit hole drilled through the thickness of the bars forming the fork-shaped structure and the cutting bar. (The size of the hole was such that the pin was not loose but could be slid into the hole easily.)

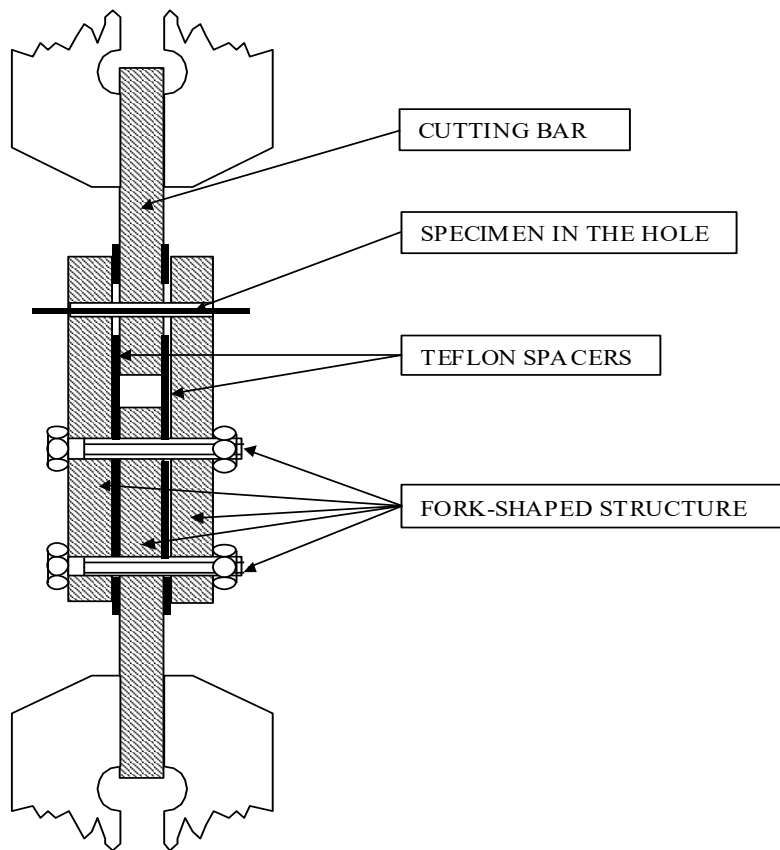


Figure 3.15 Testing rig for shear tests

Using pieces of the Teflon sheet as spacers between bars, three test set-ups were available:

- Shear with no bending – direct contact between bars (~0 mm gap)
- Shear and bending – one Teflon spacer (0.33 mm gap)
- Shear and bending – two Teflon spacers (0.66 mm gap)

Teflon spacers were located symmetrically on both sides of the cutting bar. Because of holes cut in the Teflon sheets, the tested Z-Pin rod-stocks were not in contact with the spacers. Application of the Teflon assured no or little friction between aluminium bars and spacers. The crosshead speed was set at 0.25 mm/min.

3.5.7 SUMMARY

The simple Mode I testing rig was used initially for Mode I tests on a limited number of specimens, prepared with Method A only. It was used to compare the results with the similar tests described in [72].

The necessity to perform tests in various modes led to development of the multi mode testing rig, with the facility to control the opening displacement in Mode II tests with springs of three different stiffnesses. A facility of measuring the displacement in the direction perpendicular to the acting force in any mixed mode was also added. The majority of the specimens, manufactured with the alternative methods, were tested using this multi mode rig.

For an additional investigation of the behaviour of the Z-Pins under pure shear or shear with bending, a simple rig was developed, which allowed pieces of Z-Pin rod-stock to be tested.

4 MICROSCOPIC OBSERVATIONS

4.1 OVERVIEW

The microscopic observations were undertaken in order to study the influence of the Z-Pin insertion on the surrounding composite: formation of the resin pockets, composite fibre waviness and chamfers. Different observations were undertaken in order to provide exact measurement of the Z-Pin diameter and its variation, as well as to observe longitudinal cross-sections of the Z-Pins. The purpose of these observations was inspection of the quality of the Z-Pins. A special note was taken of air or resin bubbles formed inside of Z-Pins during manufacturing process.

Various types of specimens were observed for different purposes:

- Z-Pin embedded into composite structure – for internal damage of the laminate due to Z-Pinning
- Z-Pin embedded into composite, observations post mortem (i.e. after testing) – for understanding of the pull-out process.
- Transverse cross-section of a Z-Pin – for Z-Pin measurement and defect assessment.
- Longitudinal cross-section of a Z-Pin – for assessment of the quality of the Z-Pins internal structure
- Sequential transverse cross-section of a Z-Pin – for investigation how the diameter, shape of cross-section, twist of the fibres or any internal irregularities (e.g. air or resin bubbles) might change along the Z-Pin.

Each specimen, after cutting out from the panel, was immersed in transparent polyester resin. The required face was ground to achieve the proper view of Z-Pin using 600grit paper followed by 1200grit paper and then the prepared face was polished with 6 μ m (micrometre) and 1 μ m polishing liquid. However, often in order to preserve the view achieved after the paper grinding, the 1 μ m and 6 μ m were used for limited time, which resulted in visible scratches on the surface. The scratches did not obstruct the final view, and they could be clearly distinguished from, and did not to change, the important features of the micrographs.

The specimens were observed using Olympus BH-2 light reflecting optical microscope with Olympus Soft Imaging Solutions digital camera (SIS, D-48153 Muenster, 768 x 576 pixels), connected to a computer equipped with an image processing software AnalySIS 2.1. Each

image was recorded as a separate TIFF file. In order to maximise the resolution of the final images, the optical magnification of the microscope was set to show only a part of Z-Pin cross-section in a single field of view. The recorded images were then joined together using Adobe Photoshop CS2 to create a full view of the Z-Pin cross-section. Final recorded image resolution, as a result of optical magnification and camera resolution, was:

- 1120 px/mm in the subsequent cross-sections (**Figure 4.10**)
- 560 px/mm in the longitudinal cross-sections (**Figure 4.9**), other cross-sections (**Figure 4.1, Figure 4.2, Figure 4.3**) and post mortem images (**Figure 4.4, Figure 4.5**)
- 2240 px/mm in the close-up image (**Figure 4.2**)

4.2 Z-PINS EMBEDDED IN THE COMPOSITE STRUCTURE

These specimens were cut out of the pinned panels of composites of UD and QI lay-ups. Z-Pins were observed from two different “views” in each lay-up case:

- Top view – transverse cross-section of Z-Pin in surrounding composite
- Side view – longitudinal cross-section of Z-Pin in surrounding composite

As can be seen in **Figure 4.1** and **Figure 4.2** during the process of embedding Z-Pin into the composite structure, the fibres of the composite were pushed apart making rhomboid-shape structure filled with resin. This resin pockets are up to eight times longer than the diameter of inserted Z-Pin. The fibres of the laminate stay in contact with Z-Pin in a short section of the circumference of Z-Pin. In the far corners of the resin pocket the laminate fibres meet together and return to the original orientation. The resultant fibre waviness causes a reduction in the in-plane properties of a pinned laminate [43,76].

Regarding the quality of the Z-Pinning process using Method A, B and C, the difference is clearly visible in **Figure 4.1**. Z-Pins inserted using Method A and B are often significantly inclined to their intended direction and for Method A often only achieve partial insertion. Also, rather remarkable fibre waviness across the layers can be observed, as the fibres of prepreg are being pushed along by the blunt tip in the Z-Pin during insertion.

In comparison the micrograph of a Z-Pin inserted using Method C reveals clear, full insertion with practically no fibre waviness present across the layers (see **Figure 4.1**). The sharp and smooth steel needle used in Method C insertion pushed the fibres apart more gently than the blunt tip of the Z-Pin. Also, due to a good control of the needle insertion, the insertion angle is practically as intended.

In the side view (**Figure 4.1**), resin pockets and air bubbles are visible adjacent to the Z-Pins. The diameters of the air voids may be as much as twice the Z-Pin diameter. As already noted, insertion of Z-Pins also causes through-thickness distortions of the laminate. These resin pockets, air bubbles and layer distortions may have a significant effect on the pull-out and shear-out process as well as on the properties of the pinned laminate.

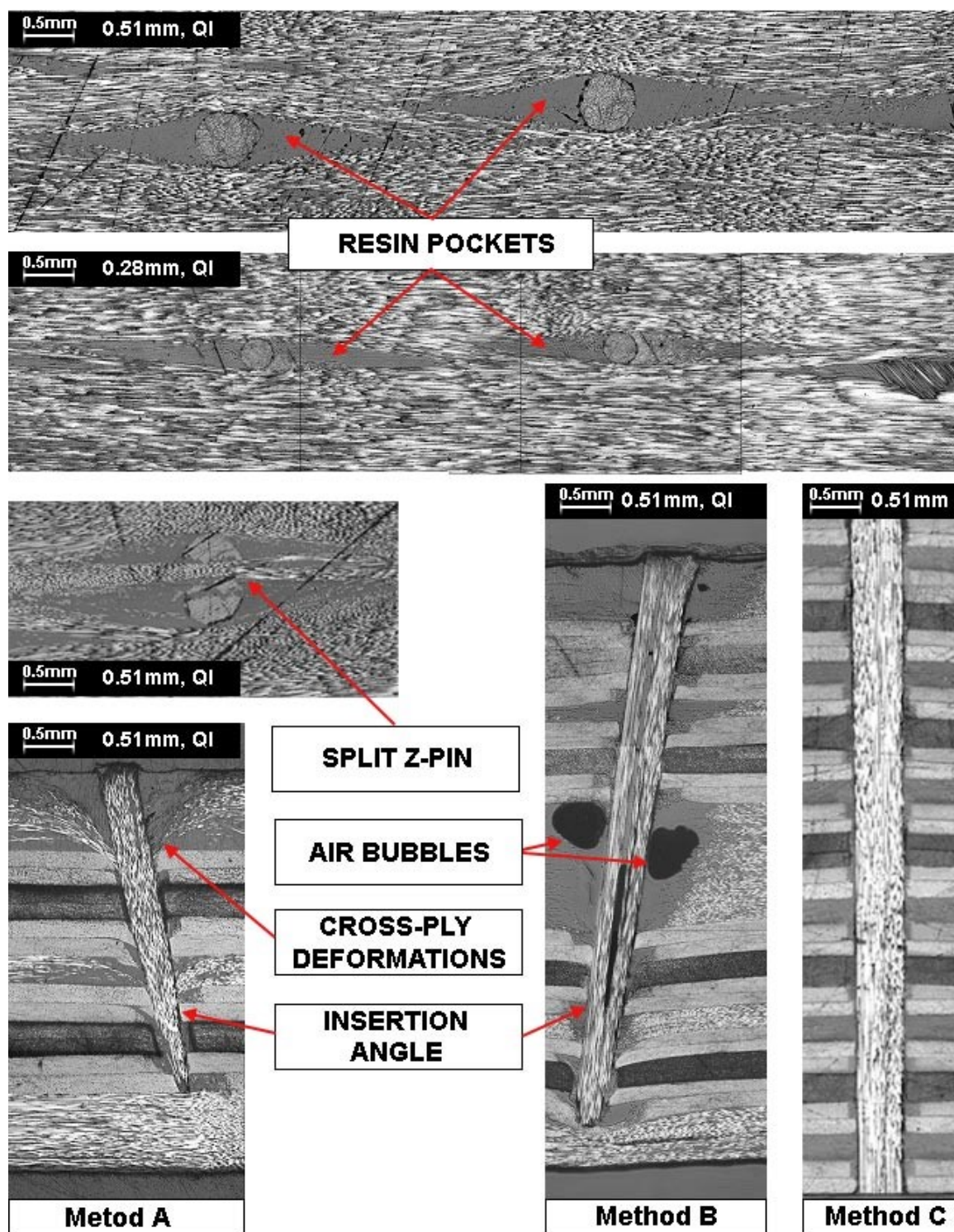


Figure 4.1 Resin pockets, fibre waviness and fibres deformations - damage made to the composite and quality of Z-Pinning in Method A and B (UAZ insertion) and Method C (needle assisted manual insertion).

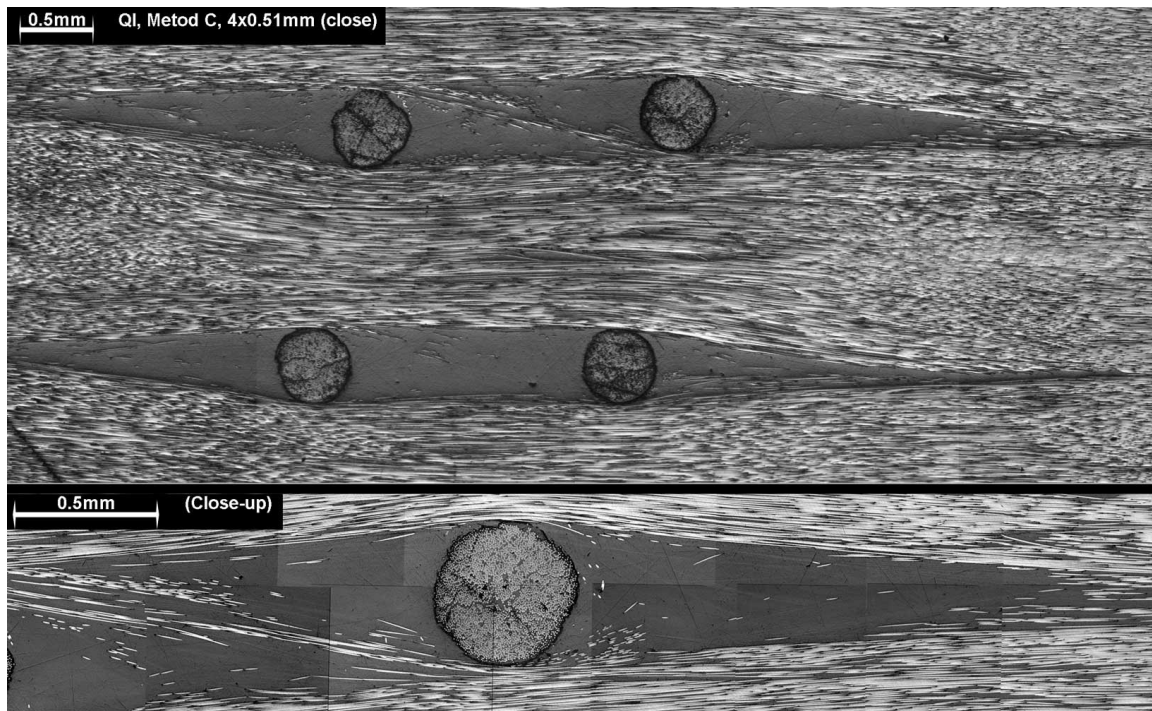


Figure 4.2 Resin pockets in a four pin, 0.51 mm Z-Pins, QI, Method C specimen.

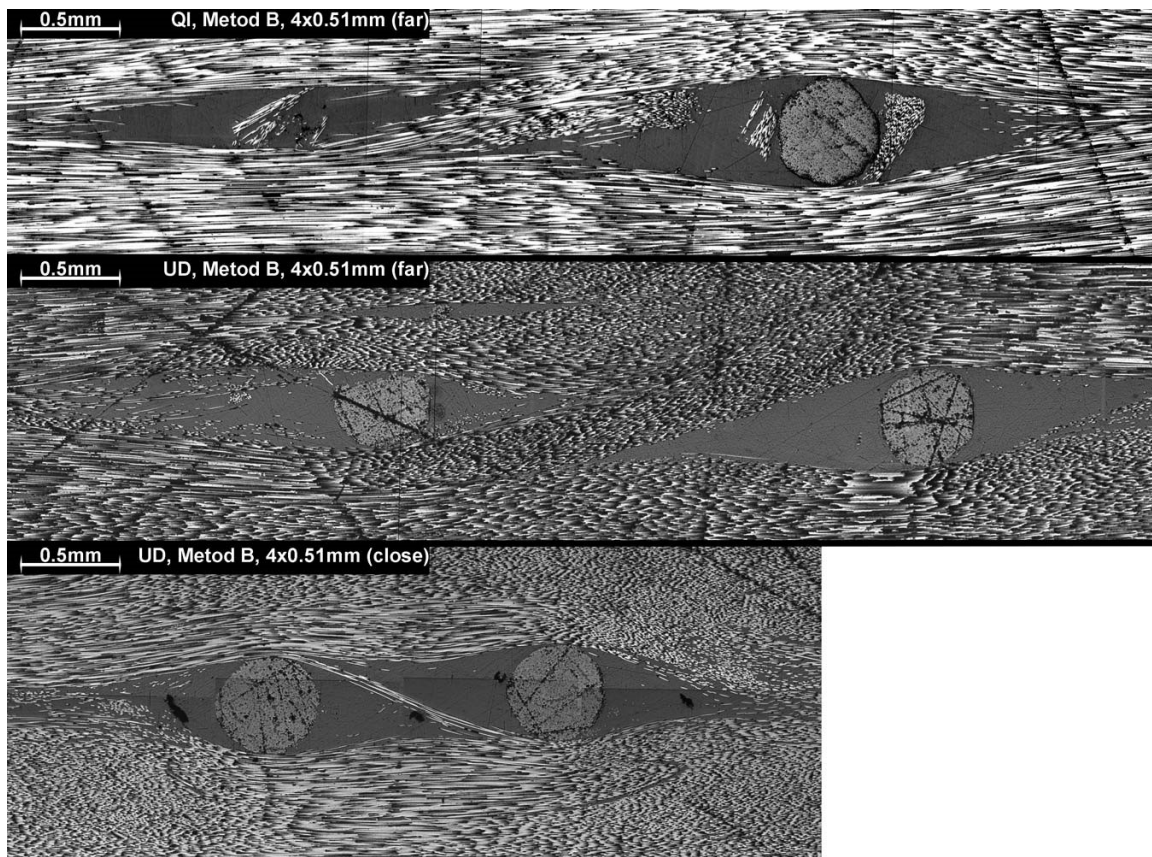


Figure 4.3 Resin pockets in a four pin, 0.51 mm Z-Pins, QI and UD, Method B specimen.

The shapes of resin pockets for various specimens and panels can be seen in **Figure 4.2** and **Figure 4.3**. The panel lay-up, QI or UD did not seem to have an influence on the proportions of the resin pockets, as it might be expected.

Resin pockets in Method C composite (manual insertion with a needle) seem to have more regular shapes than in Method B (UAZ insertion). The pockets are parallel to each other and seem to follow the general direction of the fibres more closely. The pockets in Method B appear to be relatively shorter (three to four times the Z-in diameter) than the ones in Method C (up to eight times the Z-Pin diameter). It might be explained by the application of a needle of the diameter slightly bigger than the Z-Pin itself, so the fibres of a prepreg had to be pushed further apart. However, slow fibre “relaxation” after the insertion of a Z-Pin resulted in the lower fibre waviness.

Features like resin pockets, laminate fibre waviness, transfer of the laminate fibres across the layers were reported in [84,35,34,4,5,6,67,79,47,48].

4.3 Z-PINS EMBEDDED INTO COMPOSITE STRUCTURE – OBSERVATIONS POST MORTEM

These observations were made on specimens after the tests. The tests were stopped at various moments after the rapid drop of the force. Single 0.51 mm Z-Pin specimens of UD and QI lay-ups were investigated. Side views of the Z-Pins were observed – longitudinal cross-section of Z-Pin in surrounding composite. Surprisingly the images did not show the longitudinal splitting of the Z-Pins or any artefacts confirming the “snubbing” effect, widely reported in [79,66,67], even though the insertion angles were significant.

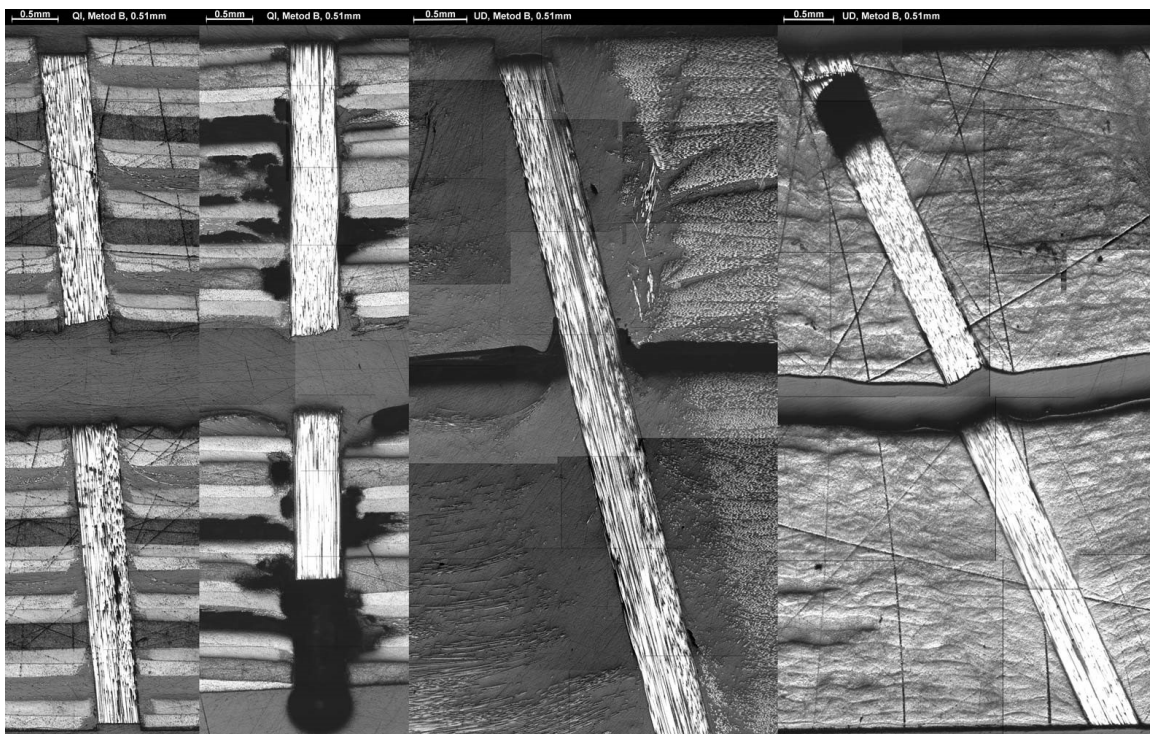


Figure 4.4 Post mortem micrographs of QI and UD single 0.51 mm Z-Pin, pull-out tests, Method B specimens (Z-Pins broken during handling after tests).

As seen on **Figure 4.4**, besides the visible damage caused during the Z-Pin insertion, no additional damage due to the pull-out process could be observed. The Z-Pins seem to smoothly slide out of the composite. Some coarseness of the Z-Pin surfaces could be seen at this level of magnification. Also, the fibre waviness caused by the Z-Pin insertion is clearly visible (**Figure 4.5**), especially at the delamination surfaces of the specimen

Interestingly, in some cases it could be clearly seen that the Z-Pin was pulled from the both sides of the specimen, simultaneously.

A number of images depicting the longitudinal cross-sections of the Z-Pins showed dark elongated features, stretching along fibres for several millimetres, usually close to the axis. Those features, which could be observed on the post mortem images of Z-Pins embedded in the composite as well as in the longitudinal (and transverse) cross-sections of untested Z-Pins (see later **Figure 4.7**, **Figure 4.8**, **Figure 4.9**), were likely to be voids or resin pockets caused during the Z-Pin manufacturing process – they were not caused during pull-out tests.

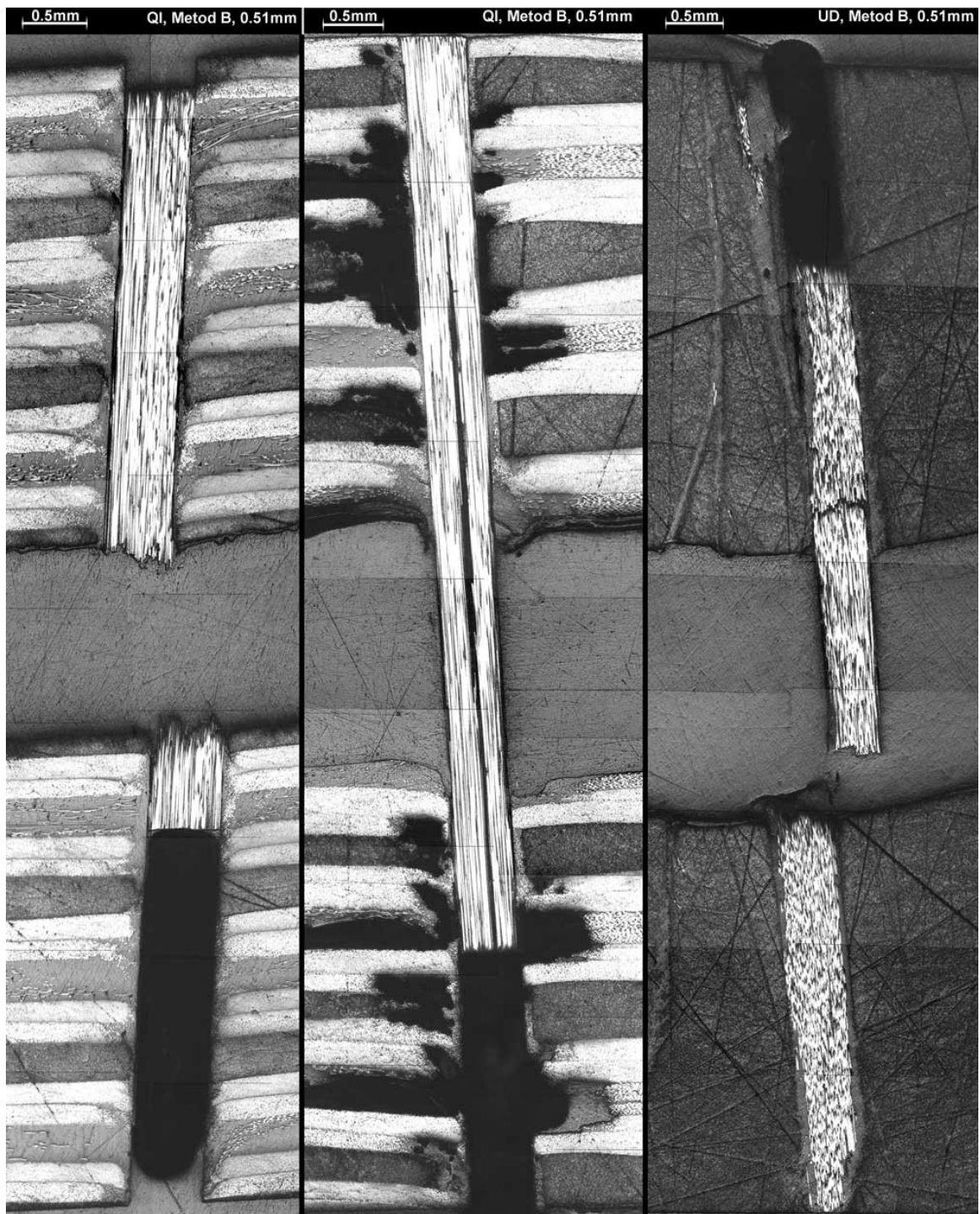


Figure 4.5 Post mortem micrographs of QI and UD single 0.51 mm Z-Pin, pull-out tests, Method B specimens (Z-Pins broken during handling after tests).

4.4 TRANSVERSE CROSS-SECTION OF Z-PIN

These observations were made with use of excess Z-Pins pulled out of the pre-form, which had not been embedded in the composite. The aim was to achieve the view of the cross-section exactly perpendicular to the Z-Pin axis. About eighty Z-Pins of three different types were measured:

- 0.28 mm diameter Z-Pins
- 0.51 mm diameter “grey” Z-Pins
- 0.51 mm diameter “brown” Z-Pins

The Z-Pins were inserted into a flat rolled piece of BlueTac in a uniformly distributed grid, see **Figure 4.6**. The free ends of the Z-Pins were then dipped in transparent polyester resin leaving the BlueTac above the surface. After the resin had cured, the BlueTac was removed and the remaining tips of Z-Pins were covered with resin. Both surfaces of the resin block were then ground perpendicularly to the axes of the Z-Pins and polished to expose the detail of the Z-Pin cross-sections (see **Figure 4.7**).

The cross-sections of Z-Pins were observed using an optical microscope equipped with a digital camera. The measurements of the diameters of the Z-Pins were performed using image processing software. The cross-section of every pictured Z-Pin was measured in two mutually perpendicular directions (using the grid available in the imaging software): vertically (giving diameter D_v) and horizontally (giving diameter D_h) in relation to the screen.

The microscope observations revealed serious imperfection in the shape of Z-Pin cross-sections, which can be divided in two categories:

- Shape imperfections
- Structure imperfections

Most of the observed Z-Pins had ellipsoidal (rather than circular) or irregular outline with a number of bumps. The “brown” 0.51 mm Z-Pins were found the most deformed, The 0.28 mm Z-Pins seems to be the least distorted.

The structural imperfections like resin bubbles or air voids, described by Ustamujic in [51], are probably responsible for the black spots observed in the cross-sections. The” brown” 0.51 mm Z-Pins, with numerous spots observed in each Z-Pin cross-section, are definitely the most faulty ones. The “grey” 0.51 mm and 0.28 mm Z-Pins, in which only single spots in some cross-sections were observed, seem to have better internal structure.

The average measured diameter seems to differ from the manufacturer’s nominal diameter. In the case of 0.28 mm Z-Pins the measured diameter was 4.4% lower than the one given by manufacturer, in case of “grey” 0.51 mm it was 6.5% lower and in case of “brown” 0.51 mm Z-Pins the measured diameter was 4.7% higher. The results are summarised in **Table 4.1**.

	0.28 mm	0.51 mm (grey)	0.51 mm (brown)
MEAN DIAMETER, $ D $ [μm]	268	477	534
STD. DEVIATION [μm]	9	14	11
DEV. FROM CIRCULARITY* [μm]	17	24	19
AMOUNT OF SPECIMENS, n	22	29	28
* deviation from circularity, average absolute difference between D_v (vertical) and D_h (horizontal) diameters $(\Sigma D_v-D_h)/n$.			

Table 4.1 Results of the measurements of Z-Pins diameters

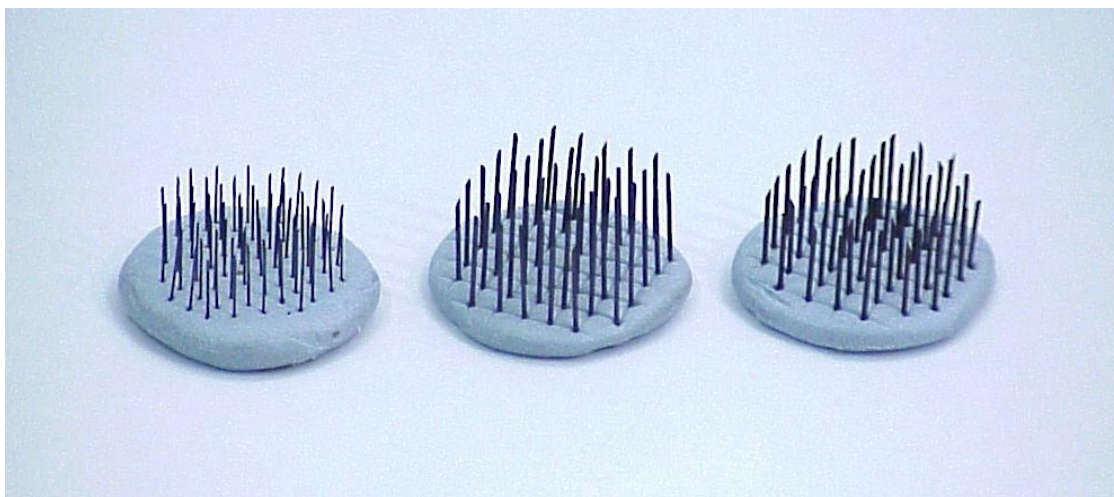
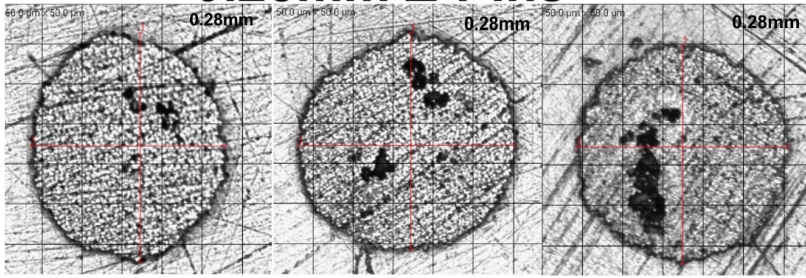
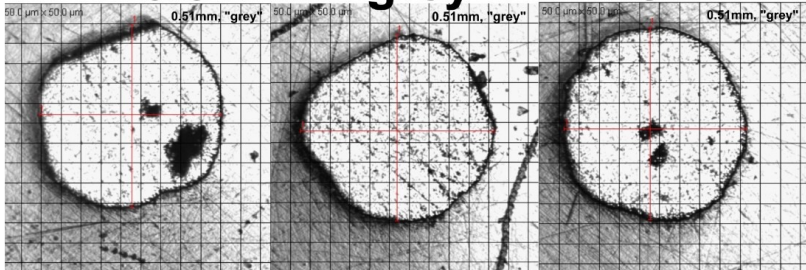


Figure 4.6 Z-Pins inserted into BlueTac

0.28mm Z-Pins



0.51mm "grey" Z-Pins



0.51mm "brown" Z-Pins

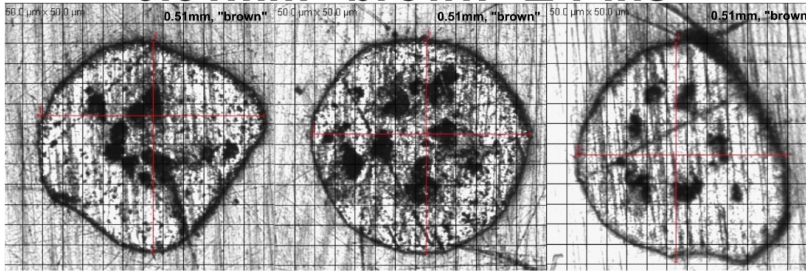


Figure 4.7 Irregularity of cross-sections of Z-Pins.

4.5 LONGITUDINAL CROSS-SECTION OF Z-PIN

The observations of the longitudinal cross-section were performed on excess Z-Pins pulled out of the pre-form.

A number of Z-Pins were put in the bottom of a plastic cup, which was then flooded by transparent polyester resin. After curing the block of resin was ground to uncover the longitudinal cross-section of the Z-Pins and then polished.

The observations revealed flaws in the internal structure of the Z-Pins (see **Figure 4.8** and **Figure 4.9**). Air and/or resin-filled voids were observed inside of the pin structure, which are suspected to form during the Z-Pins manufacturing process. The air voids were elongated shapes lying parallel to the fibres and were of various lengths (some seem to continue all along the Z-Pin rod). Up to three parallel voids could be observed in a single Z-Pin. The widths of the voids were many times the diameter of the fibres (**Figure 4.8**). These defects may have a significant influence on the strength of the Z-Pins. Similar observations were carried out by Ustamujic [51].

Also, worth noting are the tips of the Z-Pins, which are supposed to be sharp in order to help penetrating through the prepreg. As seen in **Figure 4.9**, the tips of the Z-Pins were substantially damaged during the UAZ insertion, e.g. the fibres are visibly split at the tips.

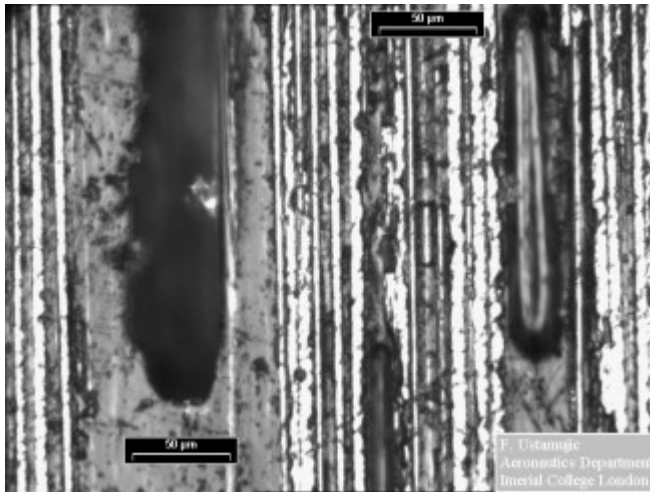


Figure 4.8 The voids in the structure of Z-Pin, [54].

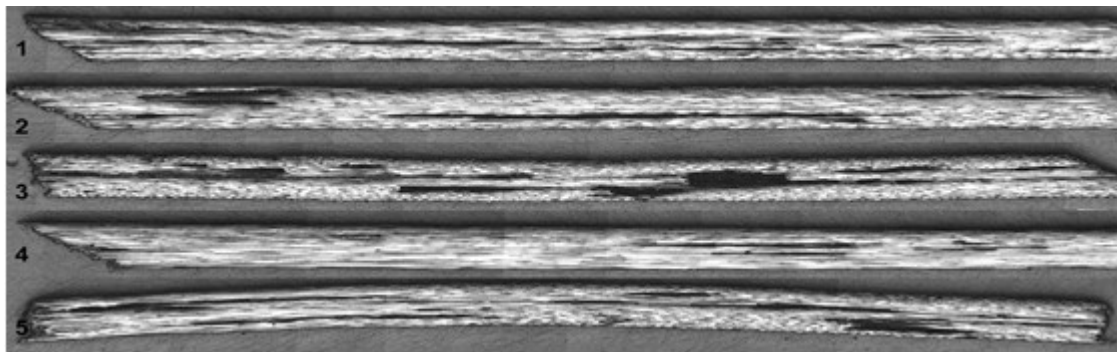


Figure 4.9 Longitudinal cross-sections of 0.51 mm Z-Pins.

4.6 SEQUENTIAL TRANSVERSE CROSECTION OF Z-PIN

The purpose of these observations was to analyse how the cross-section changes along the length of a Z-Pin. Single Z-Pins, taken out of the pre-form, were immersed in polyester resin with their axes perpendicular to the surface of the resin block, using the method described before. The surface of the block was ground off to reveal full cross-sections of the Z-Pins and first observations were made. A hand-held grinding aid was then used, which allowed grinding off the surface of the resin block to the specified depth, such that the new surface was exactly parallel to the previous one.

The surface was ground off to a depth of 0.2 mm, polished and the chosen Z-Pins cross-sections were photographed, with the specimen placed in exactly the same, previously marked position on the microscope table. Repeating this process, fourteen observations were made over a distance of approximately 2.6 mm along the Z-Pin. The resulting subsequent cross-sections of two selected Z-Pins are shown in **Figure 4.10**.

It can be clearly seen that the Z-Pins were twisted. The twist angle was assessed as approximately 52° over the 2.6 mm distance. Considering irregularity of the transverse cross-section of Z-Pins, with all the bumps on the outline, the twist could be a reason for the growth of the force in the frictional sliding phase of the pull-out process.

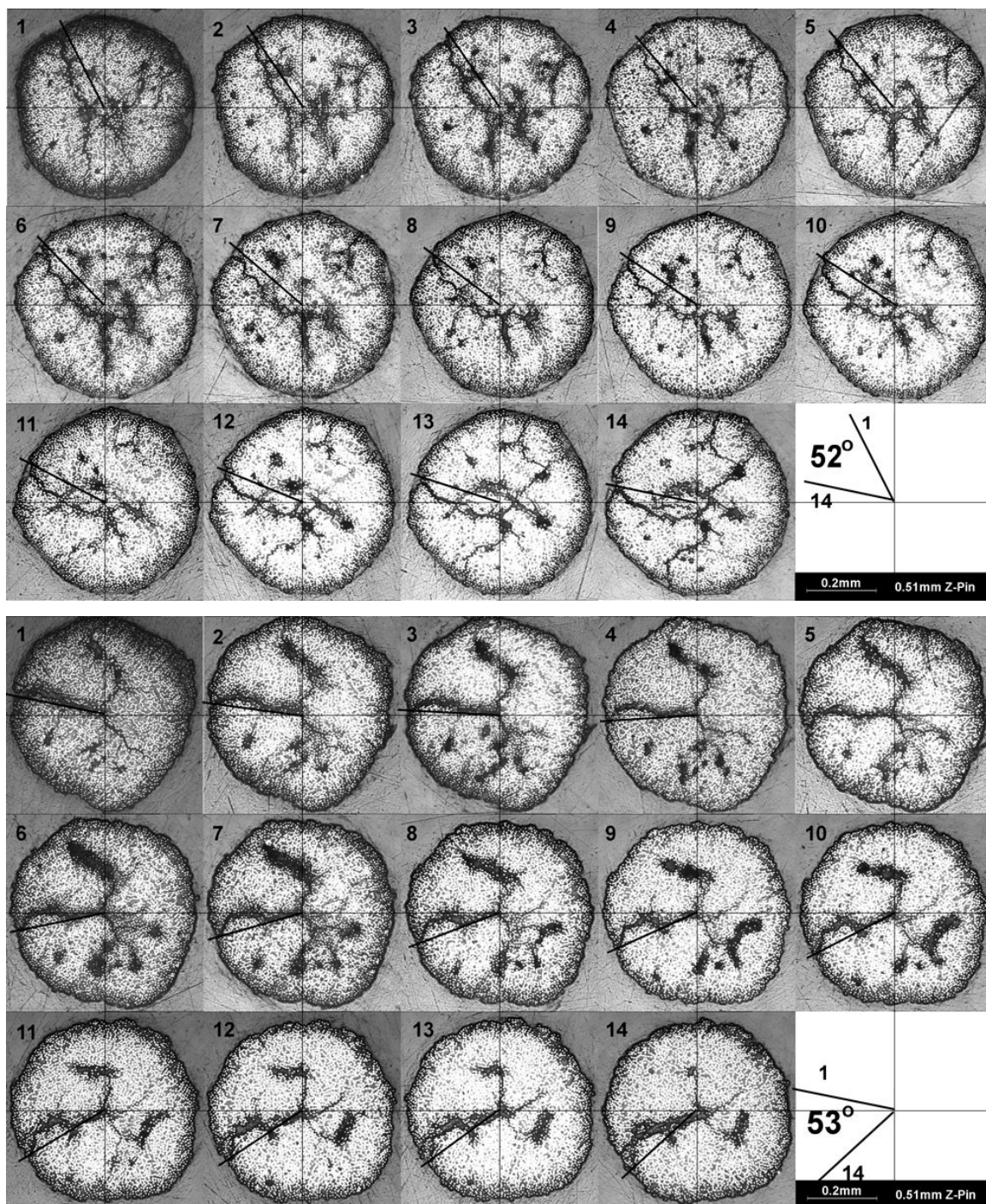


Figure 4.10 Subsequent, made every 0.2 mm, cross-sections of a Z-Pin.

4.7 SUMMARY

The microscopic observations of the internal structure of unused Z-Pins and Z-Pins embedded in the composite revealed the following features:

Faults in the internal structure of unused Z-Pins:

- Elongated voids, or empty bubbles, stretching for several millimetres along the Z-Pin axis, usually (but not exclusively) close to the centre -
- Split fibres at the sharpened ends of the Z-Pins - possible cause of splitting during z-pinning process
- Sharpening of the Z-Pin tips not axially symmetrical – possible cause of changing direction of the Z-Pin during insertion
- Irregularity of the Z-Pin transverse cross-section
- Twist of the Z-Pin, approximately 50° per 2.5 mm of the length

Structural faults caused by z-pinning:

- Resin pockets, caused by the Z-Pin pushing the fibres apart
- Voids or air bubbles near the Z-Pins
- In-plane fibre waviness
- Crimp, or pushing the fibres of the laminate across the layers during Z-Pin insertion
- Fibre breakage in the laminate
- Splitting of the Z-Pin fibres

In order to preserve a particular view achieved after the paper grinding, the 1µm and 6µm were used for limited time, which resulted in visible scratches on the surface. The scratches did not obstruct the final view, they could be clearly distinguished from and did not to change the important features of the micrographs.

5 RESULTS OF PULL-OUT, SHEAR-OUT AND MIXED MODE TESTS

5.1 OVERVIEW

This chapter presents the results from the experimental tests program. The following tests were successfully performed:

- Pull-out tests on simple rig and multi mode rig, pin insertion Method A and C
- Shear-out tests on multi mode rig, with crack opening controlled with springs of three different stiffnesses, pin insertion Method B and C
- Mixed mode (30°, 45°, 60°, 70° and 80°) tests on multi mode rig also with opening displacement measurement, pin insertion Method C

The following types of Z-Pins were used in the tests:

- 0.51 mm diameter, single and in group of four pins
- 0.28 mm diameter single and in group of four pins

The specimens were based on the following lay-ups:

- QI (quasi-isotropic)
- UD (unidirectional)

The following pinning depths were investigated:

- 1 mm
- 1.5 mm
- 2 mm
- 2.5 mm
- 3 mm

The following pull-out speeds were tested:

- 0.05 mm/min
- 0.50 mm/min
- 5.00 mm/min

Also, the test results of the different insertion methods were compared.

Due to low quality of the specimens manufactured with Method A, the results of the tests here were for the reference purpose only, or trial runs. The bulk of the tests were carried out with specimens prepared with Method B or C.

5.2 PULL-OUT TESTS

5.2.1 RESULTS

Method A – Simple Rig

These tests, performed on the simple rig, were the first attempt to investigate the Z-Pin pull-out process. Due to the bad quality of the Z-Pinning using Method A many specimens were not suitable for testing and the results were characterised by a high scatter. The Method A tests results were used mainly for comparison with other Z-Pinning methods. Out of 108 prepared specimens, only 20 single 0.51 mm Z-Pin specimens, and 16 group of four Z-Pins specimens, were successfully tested (losses were due to both insufficient insertion depth and imperfection of the glue joints). Most of the 0.28 mm diameter Z-Pins were not inserted to the proper depth (most of them did not get to the depth of the delamination film), and only one of 0.28 mm Z-Pin specimens was properly tested, which was not enough for any reliable data.

The post-mortem measurements of the Z-Pins insertion angle were performed using a macro camera, projecting the image of each Z-Pin on a TV with calibrated marks on the screen (see **Figure 5.1**).

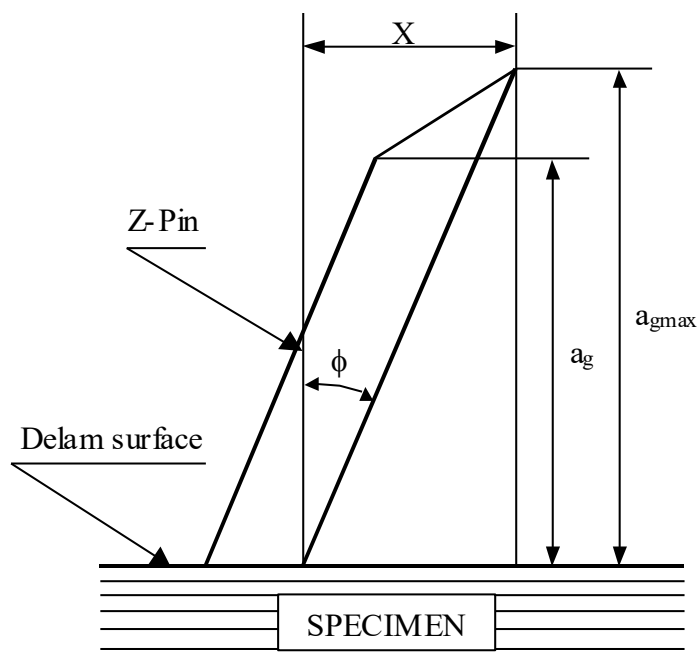


Figure 5.1 The method of post mortem measurement of the pulled-out part of Z-Pin, Method A.

Post-mortem analysis of the remnants of the Z-Pins sticking out of the halves of specimens revealed high scatter of the insertion angles. The angle of insertion ϕ of QI specimens generally varied from 6.8° to approximately 18° with two exceptions at values of 28° and 30.3° . The average insertion angle for QI specimens was 14.15° for 2 mm “working part” and 16.8° for 3 mm “working part” (the part of the composite in the specimen from which the Z-Pin was supposed to be pulled out – thinner than the “holding part”). The insertion angles of UD laminate specimens were much higher and ranged from 15.6° to 33.7° with an average magnitude 26.9° . The post mortem observations of the specimens revealed that the Z-Pins were tilted along the direction of the composite fibres. This may suggest that during the insertion process, the fibres of UD prepreg assembly easily parted and did not provide sufficient support for the Z-Pins in fibre direction. Z-Pin insertion angles averaging at 13° - 14° and ranging from 2° to 33° in case of the standard UAZ insertion method have been reported by [48,67,47], see earlier **Figure 2.35**.

It is noticeable that the “close distance” Z-Pins specimens (1.75 mm pin-to-pin distance) in QI and UD laminates all four Z-Pins were fully inserted (as visible during post mortem observations and confirmed in the magnitudes of joint pulled out length) and showed low insertion angles. These specimens were pinned using a different pre-form (yellow, brittle one), and hence different Z-Pins (“brown” Z-Pins). The rest of the specimens (pinned using standard, white pre-form and “grey” Z-Pins – used in all the remaining tests) were characterized by highly scattered lengths of Z-Pins embedded into “working part”; in many cases only two or three out of four Z-Pins went through the delamination foil. This may suggest that the pre-form itself can have an important influence on pinning quality. Although the supplier did not reveal any technical information about the “grey” and “brown” Z-Pins, they were used in the trial only.

In single 0.51 mm diameter Z-Pin specimens the pull-out curves seem to follow certain pattern, different for specimens based on QI and on UD laminate, seen on **Figure 5.2**. In all single Z-Pin pull-out tests a rapid, linear growth of the force to a peak value of approximately 100 N in case of QI and 200 N in case of UD laminate (first maximum), at the displacement of approximately 0.1 mm - 0.2 mm respectively was followed by a rapid drop (UD) or a small drop or significant flattening of the curve (QI). Then the force started to decrease (mainly UD laminate) or gradually grew up to 50 N – 100 N at the displacement of approximately 0.5 mm

- 1.5 mm from where it gradually decreased to 0 (mainly QI laminate). In case of UD laminate the force at the first maximum was approximately twice as high as in case of QI laminate. Also, the second maximum, although of similar amplitude, generally seemed to be reached later in case of QI than UD laminate.

In specimens containing groups of four 0.51 mm Z-Pins the similar pattern was observed: the first maximum of 200 N to over 400 N at the displacement of between 0.1 mm – 0.6 mm, approximately two times higher in UD than in QI laminate. In specimens with “far” Z-Pin pattern in UD laminate, a much slower growth of the force at the very beginning of the pull-out process than in any other cases was observed, as seen in **Figure 5.3**. This might be due to an imperfection of the experiment as this was the first group of specimens tested. Also, exceptionally high pull-out force values were observed in specimens with “far” pattern in QI laminate, see **Figure 5.3**.

Post-mortem observations revealed that Z-Pins were more likely to be pulled out of “holding part” (each specimen was divided into two parts of various thickness: “working part” – thinner, 2 mm or 3 mm, and “holding part” – thicker, 4 mm or 5 mm). For example, for the single Z-Pin pull-out tests in QI laminate with 2 mm “working part”, in six out of seven properly tested specimens, the Z-Pins were pulled out from “holding part” - the thicker one. This was also evident from the **Figure 5.2** where pull-out distances are often greater than the thickness of the “working part”. This was probably a result of the “chamfers” created during UAZ insertion by the hammer head. Z-Pins were inserted from the “working part” side of the specimen in order to ensure insertion through the entire thickness of the “working part”, which caused a chamfer formation on the “working part” side of specimens. A significant number of Z-Pins were not inserted through the entire thickness of the panel, so the chamfer could not form on the other end of the Z-Pin. It is worth noting that in a small number of specimens containing group of four Z-Pins, particular Z-Pins were pulled out of different parts in the same specimen.

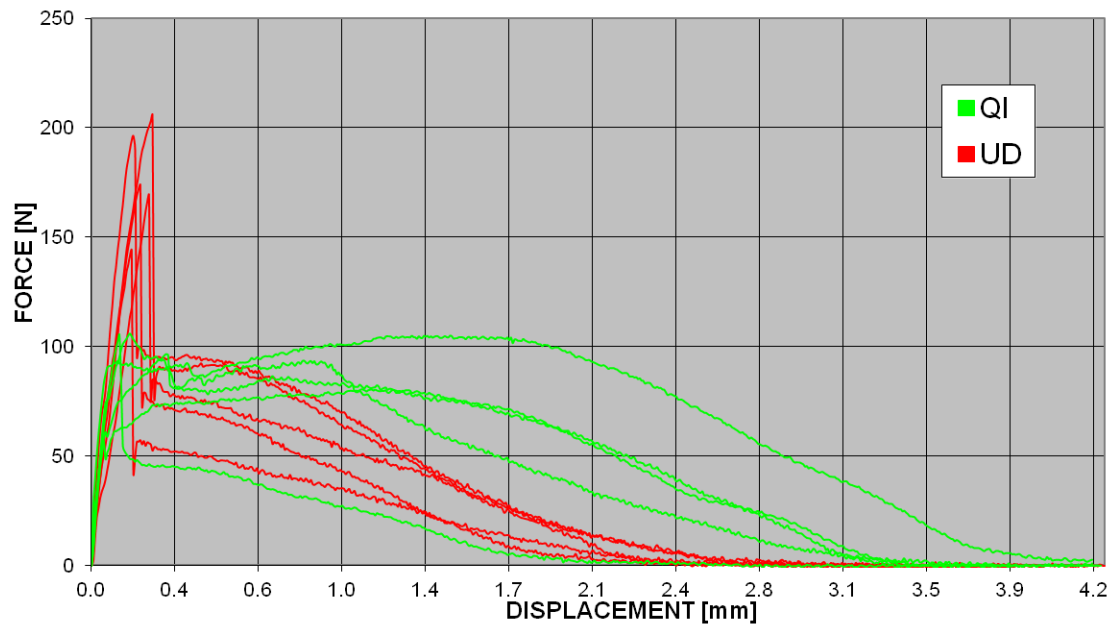


Figure 5.2 Pull-out curves – Method A, single 0.51 mm Z-Pin: QI vs. UD laminate

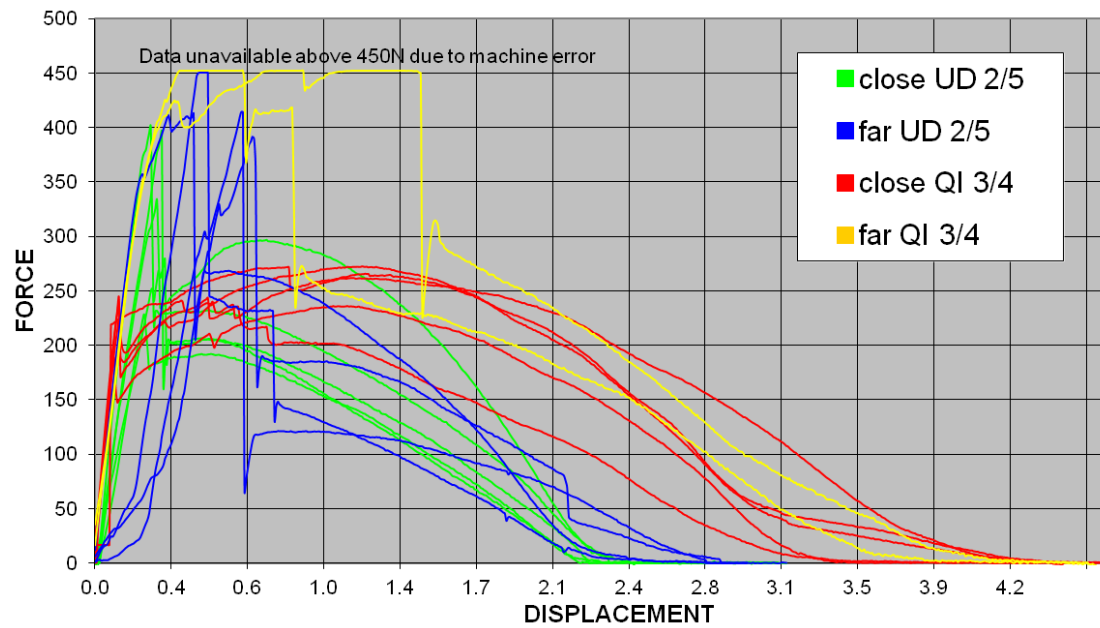


Figure 5.3 Pull-out curves - Method A, group of four 0.51 mm Z-Pins: QI vs. UD laminate, “close” vs. “far” Z-Pin pattern, various embedded lengths

Method C – Multi Mode Rig

Specimens manufactured using Method C were of significantly higher quality (many more specimens had their Z-Pins inserted through the entire thickness, at acceptingly small angles and the possibility of chamfer formation was eliminated), and these tests showed slightly lower scatter than the tests of Method A specimens. Thirteen single 0.28 mm Z-Pin specimens, 38

single 0.51 mm Z-Pin specimens and 28 specimens containing groups of four Z-Pins were successfully tested.

Similarly to the Method A test results, the pull out curves of Method C seemed to follow specific pattern, different for UD and QI laminates, but similar for 0.28 mm and 0.51 mm Z-Pins, as shown on **Figure 5.4** and **Figure 5.5**.

In all cases, the force initially grew linearly to the first maximum, then either rapidly dropped (UD laminate) or significantly flattened (QI laminate). After the drop the force tended to grow slowly until it reached the second maximum after which it gradually decreased to zero, at the displacement corresponding to the embedded length of the Z-Pin. The first maximum of UD specimens were approximately twice those of the QI specimens.

In case of single 0.51 mm Z-Pins in QI laminate (see **Figure 5.4**) the force initially grew to the first maximum of approximately 50 N at the displacement of 0.06 mm. Then after a small drop of the force a gradual growth up to the second maximum of 50 N – 70 N at the displacement of 0.8 mm - 1.7 mm was observed, followed by a gradual decrease to 0.

Single 0.28 mm Z-Pins in QI laminate closely followed pattern observed in 0.51 mm Z-Pins with force reaching approximately half of the values (see **Figure 5.5**). The first maximum of 20 N – 30 N was reached at approximately 0.03 mm (approximately half of the values observed in 0.51 mm specimens). The second maximum of 25 N- 35 N was observed at 0.5 mm – 1.5 mm (only slightly earlier than 0.51 mm specimens).

In case of single 0.51 mm Z-Pins in UD laminate (see **Figure 5.4**) the force initially grew to the first maximum of approximately 100 N at the displacement of approximately 0.04 mm. Then, after a rapid drop of the force to 50 N – 70 N a slow growth up to the second maximum of 55 N – 85 N at the displacement of 0.5 mm – 0.7 mm was observed, followed by a gradual decrease to 0.

In 0.28 mm Z-Pins in UD laminate a similar pattern was observed – the force values being approximately halved (see and **Figure 5.5**). The first maximum reached 50 N – 65 N (approximately half of the values measured in 0.51 mm specimens) at approximately 0.03 mm,

was followed by a rapid drop to approximately 35 N – 40 N and then gradual growth to 40 N – 45 N at 0.2 mm - 0.4 mm (earlier than in case of 0.51 mm specimens).

In case of QI laminate (see **Figure 5.4** and **Figure 5.5**) for a given Z-Pin diameter the force was approximately half of that in UD laminate. Also, QI laminate specimens did not show the rapid drop of the force after the first maximum, observed in case of UD laminate. Additionally, in QI laminate specimens the second maximum seemed to be reached at significantly greater displacements than in UD laminate.

In four Z-Pin specimens the same behaviour as in single Z-Pins was observed, as seen on **Figure 5.6** and **Figure 5.7**. Also, Method C results seemed to follow similar patterns as results of Method A, regardless of the results scatter and bad quality of specimens in the latter.

As seen in **Figure 5.6** and **Figure 5.7** the close (1.75 mm apart) or far (3.2 mm apart) Z-Pin pattern did not seem to have any influence on the pull out process. It is also noticeable that the general shape of the pull-out curves remain similar in four Z-Pin and single Z-Pin specimens (UD and QI laminate respectively), with forces in four Z-Pin specimens reaching approximately three to four times higher values than for single Z-Pins (giving approximately the same magnitude per pin).

As seen on **Figure 5.8** the embedded length had a significant influence on the pull-out process (QI laminate, single 0.51 mm Z-Pins). Specimens with 3 mm embedded length had the highest first maximum of approximately 50 N, and their pull-out curves show significant growth of the force afterwards – up to values twice as high as at the first maximum. In case of 2 mm embedded length the first maximum of the force oscillated around 40 N and only slight growth of the force after the first maximum was observed. In case of 1 mm embedded length the first maximum reached up to 30 N only and the second maximum was not observed – the force gradually decreased to zero,

The pull-out rate, investigated at 5 mm/min, 0.5 mm/min and 0.05 mm/min did not seem to have any influence on the pull-out process (see **Figure 5.9**). However, specimens tested at 5 mm/min seemed to produce the lowest scatter in shape of the curves.

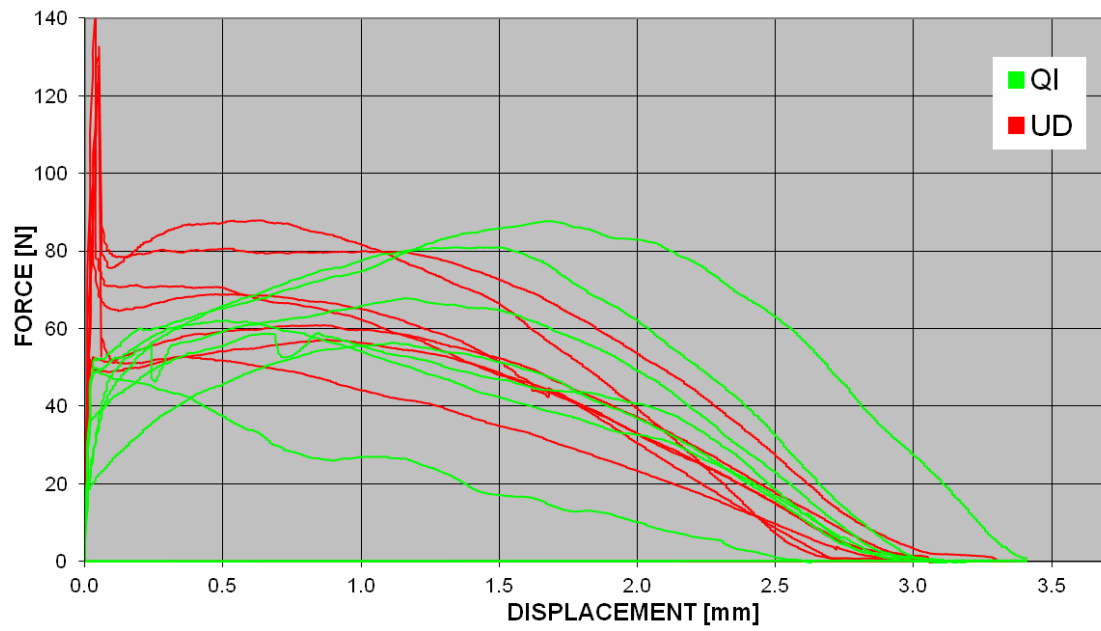


Figure 5.4 Pull-out curves –Method C, single 0.51 mm Z-Pin: QI vs. UD laminate

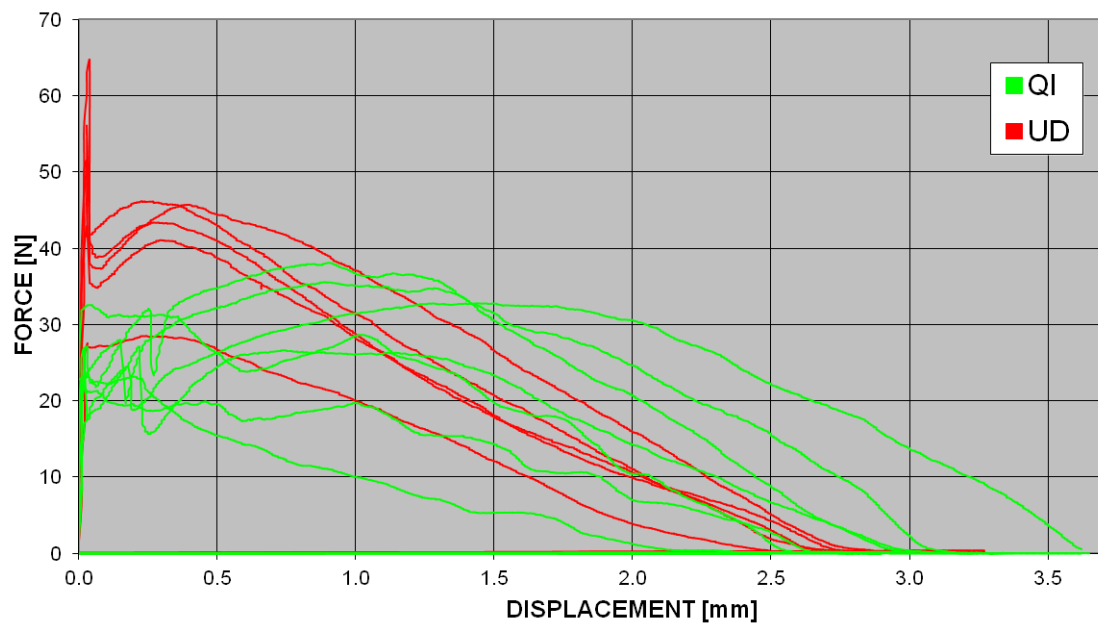


Figure 5.5 Pull-out curves – Method C, single 0.28 mm Z-Pin: QI vs. UD laminate

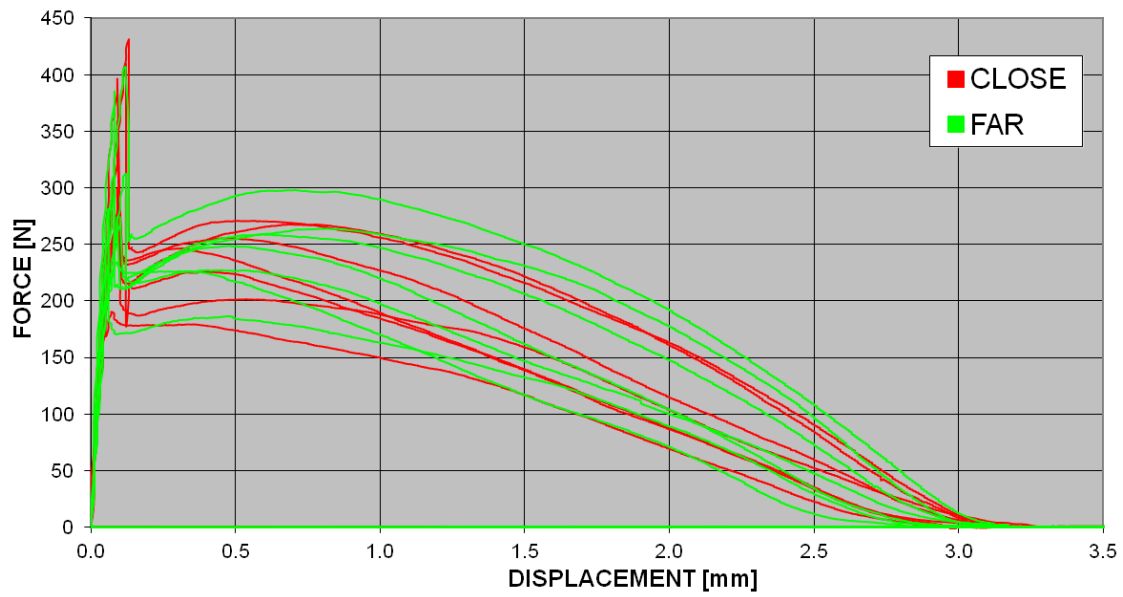


Figure 5.6 Pull-out curves, group of four 0.51 mm Z-Pin, UD laminate: “far” vs. “close” Z-Pin pattern

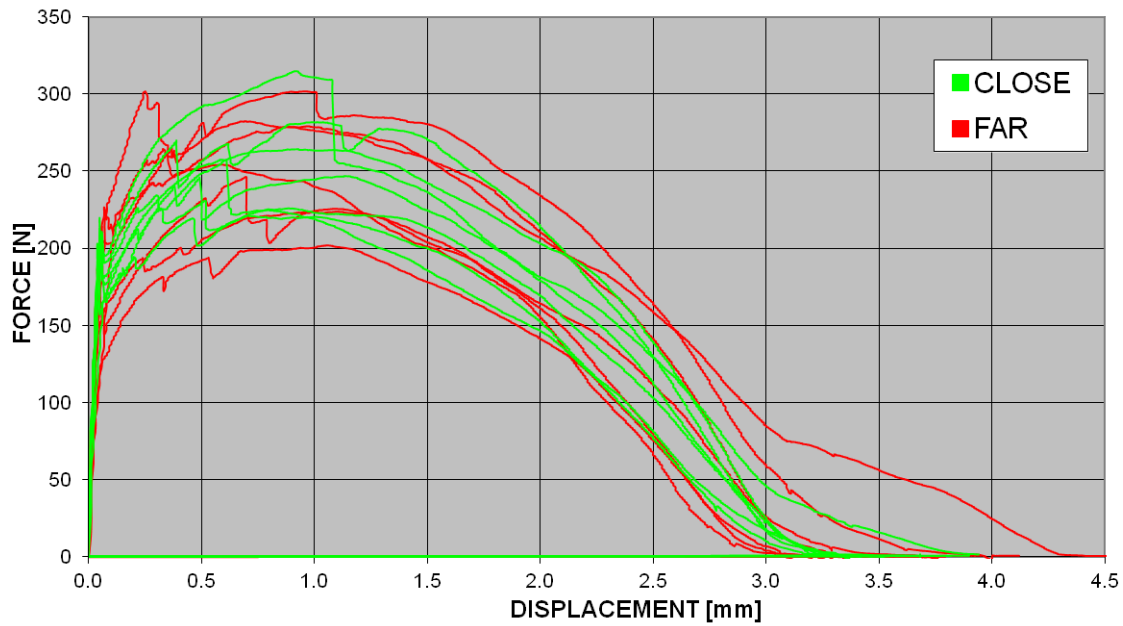


Figure 5.7 Pull-out curves – Method C, group of four 0.51 mm Z-Pin, QI laminate: “far” vs. “close” Z-Pin pattern

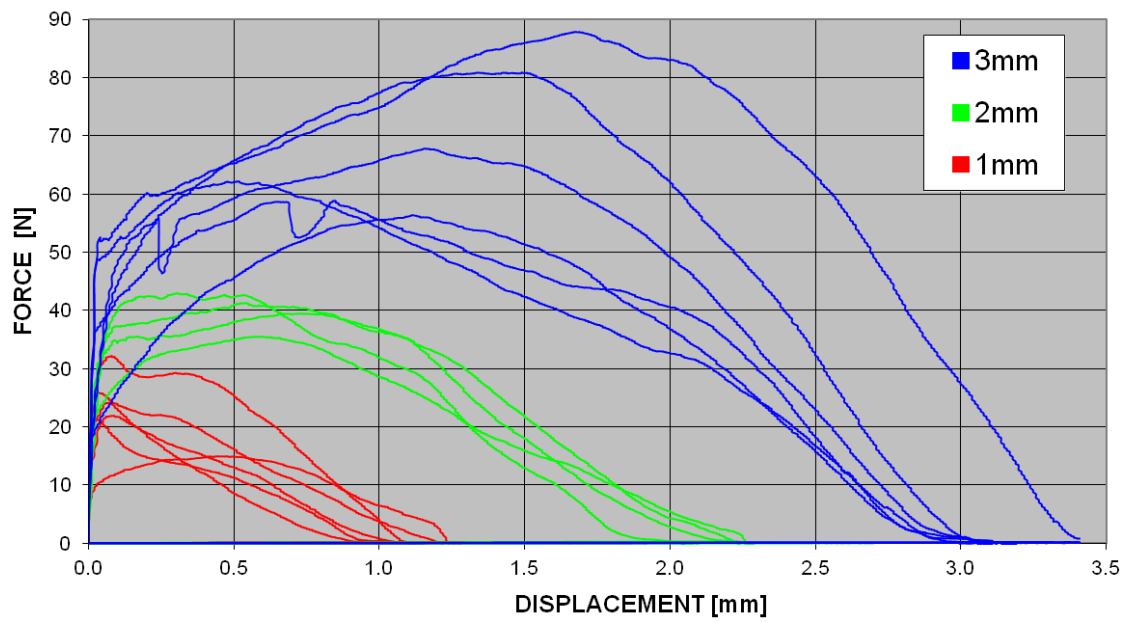


Figure 5.8 Pull-out curves - Method C, single 0.51 mm Z-Pin, QI laminate: various embedded lengths

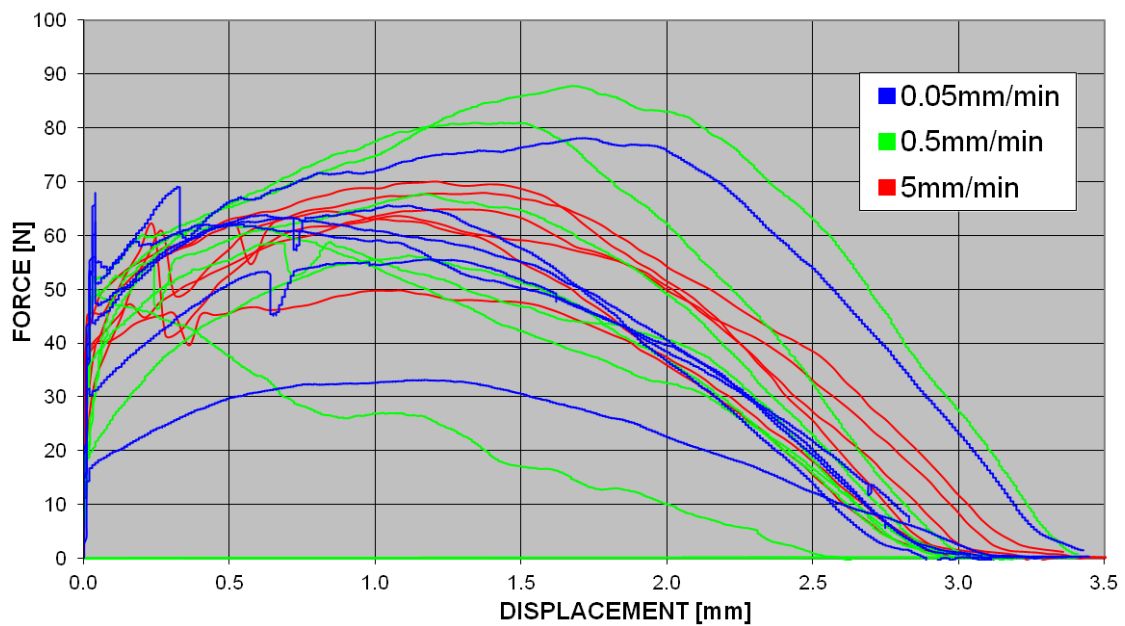


Figure 5.9 Pull-out curves - Method C, single 0.51 mm Z-Pin, QI laminate: various pull-out speeds

5.2.2 DATA REDUCTION

Introduction

During each test the displacement **a** (mm), and the load cell force **P** (N) were recorded at a rate of 100/sec. The cross-head speed was set at 0.5 mm/min (except for the specimens tested for 0.05 mm/min and 5.00 mm/min). The test was carried beyond the breakage of the specimen to establish a visible plateau in load value. The following values were derived:

P₀ – force at the end of linear part of the curve (see **Figure 5.10**)

P₁ – first maximum force or the force at first strongly defined drop

P₂ – force right after the first drop

P₃ – maximum force of the frictional sliding phase (or equal to **P₂** if the force gradually decreases after **P₂**)

P_{max} – the maximum force in the entire process

a₀ a₁ a₂ a₃ – displacements corresponding to the above forces, respectively

a_{max} – displacement at the point where force drops to 0

U – energy consumed in pull-out process, measured from the area under the curve

U/a_{max} – normalised pull-out energy (for group of four Z-Pins it was U/a_{gsum} in Method A and U/4·a_{max} in Method B, where a_{gsum} was sum of four Z-Pin's lengths measured post-mortem)

$\tau_f = \frac{U}{\pi \cdot d \cdot (a_{\max} - a_1)^2}$ - frictional stress in the sliding phase (after Cartié [72])

$\tau_d = \frac{P_1}{\pi \cdot d \cdot a_{\max}}$ - adhesion stress (**d** – Z-Pin diameter)

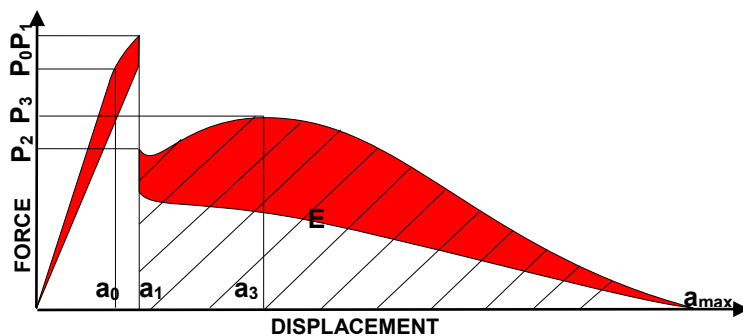


Figure 5.10 Pull-out curve

Method A – Pull-Out Energy

In case of single Z-Pin specimens, the pull-out energy U (and U/a_{max}) was approximately 0.150 J (0.050 J/mm). The influence of lay-up (QI or UI) and of the pinning depth on the value of the pull-out energy seemed to be small (see **Figure 5.11**).

Due to the formation of the chamfer during the pinning process in Method A, in many cases the “working” and “holding” parts did not function as expected and the Z-Pin was likely to be pulled out from either part. There actual embedded lengths could be read from the pull-out curves or post mortem measurements.

In case of four Z-Pin specimens (**Figure 5.11**) the pull-out energy of QI laminate (0.605 J for “close” to 0.825 J for “far”) was more than twice that for UD lay-up (0.261 J for “close distance” to 0.334 J for “far distance”). The pin distance (“close” and “far”) in four Z-Pin specimens appeared to have a deciding influence on the value of U/a_{max} : around 0.045 J/mm for “close” and twice as much, 0.090 J/mm for “far”. There was no reason for such an effect and this was more likely to be due to the different pre-forms and “grey” and “brown” Z-Pins used.

In case of four Z-Pin specimens, on many occasions the Z-Pins were pulled from both parts of the specimen (e.g. three from one part and one from the other, or two from one part and two from the other). Also, due to low pinning quality, many pins were not fully embedded and some failed to reach the delamination surface (hence, some multi-pin specimens actually contained only three or two working Z-Pins).

Also, in numerous four Z-Pin specimens each of the four Z-Pins were inserted under a different angle, which caused additional resistance during the pull-out process – higher pull out forces and, hence, higher pull-out energy.

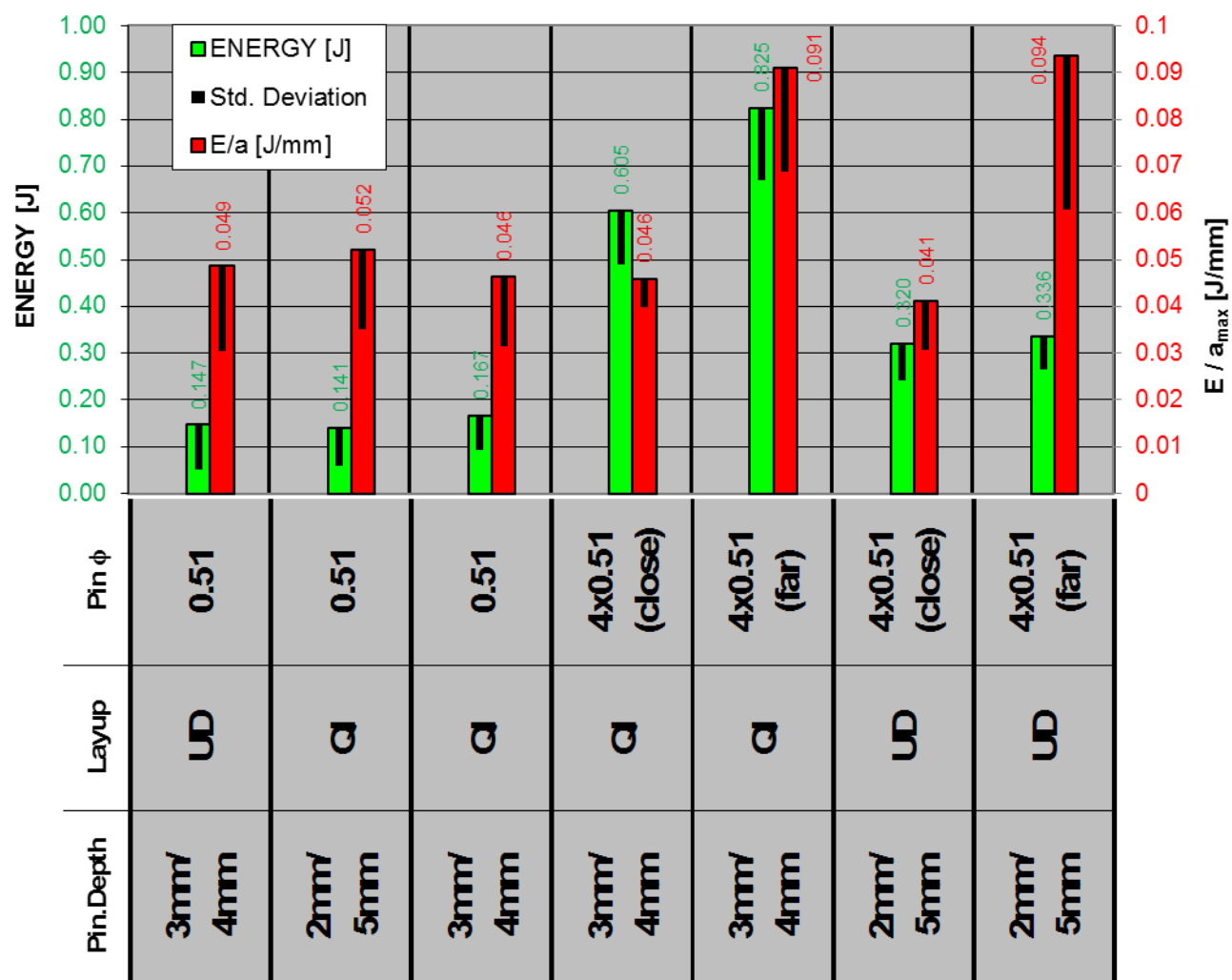


Figure 5.11 Pull-out energy chart – Method A

Method A - Adhesion and Frictional Stress

A remarkable influence of lay-up on the value of τ_d was observed, which reached nearly 40 MPa in case of UD laminate and approximately half of this value in case of QI laminate. The magnitude of τ_f for the 3 mm “working part” UD and QI laminate specimens was from 20 MPa to 17 MPa, while for the 2 mm “working part” QI specimens it was higher, reaching 25 MPa (note that many Z-Pins were pulled out from “holding part” here). Details can be seen on **Figure 5.12**.

Due to low quality of four Z-Pins specimens (i.e. pins not fully embedded, pulled out of either part, etc.) the values of τ_d and τ_f were not calculated.

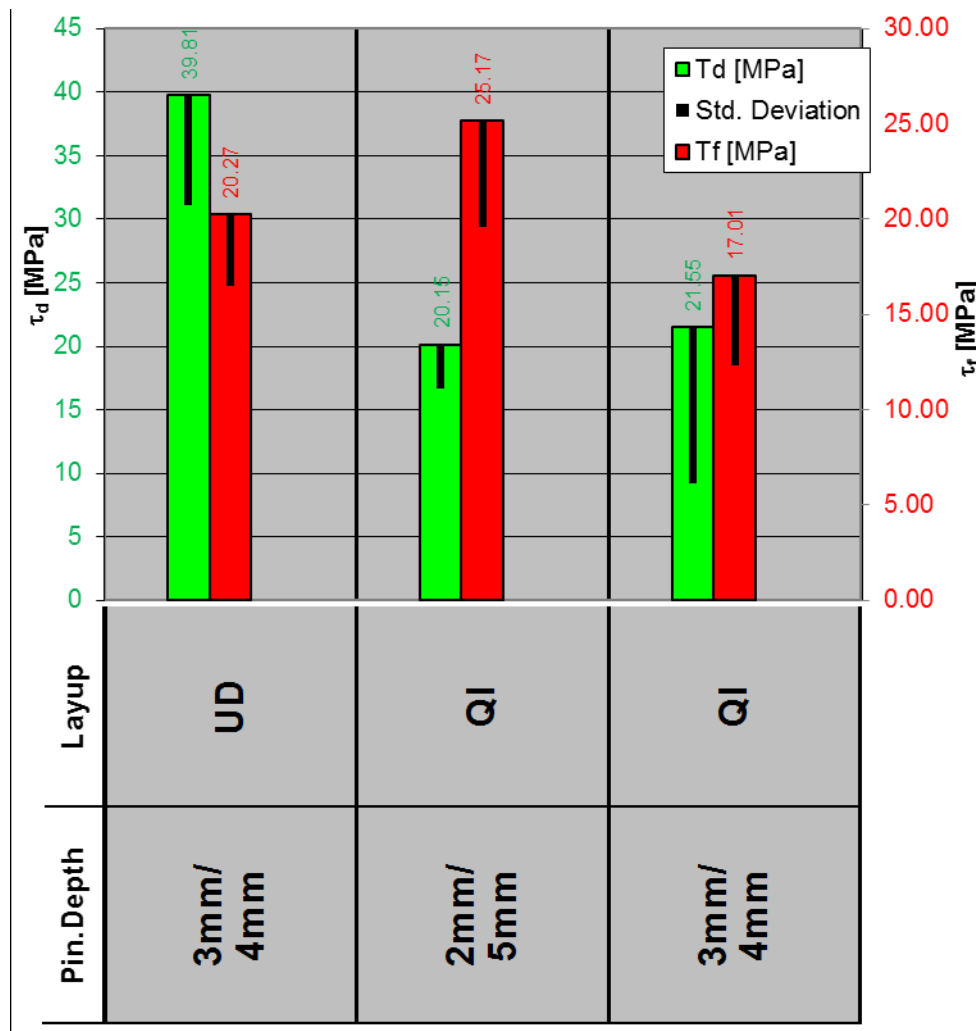


Figure 5.12 Pull-out “adhesion” and “frictional” stress chart – Method A, single 0.51 mm Z-Pins

Method A – Pull-Out Force and Displacement

A striking influence of lay-up on the magnitude of the force P_0 and P_1 was observed (see **Figure 5.13**). In case of UD laminate the forces P_0 and P_1 reached values of 170 N, nearly twice the values observed in case of QI laminate, approximately 90 N-110 N. In all cases force P_3 was slightly higher than P_2 . In case of QI laminate with 3 mm embedded length the second maximum P_3 seemed to be much later along the curve than in other cases.

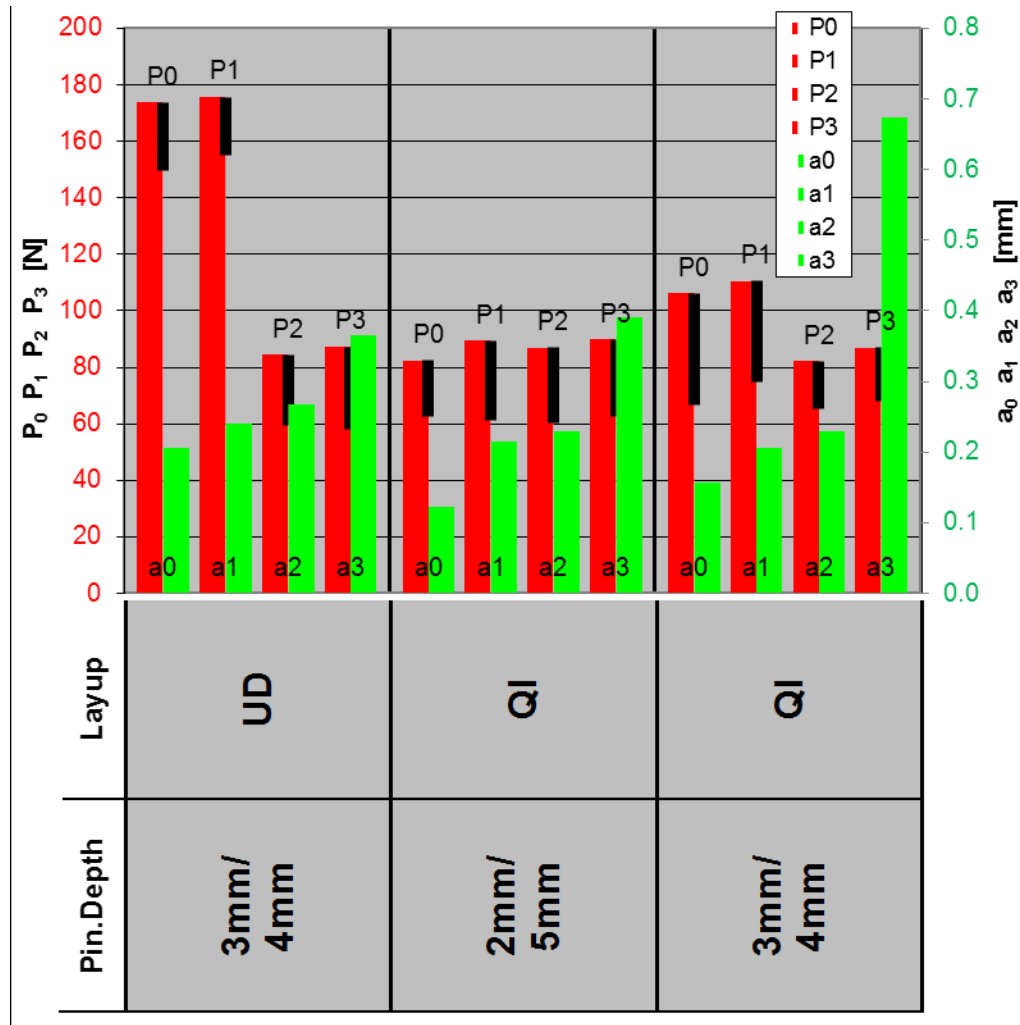


Figure 5.13 Pull-out force at specific points and corresponding displacement chart – Method A, single 0.51 mm Z-Pins

Method C – Pull-Out Energy

In case of single Z-Pin specimens the lay-up did not seem to have an influence on the pull-out energy or the value of U/a_{max} . However, in case of four Z-Pin specimens the energy was slightly higher in QI (0.56 J) than in UD (0.45 J) laminate. (See **Figure 5.14**)

Pull-out Energy in single 0.28 mm Z-Pin specimens (approximately 0.06 J) was exactly half of that in single 0.51 mm Z-Pin (approximately 0.13 J), which in turn was four times lower than in group of four Z-Pins specimens (0.44 J-0.57 J). (Details on **Figure 5.14**).

Pull-out speed did not seem to play an important role for the recorded values of U .

Pull-out energy showed a rapid grow with the Z-Pin length (note that the measurements were made for only three different lengths).

In four Z-Pins specimens the lay-up showed stronger influence on the pull out energy (0.44 J-0.47 J for UD and 0.56 J - 0.57 J for QI) than the distance between the Z-Pins. This pattern was not observed in single pin specimens, where pull-out energy reached 0.13 J for 0.51 mm Z-Pins and 0.06 in 0.28 mm Z-Pins.

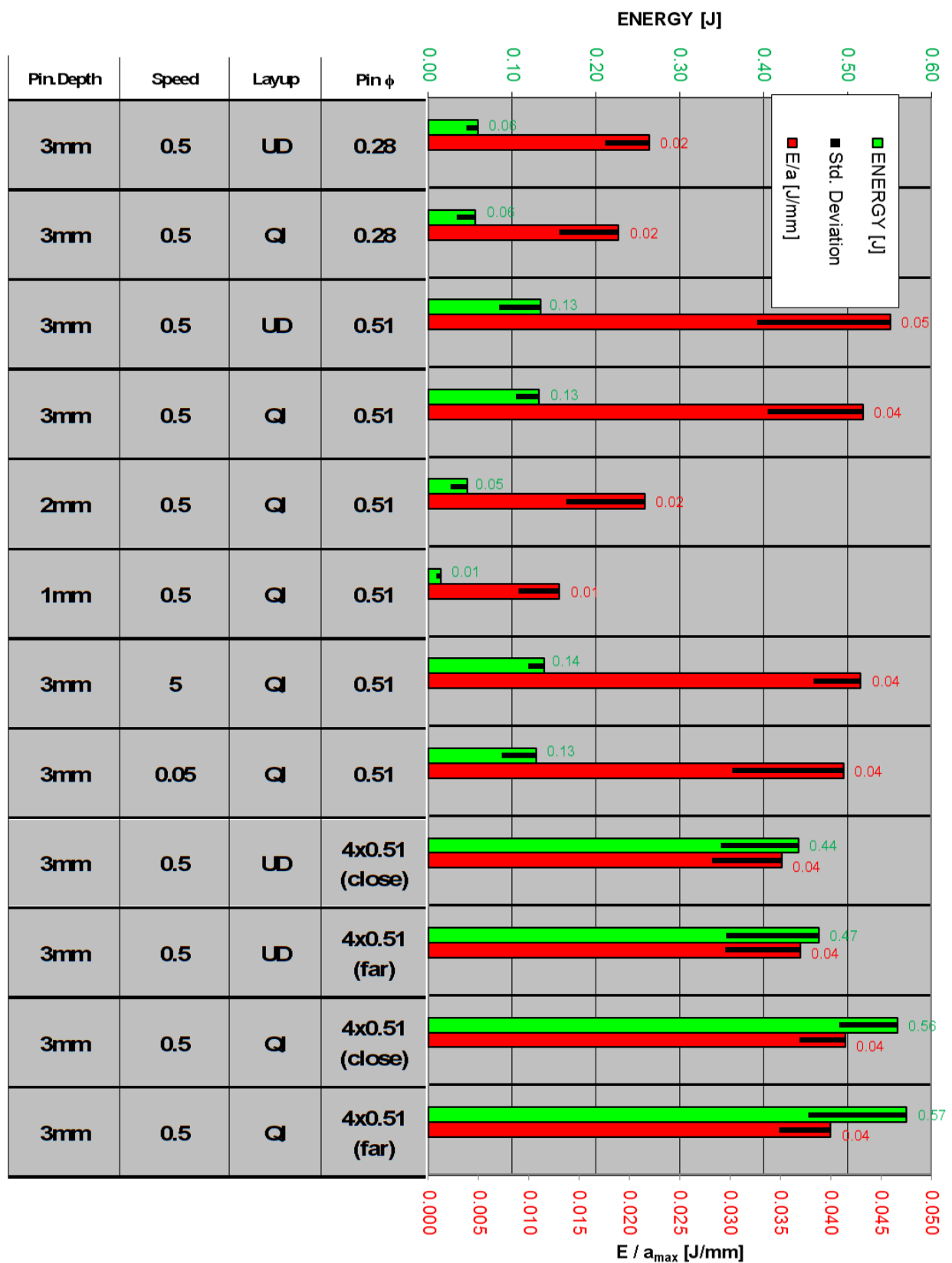


Figure 5.14 Pull-out energy chart – Method C

Method C – Adhesion and Frictional Stress

As observed in Method A, the “adhesion” stress seemed to be twice as high for UD than for QI laminate, for all Z-Pin diameters and configurations (see **Figure 5.15** for details). The “frictional” stress seemed less affected by the lay-up – higher for UD than for QI laminate in single pin specimens, and not visibly affected in four Z-Pins specimens.

Neither Z-Pin distance nor pull-out speed seemed to influence the values of τ_d and τ_f in any regular way - **Figure 5.15**)

Pinning depth did not seem to affect the “adhesion” or “frictional” stresses, however note the exceptionally high standard deviation of τ_d in case of 1 mm and 3 mm pinning depth. Independency of the value of the “adhesion” stress on the pinning depth seemed to confirm the lack of debonding on the Z-Pin interface until the first maximum of the force.

Multi Z-Pin pull-out tests on a wider range of pinning depths (1.2 mm, 2 mm, 4 mm, 6 mm and 8 mm) were described in [47]. The slope of the initial growth of the force was not significantly affected, however at 8 mm pinning depth the tensile failure of the Z-Pin was observed.

In four Z-Pins specimens τ_f was only slightly affected by lay-up and the distance between Z-Pins (13 MPa – 15 MPa). Yet τ_d was substantially higher in UD specimens (around 16 MPa) than in QI (around 9 MPa).

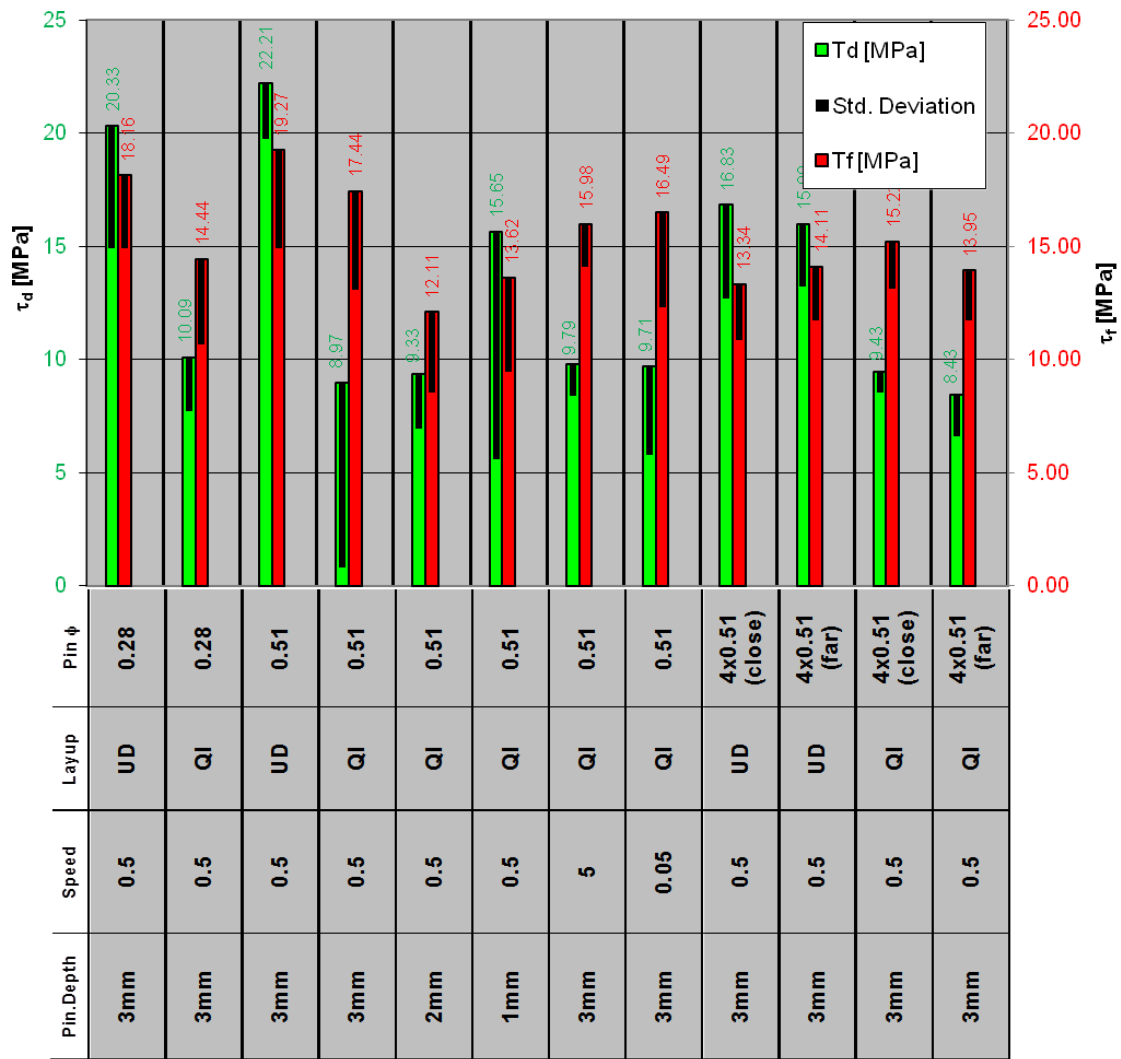


Figure 5.15 Pull-out “adhesion” and “frictional” stress chart – Method C, single 0.51 mm Z-Pins

Method C – Pull-Out Force vs. Displacement

Again, as in Method A, values of P_0 and P_1 in case of UD laminate seemed to be approximately twice higher than in case of QI laminate, in all configurations of single and four Z-Pins specimens. Also, the forces P_0 , P_1 , P_2 and P_3 seemed to follow similar pattern for single 0.28 mm, single 0.51 mm and group of four Z-Pin specimens.

Values of P_0 and P_1 showed strong dependence on pinning depth, being highest for the 3 mm.

Also remarkable was the position of the second force maximum, a_3 : it appeared at nearly twice higher displacement than in case of QI laminate (0.6 mm for 0.28 mm and around 1 mm for 0.51 mm Z-Pins) than UD. (Details on **Figure 5.16**)

Pull-out speed (**Figure 5.17**) and Z-Pin distance (**Figure 5.18**) did not show a significant influence on the pull-out forces.

Scatter

All the values, presented as an average of results of testing between 5 and 10 identical specimens, were characterised by remarkable scatter. In Method A specimens the scatter could be easily attributed to the low quality of the specimen preparation (acute insertion angles, lack of through the thickness penetration, splitting of the Z-Pin fibres). However, in Method C specimens process of manufacturing could not be a significant source of variability, hence the scatter was likely to be due to imperfections in the Z-Pins themselves, e.g. air bubbles, twist, changes of the shape of the cross-section along the z axis.

Summary

The pull-out process in all cases seemed to consist of the linear growth, finalised by a drop or a yield of the force, followed by a gradual growth until the second maximum. The character of the load-displacement curve seemed to be highly affected by the stacking sequence – QI or UD. In UD laminate the initial linear growth of the force was steeper (higher “adhesion” stress), reached a significantly higher value than in the QI laminate and ended in a substantial, rapid drop of the force. Also, although the subsequent growth of the force (after the initial peak and drop) was observed in nearly all cases, the higher values of the force were reached in UD laminate.

The embedded length seemed to have a strong influence on the force but did not show significant dependence on the “adhesion” stress.

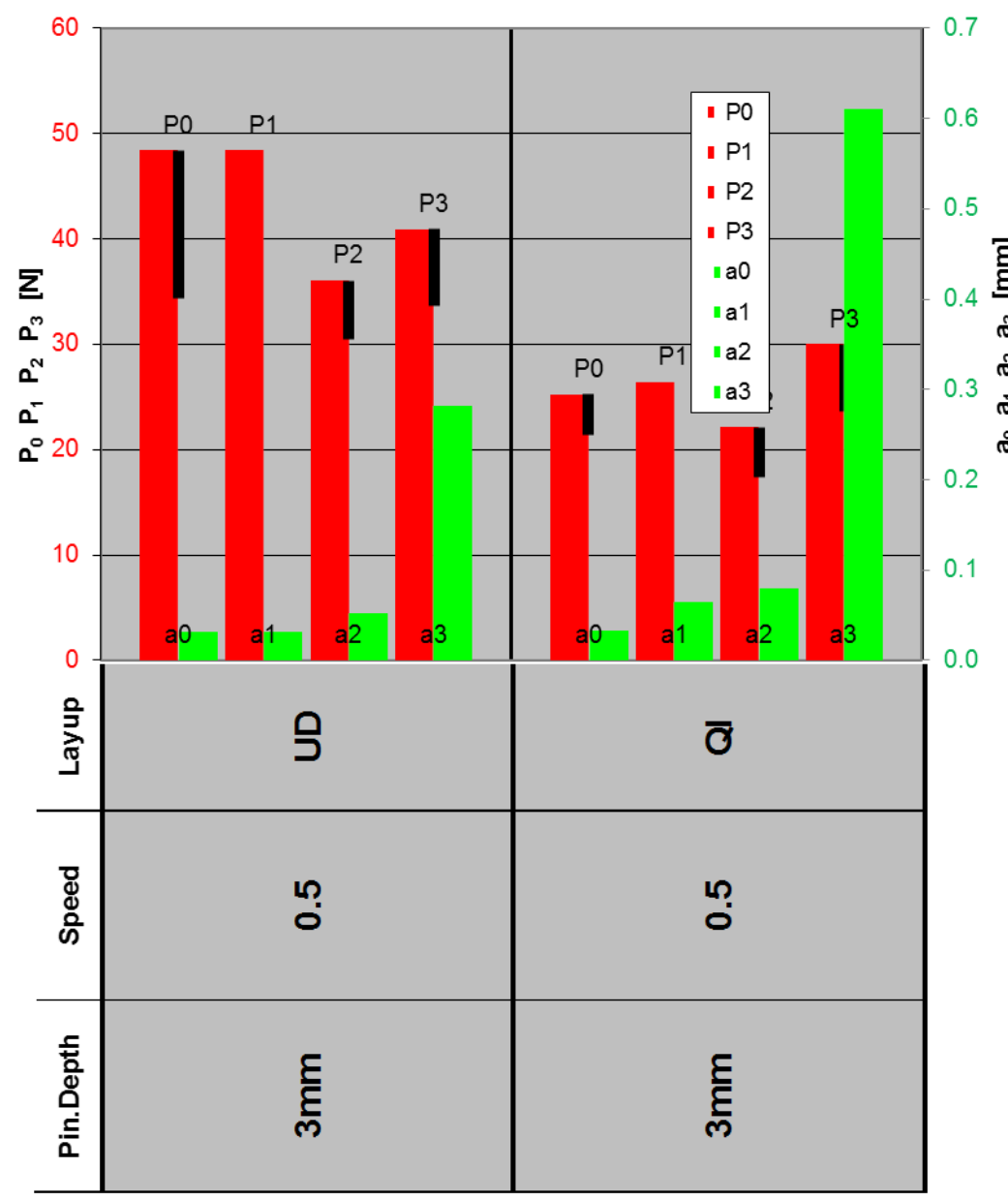


Figure 5.16 Pull-out force at specific points and corresponding displacement chart – Method C, single 0.28 mm Z-Pins (black lines indicate standard deviation)

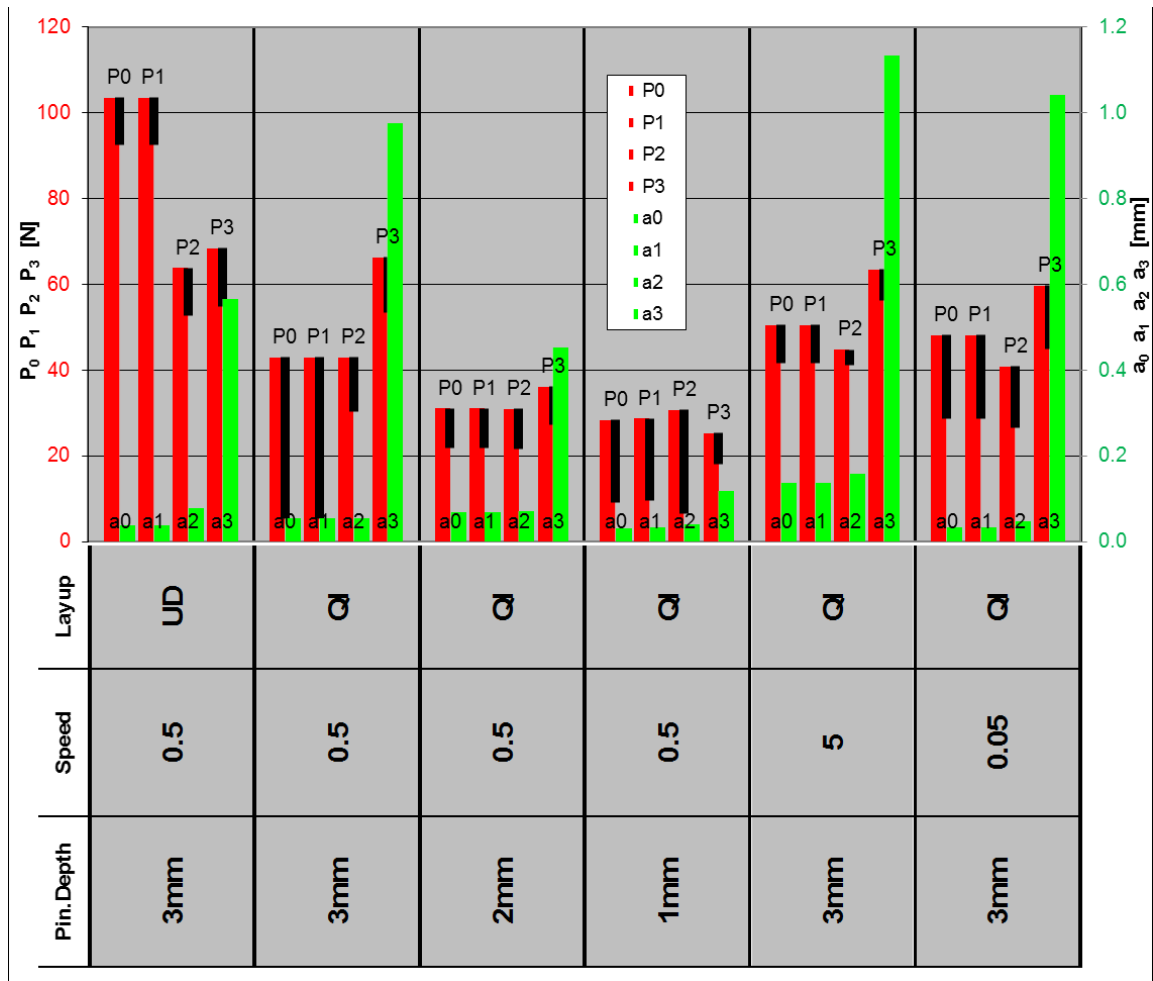


Figure 5.17 Pull-out force at specific points and corresponding displacement chart – Method C, single 0.51 mm Z-Pins (black lines indicate standard deviation)

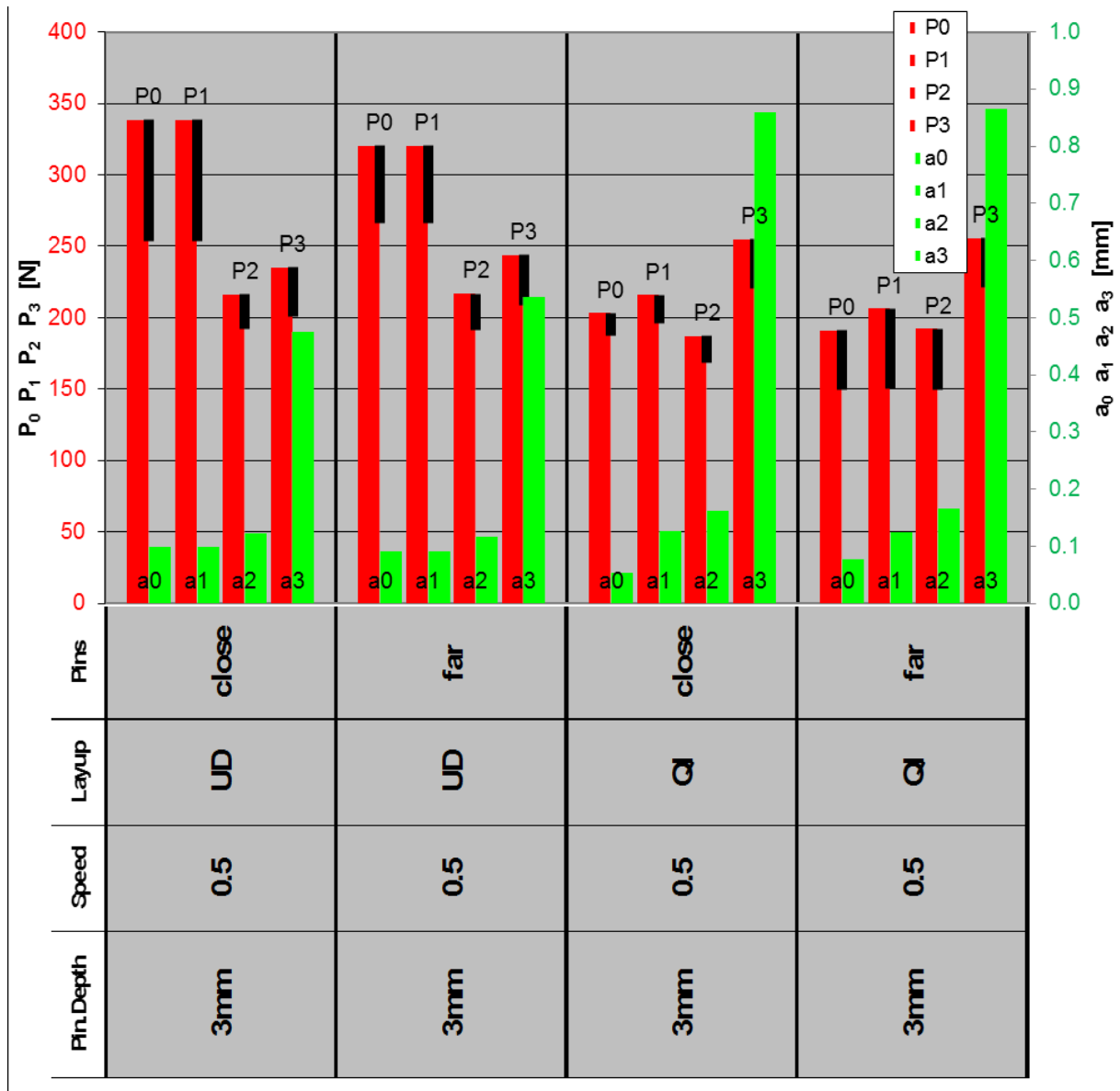


Figure 5.18 Pull-out force at specific points and corresponding displacement chart – Method C, group of four 0.51 mm Z-Pins (black lines indicate standard deviation)

5.2.3 MICROMECHANICS OF PULL-OUT

From the analysis of the pull-out graphs, the pull-out process can be divided into three phases, as summarised in **Figure 5.19** and **Figure 5.20**:

- **Linear phase**
- **Crack formation**
- **Frictional sliding**

Linear Phase

The first phase was considered to be the elastic stretch of the specimen. The force grew linearly until P_0 (and in most cases the force grew linearly until P_1). It was believed that no energy dissipation took place during this phase.

To confirm the elastic character of this phase, a number of specimens, which accidentally debonded from the specimen holders before the force reached the first maximum, were re-glued and the tests were performed again. The beginning of the pull out process was similarly linear, as shown on two examples of a single Z-Pin and a group of four pins specimens in **Figure 5.21**.

The displacement at the end of this phase oscillated around 0.03 mm (Method C) and the force could reach over 100 N in UD and over 40 N in QI single Z-Pin specimens or 400 N for a group of four Z-Pins (reaching approximately half of these values for 0.28 mm Z-Pins, accordingly). It is likely that the displacements measured were more associated with the compliance of the multi-mode testing rig than the specimen.

In case of Method A specimens the displacement at the end of the linear phase was significantly higher, reaching up to 0.3 mm for many UD laminate specimens. This was probably the result of higher compliance of the simple testing rig and the delicate load cell used. It may also be attributed to the non-zero insertion angles.

In a number of specimens the pull-out curve started to yield before reaching the first sharp maximum and could be seen as a change of the slope on the graphs, between P_0 and P_1 . It is

believed that the crack propagation in those cases started initially in a stable manner. Also, as the strength of cyanoacrylate glue bond between the composite and the steel of the specimen holder might be lower than the strength of the composite, the specimen might locally (in the area surrounding the Z-Pin, as suggested in **Figure 5.19**) disbond from the holder, which might result in the softening of the pull-out curve.

This phase seemed to be controlled by the strength of the bond between the Z-Pin and surrounding laminate. The failure at the Z-Pin interface occurred rapidly at the end of this phase – during Crack Formation

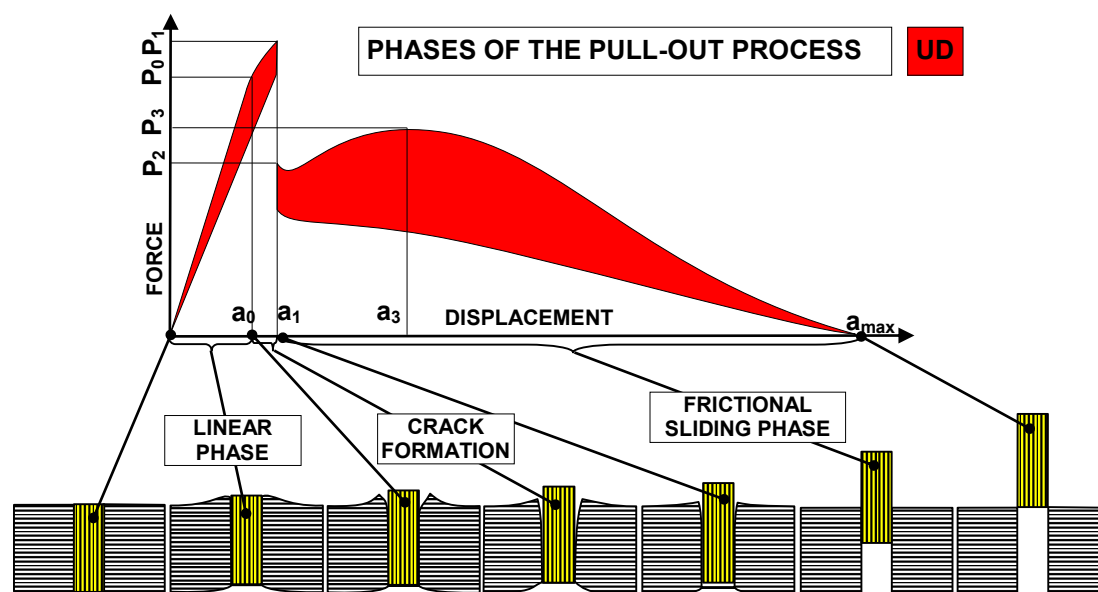


Figure 5.19 Phases of the pull-out process – UD laminate (red zone indicates the range of curves recorded in tests).

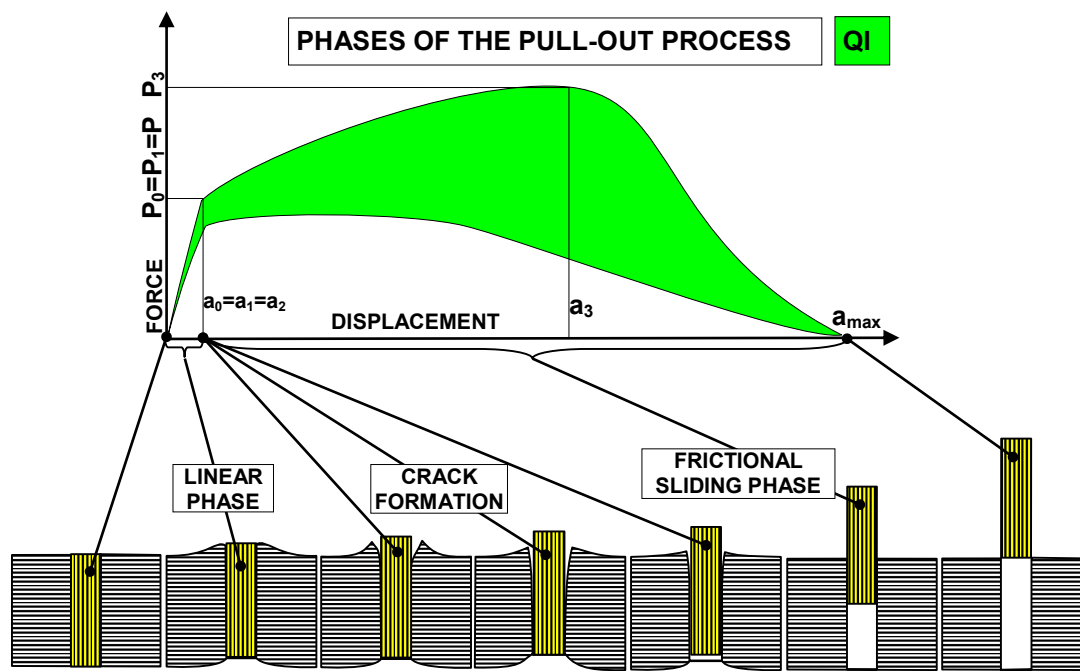


Figure 5.20 Phases of the pull-out process – QI laminate (green zone indicates the range of curves recorded in tests)

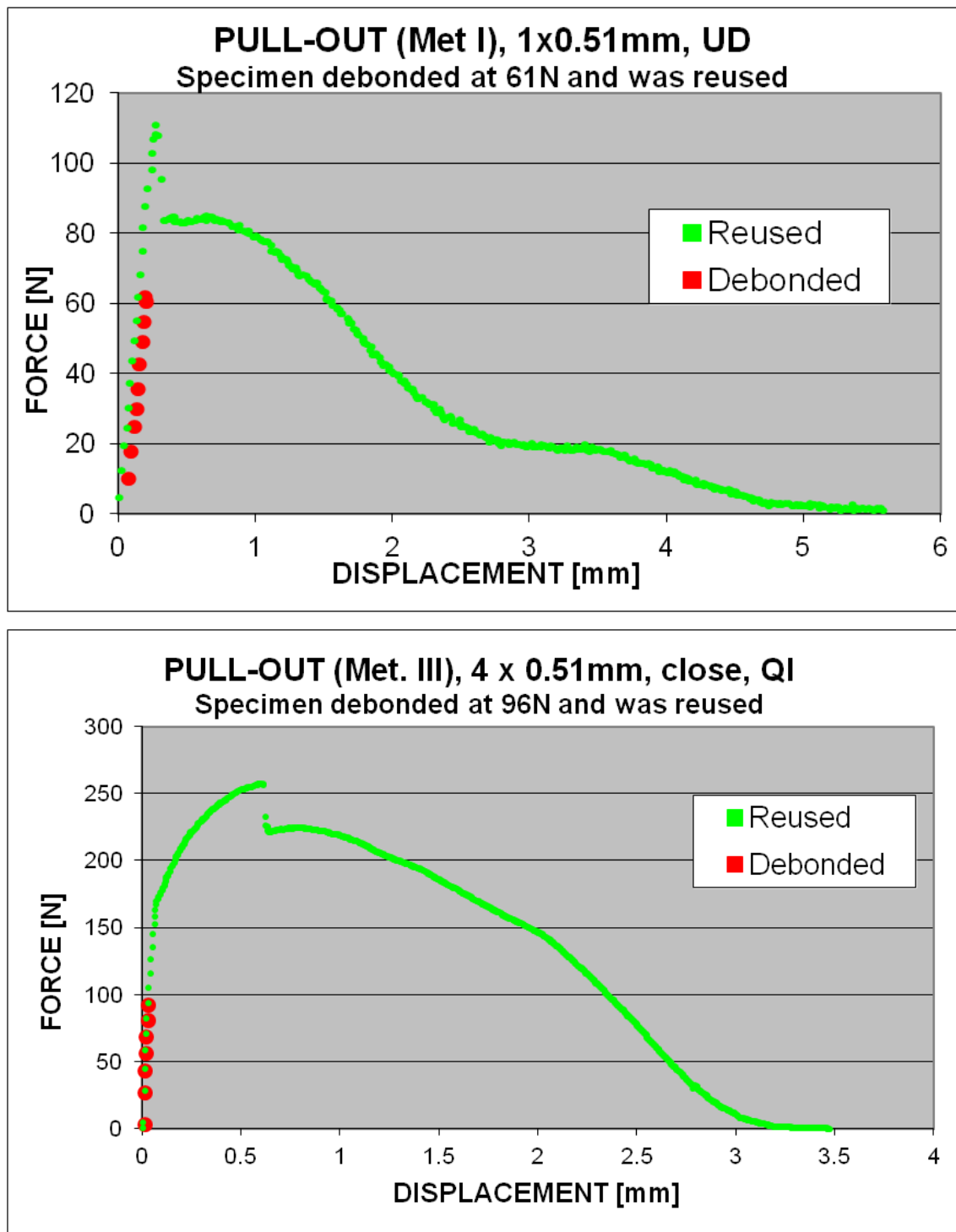


Figure 5.21 Force-displacement curves of specimens reused after accidental debonding from the rig during testing

Crack Formation

In most UD specimens the linear growth was followed by a rapid drop of the force from P_1 to P_2 (where P_2 was usually 30% - 50% lower than P_1). In case of QI specimens only small oscillations of the force were observed. This is believed to be the crack formation, when the Z-Pin gets debonded from the surrounding composite. The rapid drop observed in UD tests suggests unstable crack growth.

A clearly visible difference between QI and UD specimens pull-out curves was noticed during the tests. Z-Pins embedded in QI laminate seemed to be pulled out at significantly lower forces than those in UD laminate, with the first maximum P_1 reaching approximately twice as high values in UD than in QI laminate specimens. After this maximum a rapid drop in force occurred in UD specimens and only small force oscillations in QI specimens.

This behaviour was initially suspected to be an effect of different contact area between fibres of Z-Pin and the fibres of surrounding composite in QI and UD specimens. It was believed, that in the case of QI laminate, as the neighbouring layers restrict the separation of the fibres during Z-Pin insertion, and hence restrict the length of the resin pockets, the Z-Pins were surrounded “tighter” by the fibres of composite, giving larger fibre-to-fibre contact area. Assuming that friction between fibres (in direct contact, without resin in-between) could be much lower than between fibre and resin, the above phenomenon could be explained. However, no remarkable differences in shapes of resin pockets in QI and UD cases were observed on the micrographs.

This phenomenon could be better explained by the difference in the in-plane post-cure stresses in the QI and UD laminates. Due to the difference between shrinkage of the layers in the across-fibre and along-fibre directions, in case of QI laminate the in-plane stress had character of tension rather than compression, quite opposite to UD laminate. Due to higher thermal expansion coefficient in the direction across the fibres (controlled by resin) than along the fibres, subsequent layers stacked at an angle, mutually constrict the shrinkage of the neighbouring layers. Hence, the bond between Z-Pin and composite might be remarkably weaker in QI laminate. This phenomenon was also shown in the FE model presented in [68], causing disbonding around the Z-Pin in QI laminate and confirmed the lack of the second maximum on the force-displacement curves. The mismatch of the thermal coefficient of

expansion between the fibre and resin, causing post-cure compression of the Z-Pin was also investigated in [71] showing similar difference in the character of the post-cure thermal contraction in unidirectional and multi-directional laminates.

Also, voids in the Z-Pins (which could be visible on longitudinal cross-section micrographs) collapsing under the pressure from the surrounding UD laminate during cure could give the additional grip and, hence, higher pull-out force due to the mechanical interlocking.

Frictional Sliding Phase

After the crack formation, the fully debonded Z-Pin began sliding out of the composite. Assuming a constant frictional shear stress between the Z-Pin and the laminate, the force should gradually drop down to zero. However, for the great majority of specimens, the force started growing again up to value P_3 , in a number of cases reaching values higher than the first maximum preceding the rapid drop.

Unexpectedly, a growth of the force during the sliding phase was observed in practically all the pull-out tests, for QI and UD specimens. Initially, this phenomenon was believed to be the effect of the chamfers formed at the ends of the Z-Pins during UAZ insertion (Method A), which could plough through the composite. However, the pull-out experiments performed on the specimens produced using insertion Method C (where due to manual insertion, the chamfer, usually caused by the ultrasonic hammer could not form) also showed the growth of the force, consistently.

Growth of the force during the sliding of the Z-Pin, showing similar character to the one observed in this thesis, was reported in the recent pull-out tests [67,48]. The growth was attributed by the authors to the “snubbing” effect, or “enhanced friction” between the Z-Pin and the edge of the laminate at the delamination. However, this effect could only be observed when the Z-Pin was inserted at an angle to the normal to the delamination surface (reported by authors to be approximately 13° - 14° and unavoidable during standard UAZ insertion method). The methods of insertion used in this thesis eliminated such large insertion angles. Each specimen was examined after pull-out and the offset of the Z-Pin angle was impossible to notice by naked eye, which suggested the deviation from straight angle below 2° . Such small an angle could not cause noticeable “snubbing”.

The growth of the force during Sliding Phase could be explained by a roughness of the surface of the Z-Pin. The microscope observations of the subsequent cross-sections (see **Figure 4.10**), described in detail previously, revealed twist of the Z-Pin rods (approximately. 53° every 2.6 mm). This twist, in combination with the irregularity of the shape of the Z-Pin cross-section could cause a mechanical interlocking, which would give the observed growth of the force.

In UD laminate specimens, the growth of the force was more rapid, with the force reaching the maximum earlier than in the QI laminate. This might be due to the effect of the residual compressive stress acting at the Z-Pin interface (in UD laminate), dominating the beginning of the frictional phase. Later on the effect of roughness seemed to have more influence.

To further investigate the phenomenon of the force growth during the Sliding Phase in the pull-out process a “pull-out – push-in” experiment was also undertaken. The specimens based on QI laminate with 0.51 mm Z-Pins were subjected to the pull-out tests. However, before final failure, the pull-out the test was stopped and the cross-head movement reversed, causing the Z-Pin to be pushed back into the laminate. Before the halves of the specimen contacted again, the process was reversed once more, pulling the Z-Pin out again. The recorded curves (**Figure 5.22**), show that the force during the push-in and subsequent pull-out did not reach the level of the first pull out. However, the push-in and the subsequent pull-out curves still seemed to follow the general character of the first pull-out curve on a much smaller scale – the minima and maxima were observed at the same displacements. During the second pull-out there was still a significantly high force recorded.

It suggested that during the pull-out process the roughness of the surface between Z-Pin – and the composite (caused by any irregularities of the Z-Pin surface, e.g air bubbles, twist of the fibres and irregular cross-section outline) was reduced by abrasion, however some roughness remained on the surface.

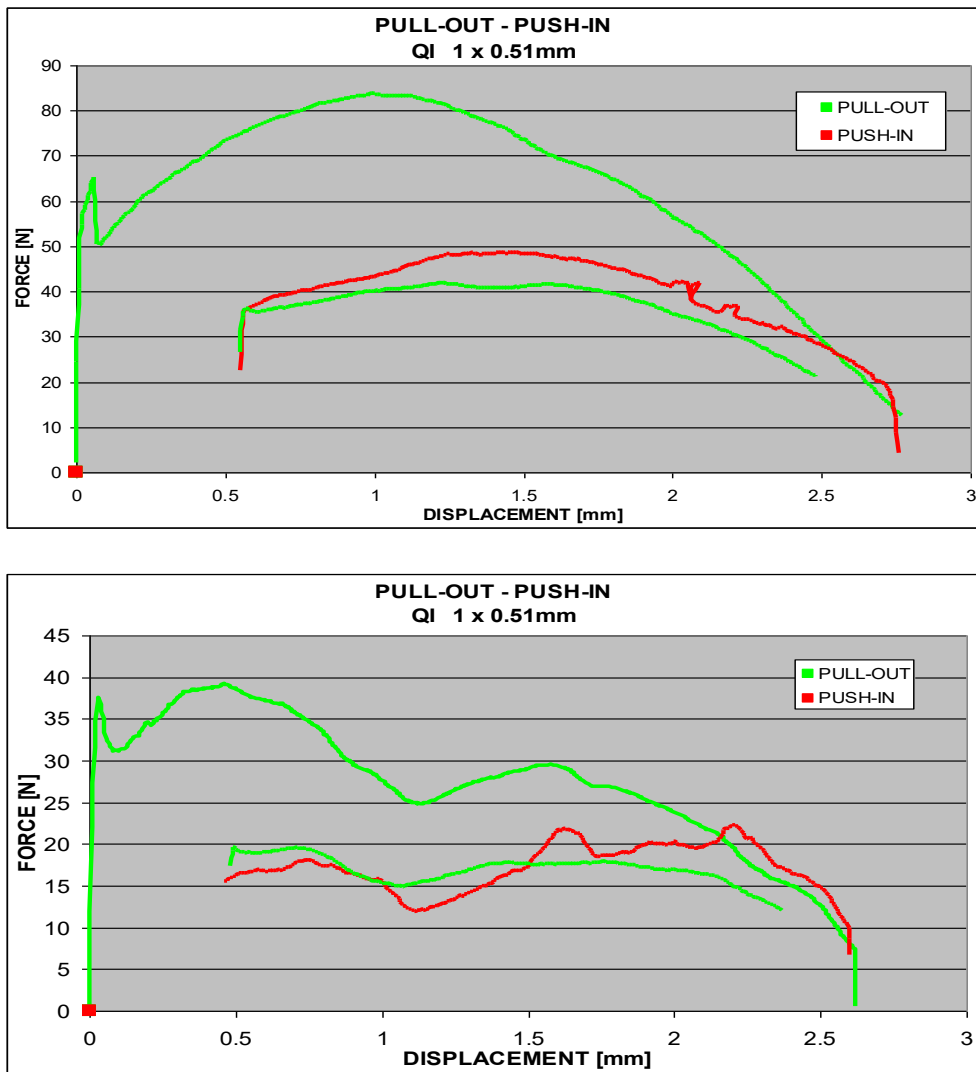


Figure 5.22 Pull-out – push-in tests results, QI, 1 x 0.51 mm Z-Pin.

It was also considered possible that an increase of the temperature during pull-out process, and possible change of the friction coefficient, could be responsible for the growth of the force during frictional phase. A change of the friction coefficient due to increase in temperature (from 20°C to 75°C) was reported in [84]. However, there were few differences in the character of the curves for the tests performed at different pull-out speeds (0.05 mm/min, 0.5 mm/min and 5.0 mm/min) indicating that this was most probably not the case.

5.3 SHEAR-OUT TESTS

5.3.1 RESULTS

Method B - Multi Mode Rig

Tests performed on the specimens based on Method B (UAZ Insertion - Excess Z-Pins removed from prepreg panel before preconsolidation) were the first attempt to shear-out testing and might be considered a trial, preceding the proper experiments of Method C (Manual Insertion - Z-Pinned after preconsolidation into the panel heated up to 50°C).

In general the tests of 0.51 mm and 0.28 mm diameter single Z-Pins (see **Figure 5.23**) seemed to follow a similar pattern of an initial linear growth of the force, followed by a short period of significantly less steep growth with a series of small, rapid drops, with a final rapid drop to near zero (where the actual pull-out process was considered finished, and the recorded negligible force was generated by the stump of the Z-Pin abrading against of the delamination surface).

As seen in **Figure 5.24** 0.51 mm Z-Pin specimens of UD laminate, sheared along and across the laminate fibre direction seemed to behave similarly, whilst QI laminate specimens showed much higher scatter than in case of UD laminate. In case of 0.28 mm Z-Pin specimens due to high scatter it is difficult to assess if the same phenomena occur, however the QI laminate specimens seemed to behave differently than UD (see **Figure 5.25**). For the range of embedded lengths investigated, the embedded length did not seem to have a significant influence on the shear-out process, see **Figure 5.26** and **Figure 5.27**.

Specimens with group of four Z-Pins does not show any significant differences in cases QI and UD laminate specimens (see **Figure 5.29**). The tests of the group of four Z-Pin specimens showed slightly steeper initial force-displacement slopes in case of close Z-Pin pattern, see **Figure 5.28**.

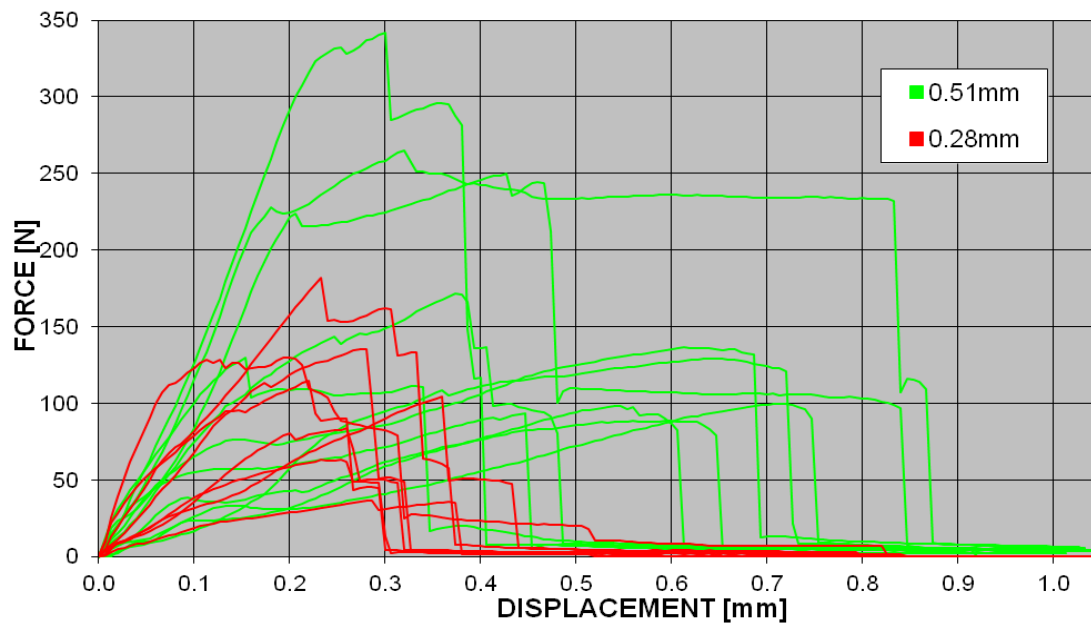


Figure 5.23 Shear-out curves - Method B, single Z-Pin, QI laminate: 0.51 mm vs. 0.28 mm Z-Pins

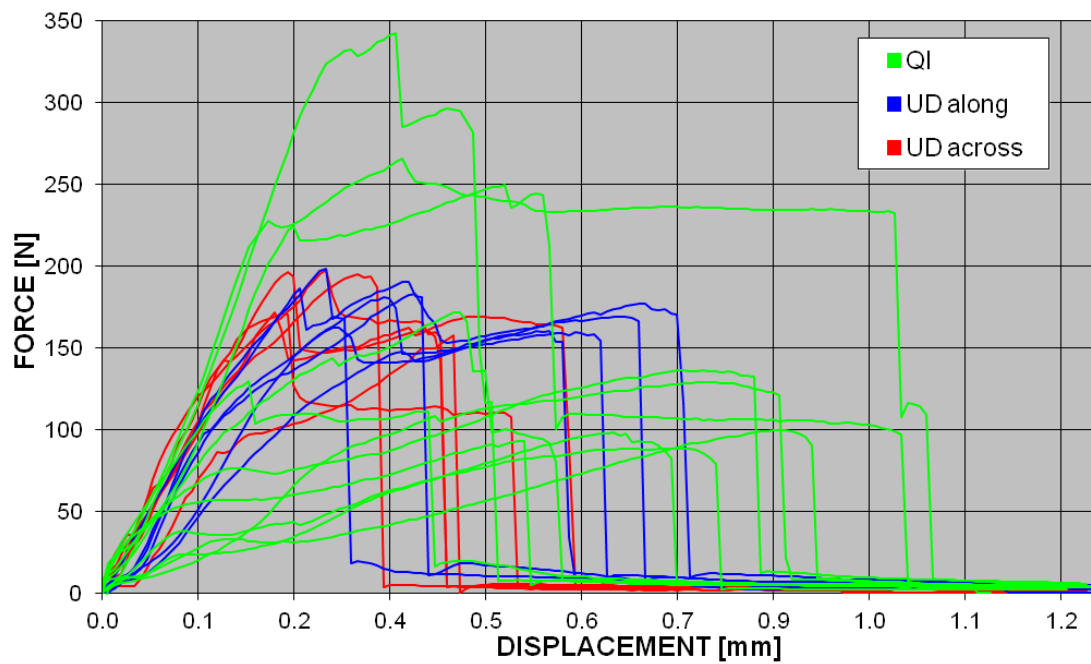


Figure 5.24 Shear-out curves - Method B, single 0.51 mm Z-Pin, medium spring: QI vs. UD “along” and “across” laminate

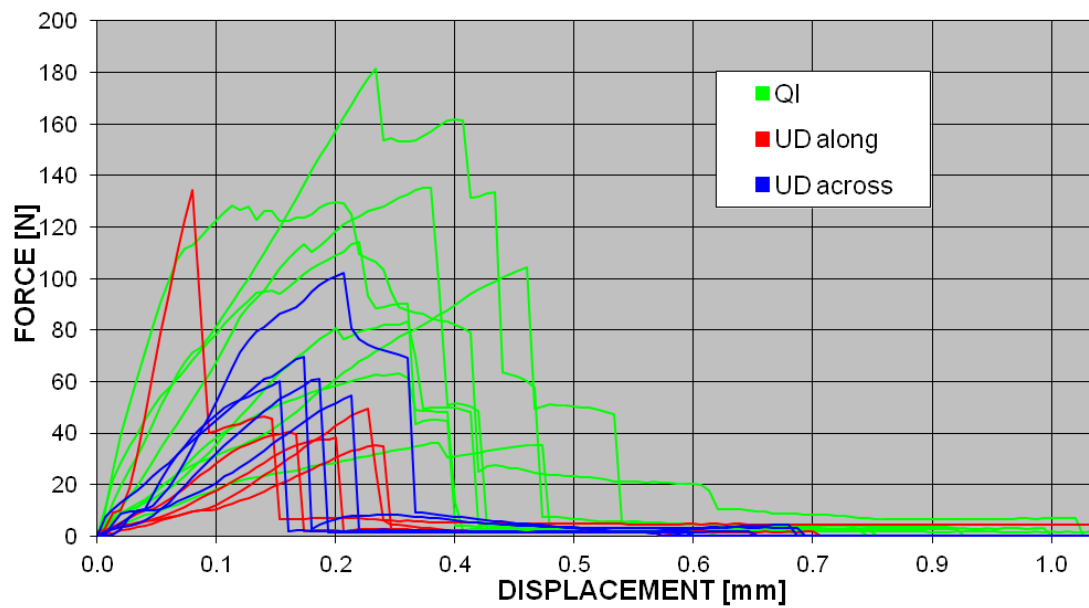


Figure 5.25 Shear-out curves - Method B, single 0.28 mm Z-Pin, medium spring: QI vs. UD “along” and “across” laminate

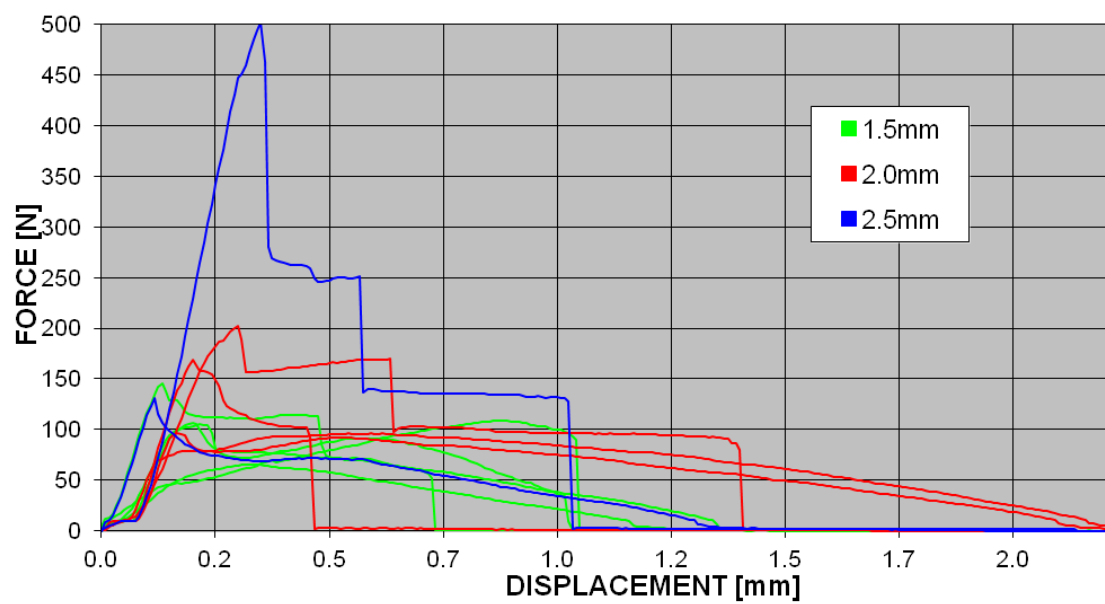


Figure 5.26 Shear-out curves - Method B, single 0.51 mm Z-Pin, QI laminate, soft spring: various embedded lengths

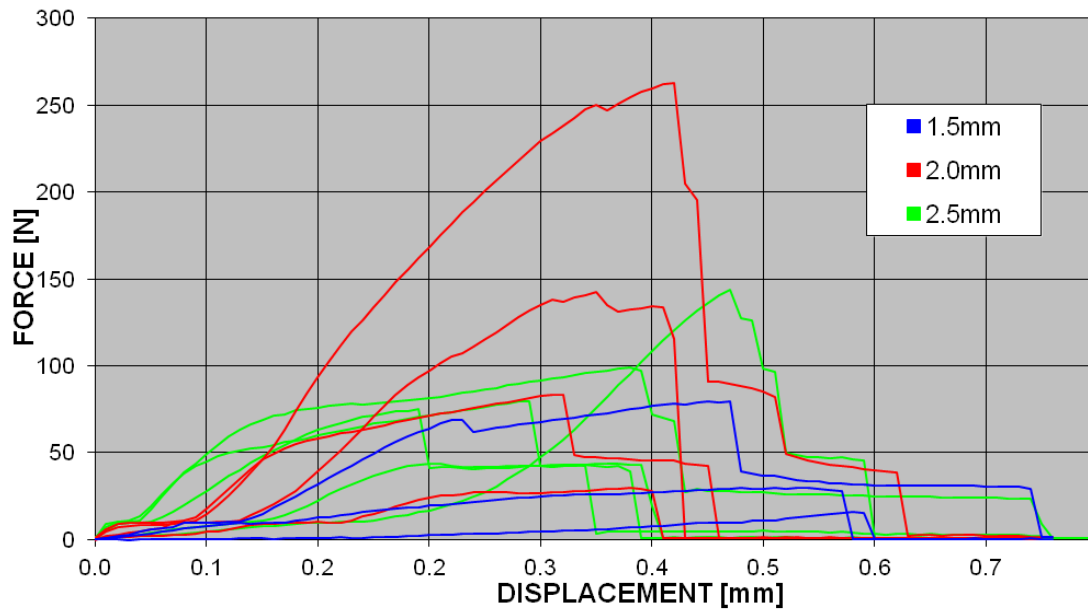


Figure 5.27 Shear-out curves - Method B, single 0.28 mm Z-Pin, QI laminate, soft spring: various embedded lengths

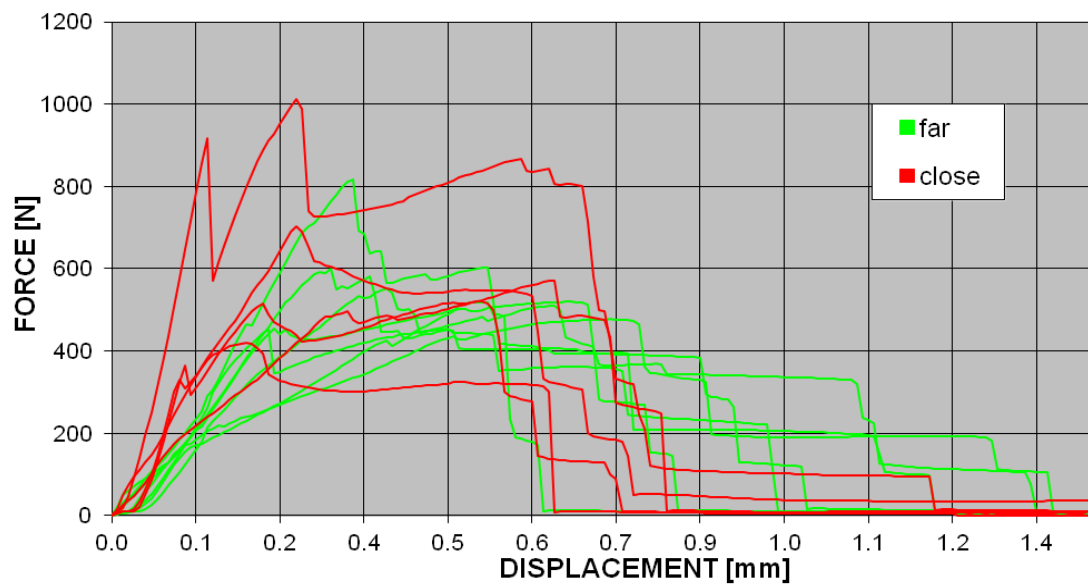


Figure 5.28 Shear-out curves - Method B, group of four 0.51 mm Z-Pin, medium spring: “far” vs. “close” Z-Pin pattern

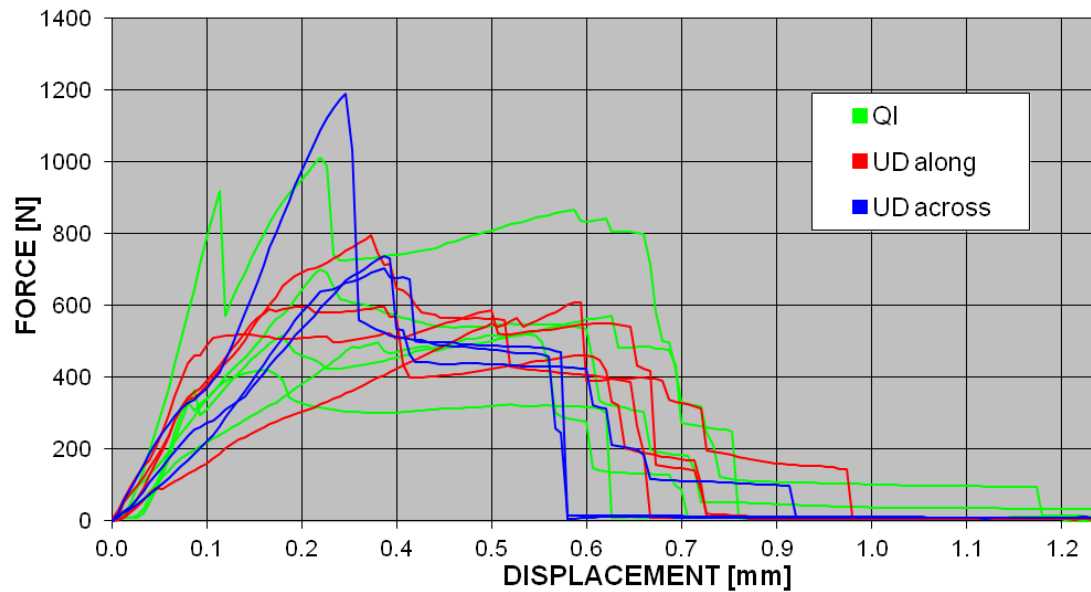


Figure 5.29 Shear-out curves - Method B, group of four 0.51 mm Z-Pin, “close” pattern, medium spring: QI vs. UD “along” and “across” laminate

Method C - Multi Mode Rig

In general, the results of Method C experiments (manual Z-Pin insertion into prepared holes) seemed to agree with those based on Method B (UAZ Z-Pin insertion), however the observed scatter was significantly lower. As an example, the comparison of the scatter of the tests results for the single 0.51 mm Z-Pin in QI laminate using Method B and Method C is shown in **Figure 5.30**.

Notably higher scatter was recorded in 0.28 mm specimens, compared to 0.51 mm specimens, in all testing configurations, see **Figure 5.31** and **Figure 5.32**. In shear-out tests 0.28 mm Z-Pins seemed to break soon after the beginning of the experiment, so the recorded data might be insufficient for any reliable analysis. Also, due to their fragility many of the 0.28 mm Z-Pins specimens were lost during installation in the rig. Most of 0.28 mm specimens showed the same behaviour as the 0.51 mm ones, however the values of the force and displacements were approximately four times lower.

As could be seen on **Figure 5.31** the lay-up of the composite (QI or UD) and shear-out direction (across or along the fibres, in UD laminate) seemed to have a significant influence on the shear-

out behaviour. In case of UD sheared across fibres the force initially grew linearly up to approximately 150 N at 0.2 mm, which was followed by a drop and plateau of approximately 120 N finished with a rapid drop to zero. In case of QI and UD laminate sheared along the force grew (with a reduced slope than in UD laminate sheared across) up to 70 N – 80 N at 0.2 mm, followed by a further slight growth or a plateau, finished by a rapid drop to zero. In case of QI laminate the force growth seemed to be the less steep than in UD sheared along the laminate fibre direction.

Surprisingly, the shear-out process seemed to be only slightly influenced by the spring stiffness (see **Figure 5.33** and **Figure 5.34**), regardless of significant difference in opening forces recorded by each set of springs (visible in the plateau after the final drop, with higher values for stiffer springs). It could be due to rather small values of the opening displacement in all cases. The same pattern was repeated for all the spring stiffnesses, and only the case of UD laminate sheared across the laminate fibre direction seemed to be noticeably affected showing slightly higher forces for stiffer springs (see **Figure 5.35** and **Figure 5.36**).

The shear-out curves of 0.28 mm specimens show high scatter and it is difficult to find any patterns, see **Figure 5.37**.

The behaviour of four pin specimens seemed to follow the pattern of the single pin ones. The force reached up to 600 N, (surprisingly high for just four pins, but complying with the values achieved by single Z-Pins). The Z-Pins never broke at the same time, showing a patterns of various steps at the end of the process (see **Figure 5.39** and **Figure 5.40**).

For the various embedded lengths, 3 mm and 2mm lengths curves seemed similar. However the maxima of the force in case of 1 mm embedded length appeared at lower displacements, after which the force decreased gradually – not rapidly as in case of 2 mm and 3 mm embedded lengths. This might suggest that the Z-Pins embedded at 1 mm were slightly pulled out during the shear process before the final break and “ploughed” (this was not clearly visible post mortem). At 2 mm and 3 mm embedded lengths the pull-out did not occur (see **Figure 5.38**).

Also the distance between Z-Pins did not seem to have an influence on the shear-out process, as shown on **Figure 5.39** and **Figure 5.40**.

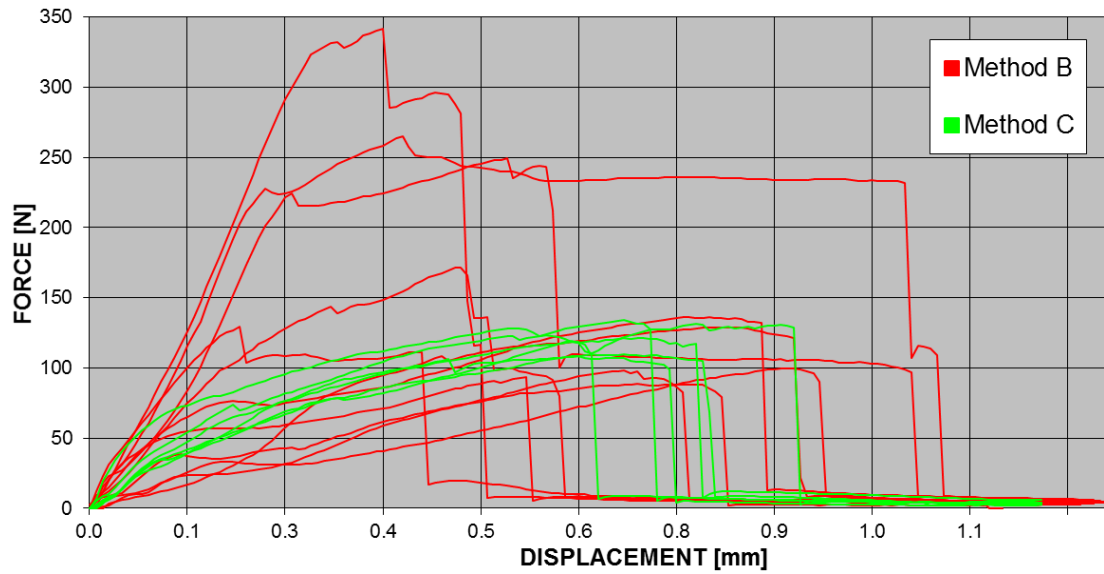


Figure 5.30 Shear-out curves - single 0.51 mm Z-Pin, QI laminate, medium spring: Method B vs. Method C

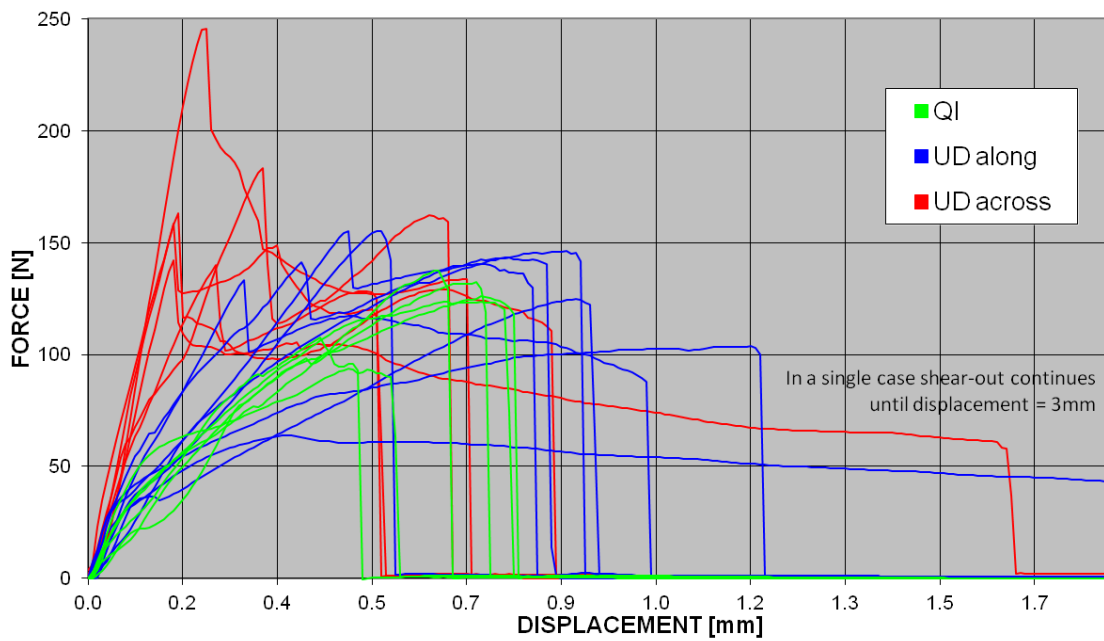


Figure 5.31 Shear-out curves - Method C, single 0.51 mm Z-Pins, soft spring: QI vs. UD “along” and “across” laminate

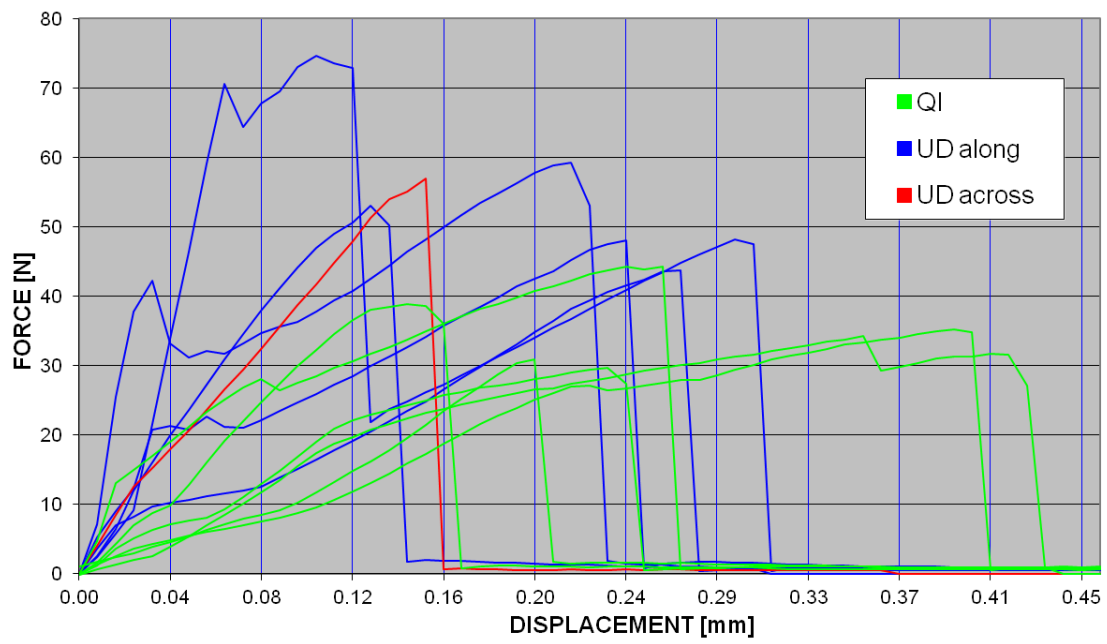


Figure 5.32 Shear-out curves - Method C, single 0.28 mm Z-Pins, soft spring: QI vs. UD “along” and “across” laminate

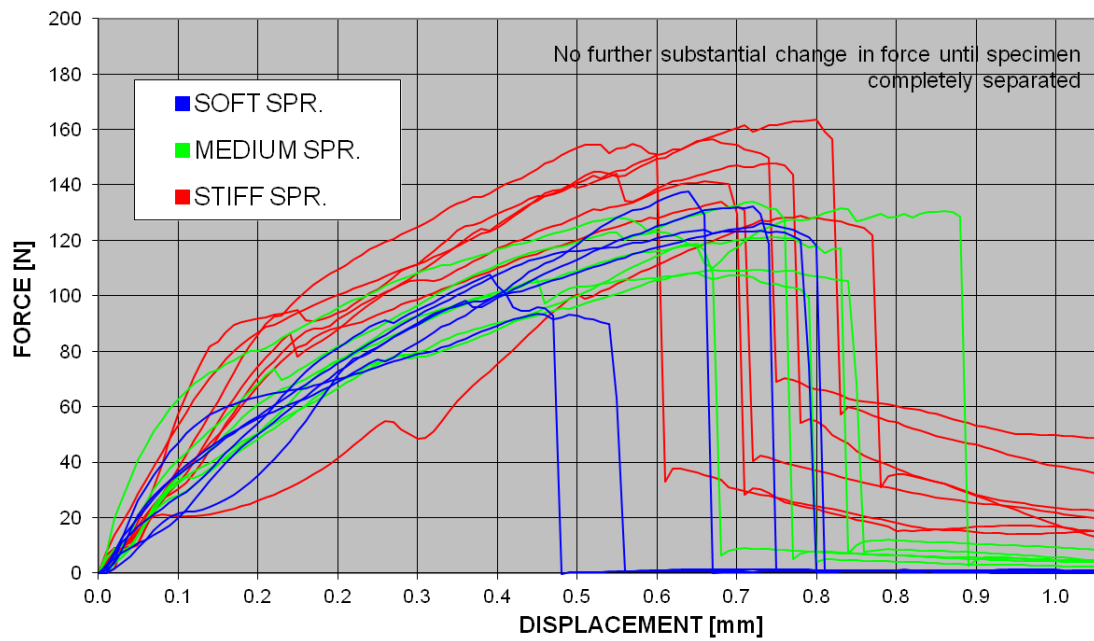


Figure 5.33 Shear-out curves - Method C, single 0.51 mm Z-Pins, QI laminate, soft spring: various spring stiffnesses

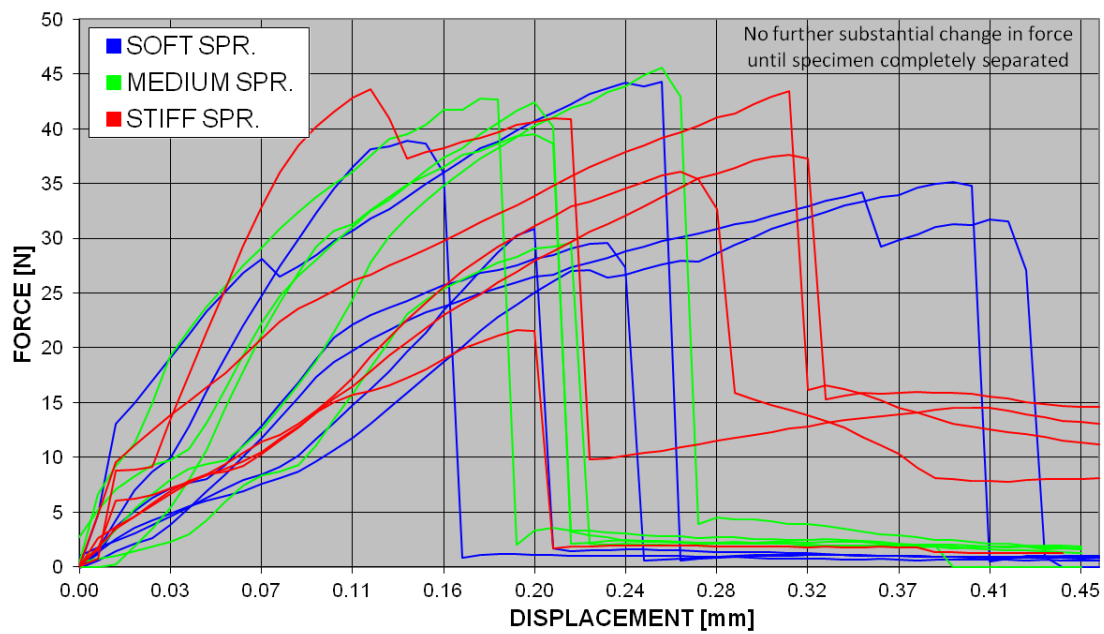


Figure 5.34 Shear-out curves - Method C, single 0.28 mm Z-Pins, QI laminate, soft spring: various spring stiffnesses

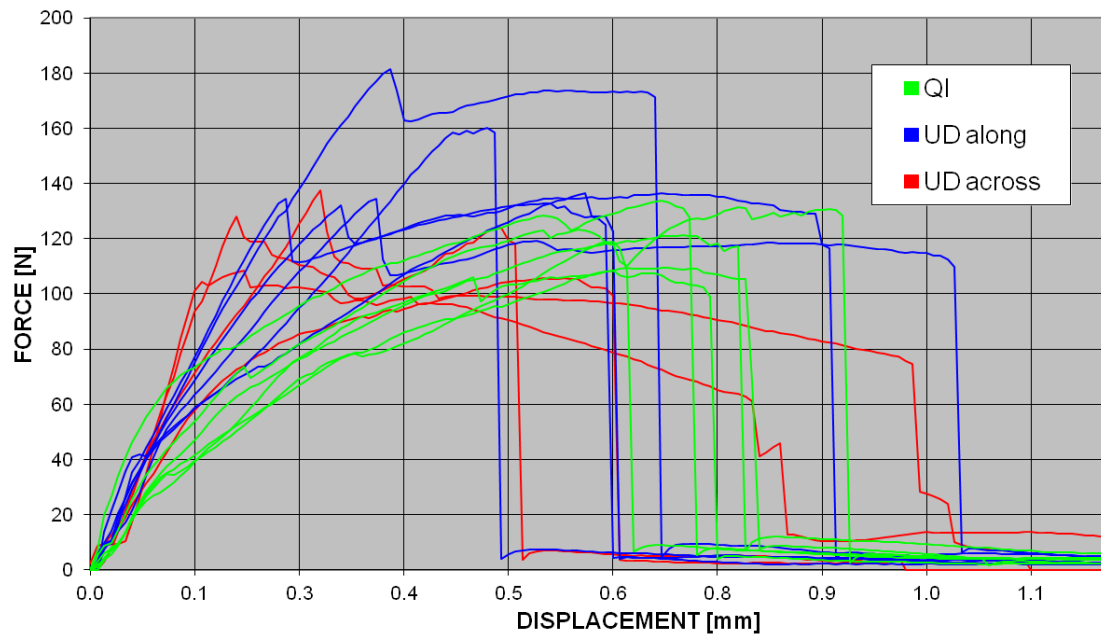


Figure 5.35 Shear-out curves - Method C, single 0.51 mm Z-Pins, medium spring: QI vs. UD “along” and “across” laminate

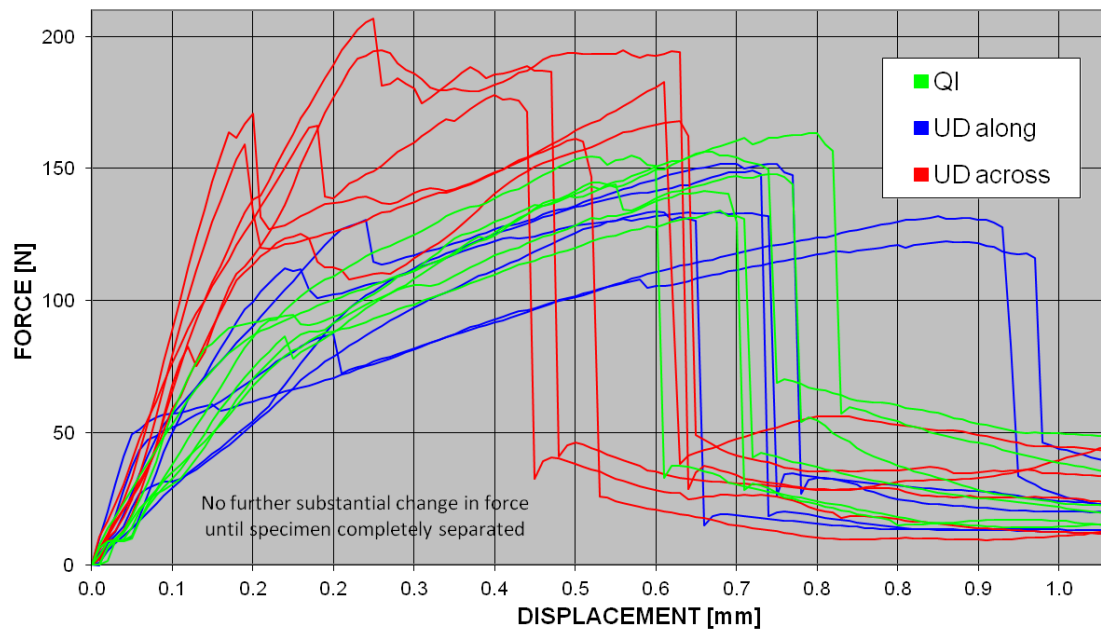


Figure 5.36 Shear-out curves - Method C, single 0.51 mm Z-Pins, stiff spring: QI vs. UD “along” and “across” laminate

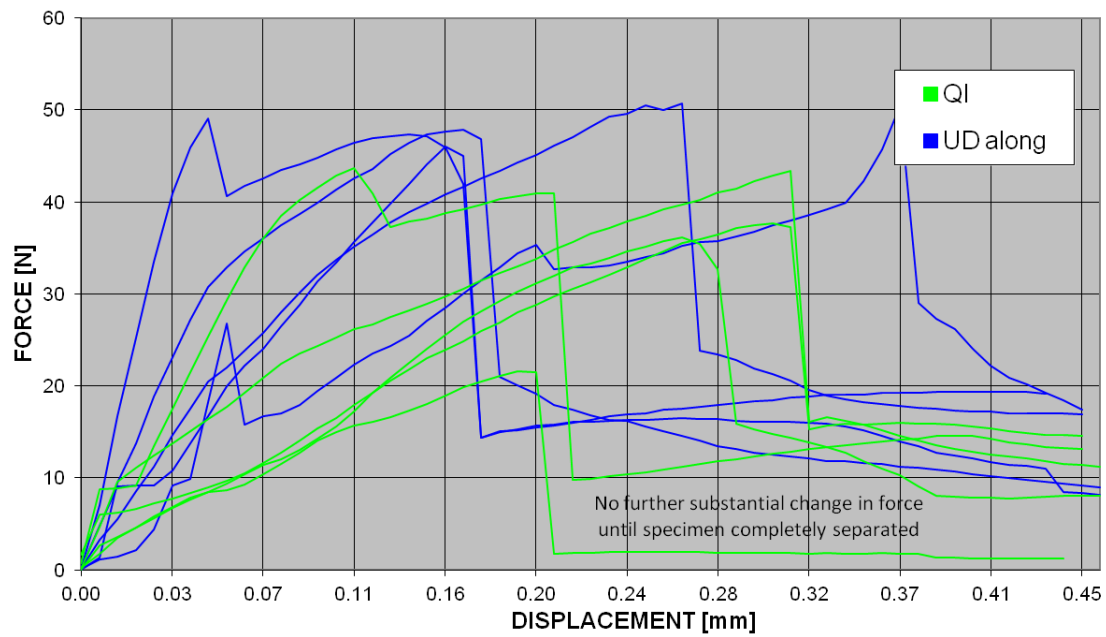


Figure 5.37 Shear-out curves - Method C, single 0.28 mm Z-Pins, stiff spring: QI vs. UD “along” laminate

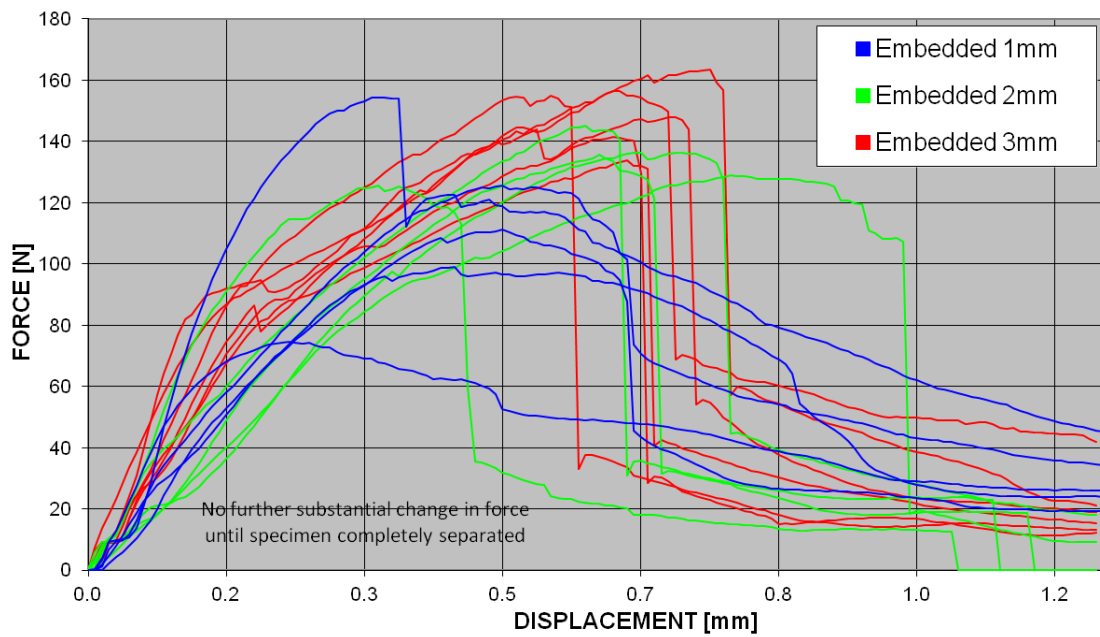


Figure 5.38 Shear-out curves - Method C, single 0.51 mm Z-Pin, QI laminate, stiff spring: various embedded lengths

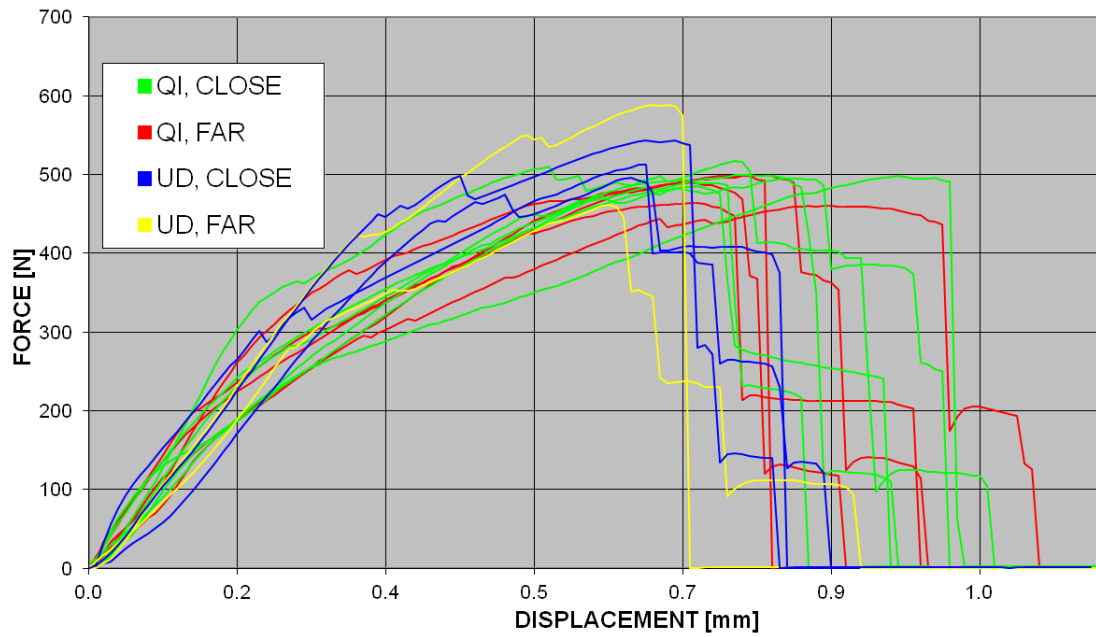


Figure 5.39 Shear-out curves - Method C, group of four 0.51 mm Z-Pins, soft spring: QI vs. UD laminate, “far” vs. “close” Z-Pin pattern

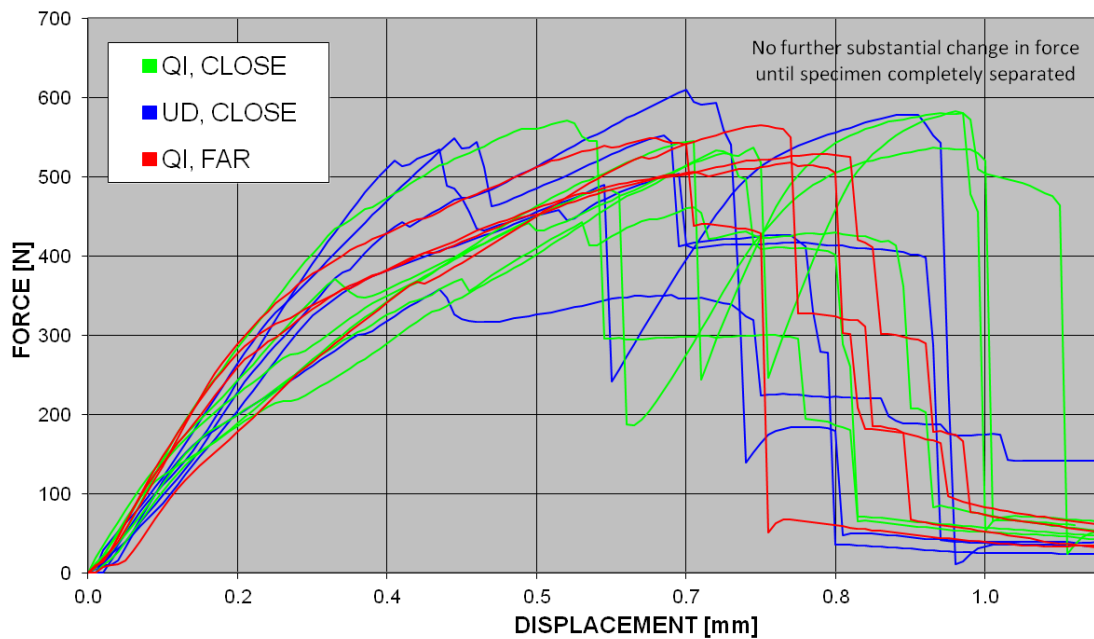


Figure 5.40 Shear-out curves - Method C, group of four 0.51 mm Z-Pins, stiff spring: QI vs. UD laminate, “far” vs. “close” Z-Pin pattern

5.3.2 DATA REDUCTION

Introduction

During each test the Instron machine cross-head movement - as displacement **a** (calibrated in mm), and the reaction on the load cell, as force **P** (calibrated in N) were recorded at a rate of 100/sec.

The following values were derived (see **Figure 5.10**):

P₀ – maximum of the force at the end of linear part of the curve

P₁ , **P₂** – forces at subsequent yield points on curve

P₃ – force at the last rapid drop

a₀ , **a₁** , **a₂** – displacements corresponding to the above forces

a₃ = a_{max}– displacements at the last drop of the force, assumed to be the point of final break of the Z-Pin

U – energy consumed during shear-out process, calculated from the area under the curve

Following the work of Cartié [72], also the shear stresses were calculated as follows:

$$\tau_d = \frac{P_0}{\pi \cdot d \cdot a_{\max}} \text{ - in the crack propagation phase}$$

$$\tau_f = \frac{U}{\pi \cdot d \cdot (a_{\max} - a_1)^2} \text{ - in the sliding phase where } d \text{ – Z-Pin diameter (see Figure 5.10):}$$

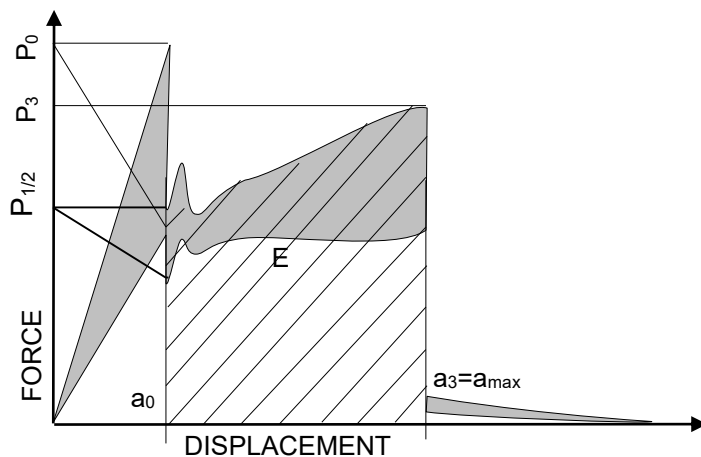


Figure 5.41 Shear-out curve.

Method B - Shear-Out Energy

The energy U seemed to follow the pattern of being the highest in case of QI laminate, followed by UD laminate sheared along the fibres, with UD sheared across being the lowest, in all Z-Pin thicknesses and configurations, see **Figure 5.42**, (with the exception of short, single pin 1.5 mm embedded length where the QI specimens showed lowest energy and 4 “far” Z-Pin specimens, in which UD sheared along the fibres was the highest but note the standard deviation in the latter).

The shear-out energy did not seem to be influenced by the pinning depth or spring stiffness in any regular way, as seen on **Figure 5.42**.

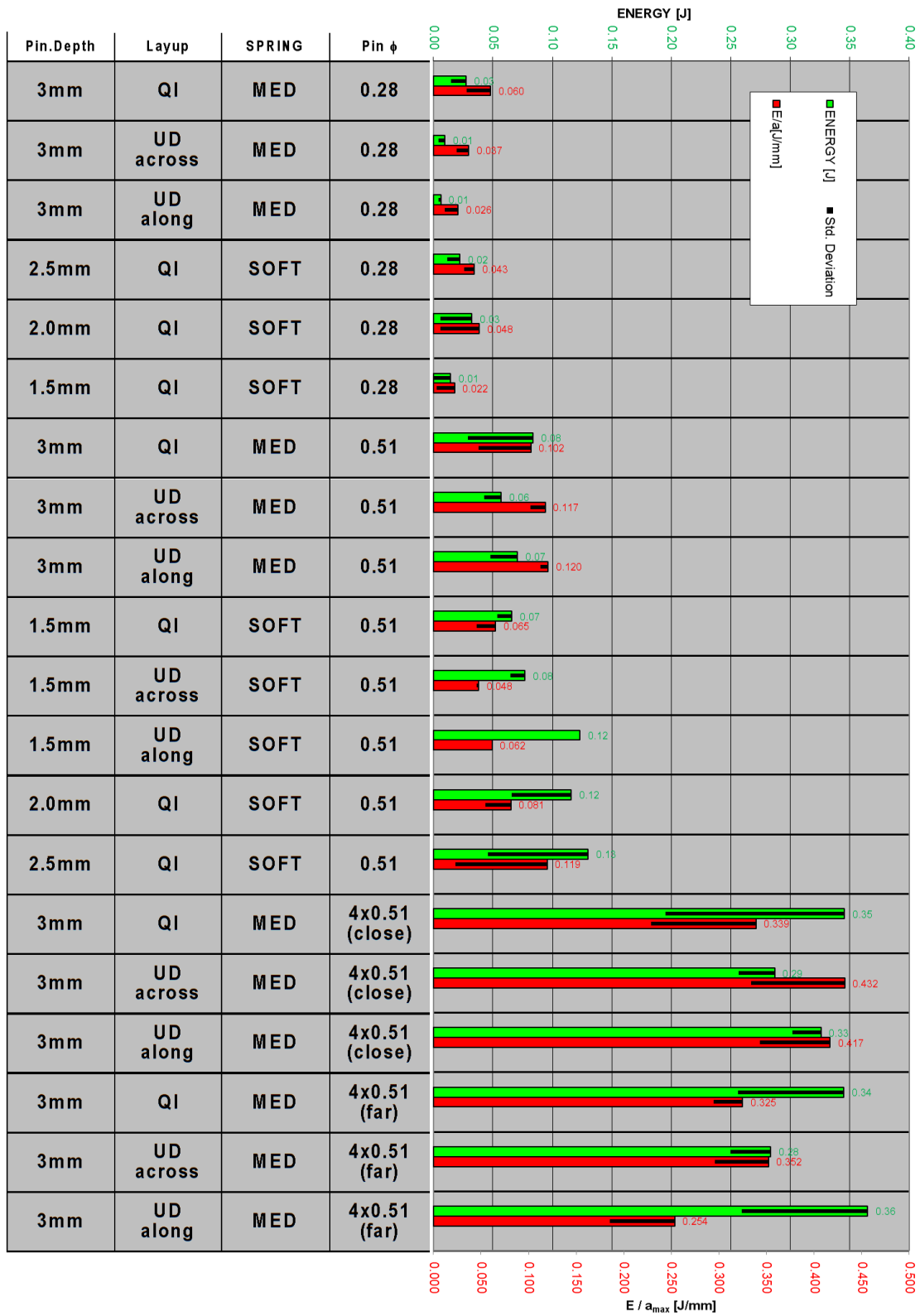


Figure 5.42 Shear-out energy chart – Method B

Method B – Shear-Out Force

It is difficult to find any striking patterns in force-displacement curves in Method B. The value of P_0 seemed to be highest for QI laminate in single 0.28 mm but for UD sheared across in 0.51 mm Z-Pin specimens. The value of P_1 followed a similar pattern. This was not the case in group of four Z-Pins. Also, softer springs seemed to dramatically decrease the values of P_0 . The value of P_1 seemed to be the least affected by the lay-up, spring hardness or pinning depth of all the forces recorded. The forces in general seemed to be approximately 1.5 times higher in case of single 0.28 mm Z-Pins than in 0.51 mm Z-Pins, but increase four fold in case of the group of four Z-Pin specimens. For details see **Figure 5.43**, **Figure 5.44** and **Figure 5.45**.

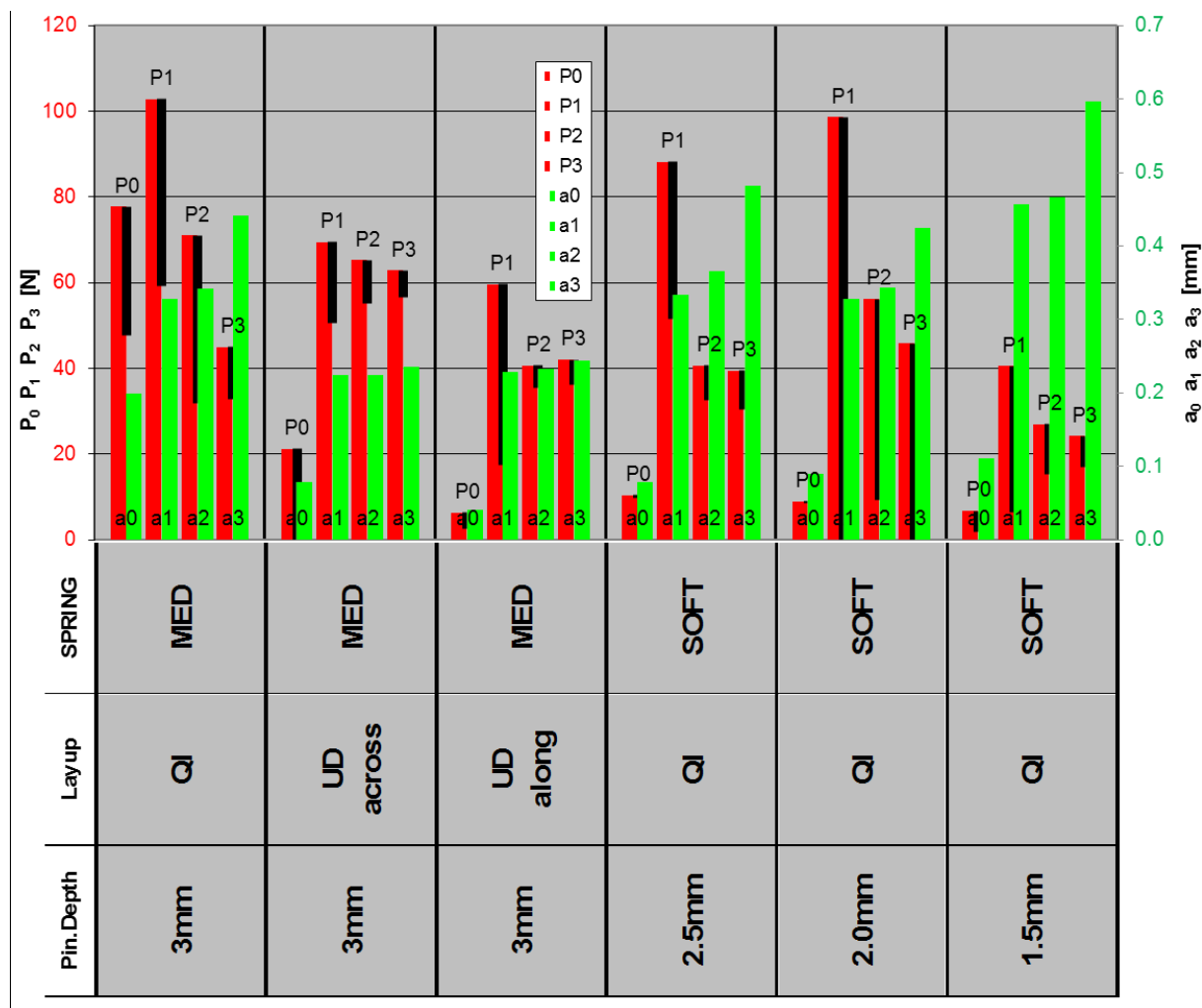


Figure 5.43 Shear-out force at specific points and corresponding displacement chart – Method B, single 0.28 mm Z-Pins (black lines indicate standard deviation)

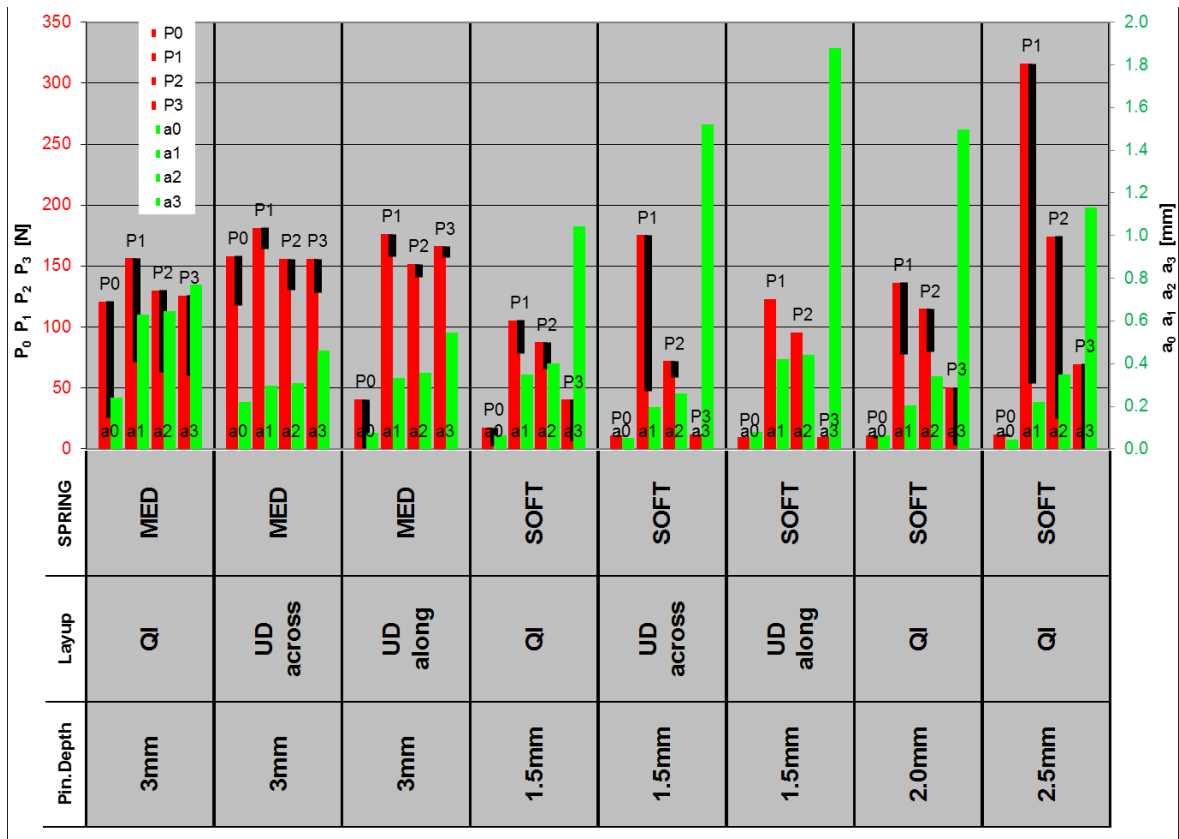


Figure 5.44 Shear-out force at specific points and corresponding displacement chart – Method B, single 0.51 mm Z-Pins (black lines indicate standard deviation)

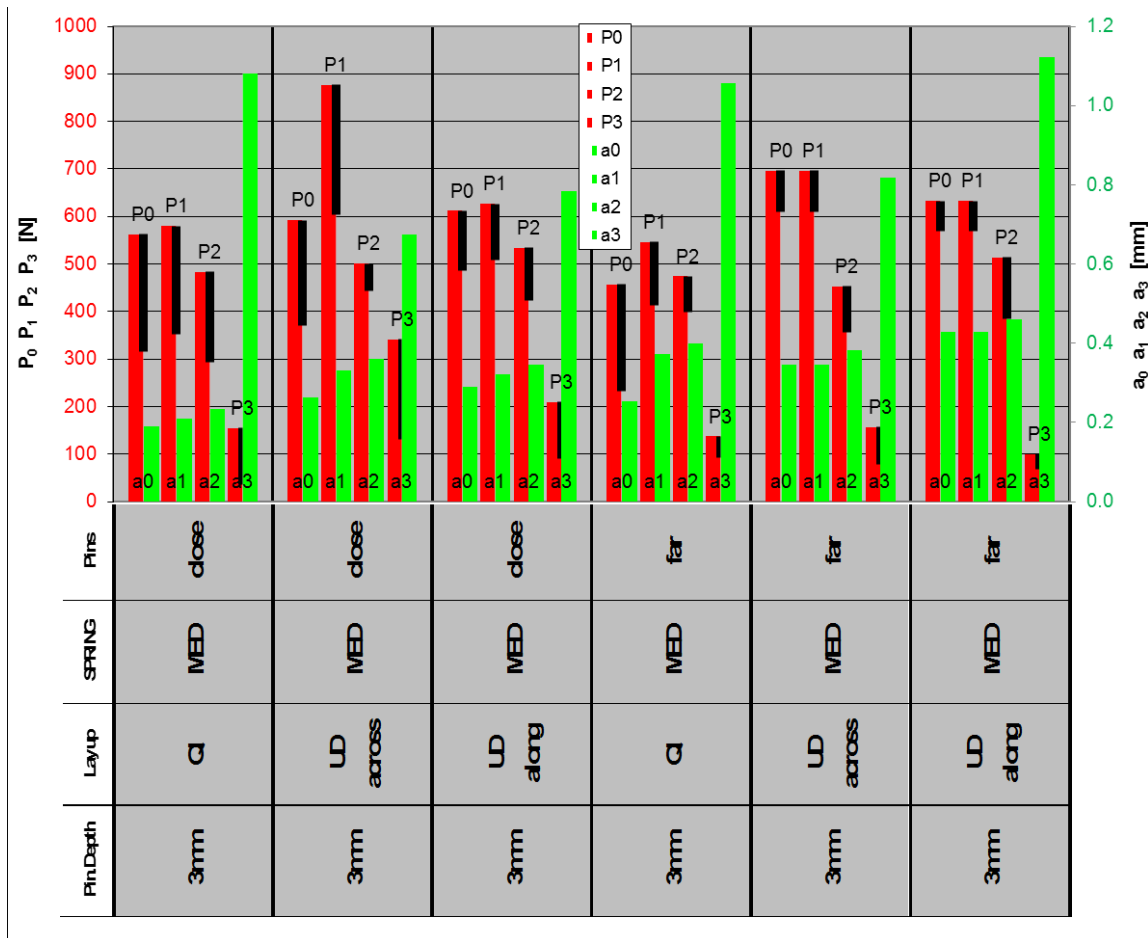


Figure 5.45 Shear-out force at specific points and corresponding displacement chart – Method B, group of four 0.51 mm Z-Pins (black lines indicate standard deviation)

Method C – Shear-Out Energy

Results of Method C tests showed more distinct patterns than those of Method B.

In all cases of Z-Pin diameters and Z-Pin distances, the shear-out energy seems to reach highest values for UD laminate sheared along the laminate fibre direction. Also, for all configurations, the shear-out energy in single 0.28 mm Z-Pins seemed to be approximately ten times lower than in single 0.51 mm Z-Pins, and this in turn, approximately four times lower than in group of four Z-Pin specimens. Surprisingly, spring stiffness (except the plateau after the final drop) and pinning depth did not seem to significantly influence the shear-out energy.

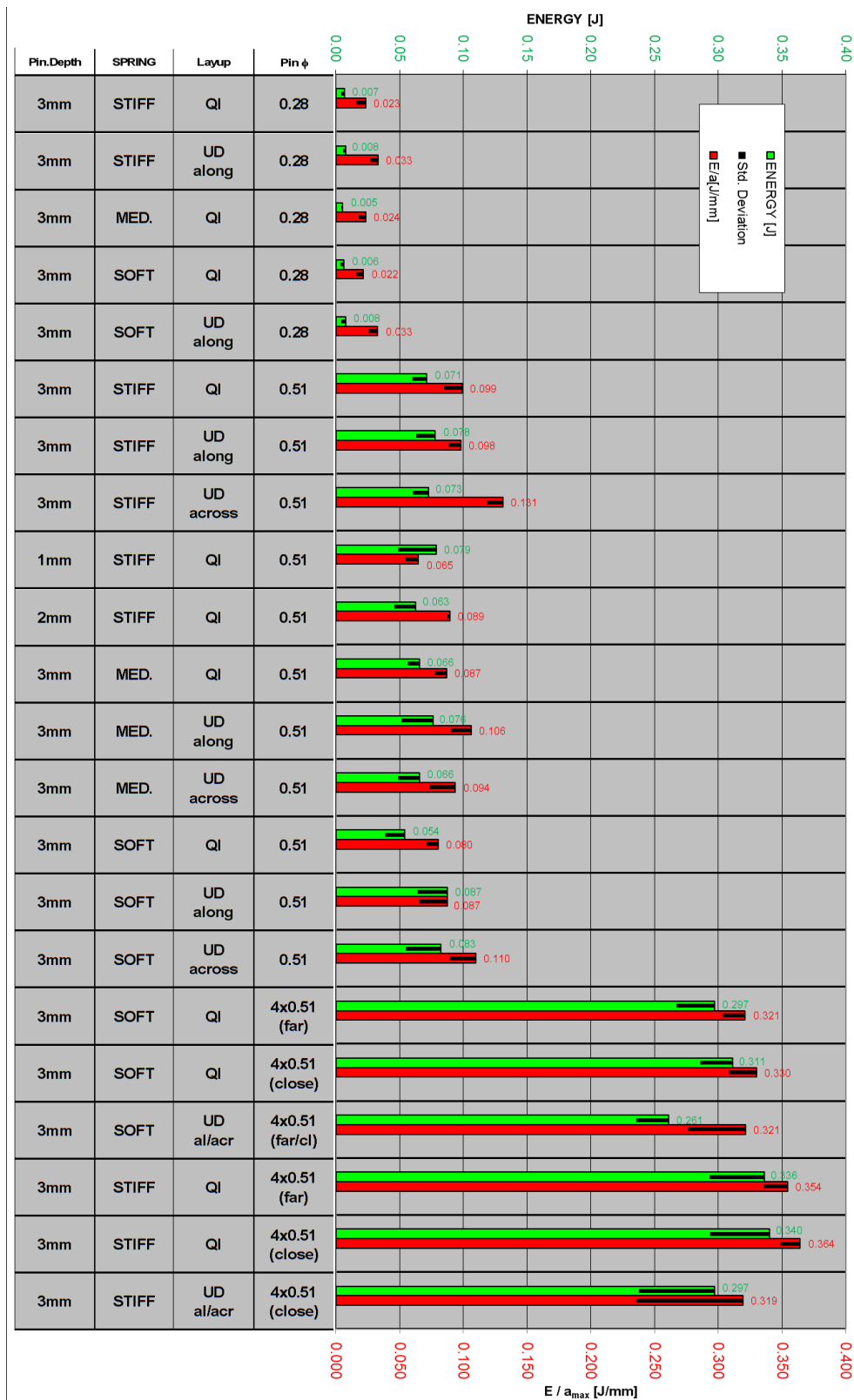


Figure 5.46 Shear-out energy chart – Method C (along and across grouped together in four Z-Pin specimens due to low number of specimens)

Method C – Shear-Out Force vs. Displacement

Cases of 0.28 mm Z-Pins and group of four Z-Pins did not show any clearly visible patterns, however, in case of single 0.51 mm Z-Pins the P_0 force seemed to be visibly higher in UD laminate sheared across, than in QI and UD sheared along (details on **Figure 5.47**, **Figure 5.48** and **Figure 5.49**). Spring hardness and pinning depth did not seem to influence the forces along the curve in any clearly predictable way. Note the difference in the value of the first maximum P_0 of UD sheared along 0.51 mm specimens with medium spring between Method B and Method C: in Method B the first maximum reached approx.40 N, while in Method C it reached over 100 N.

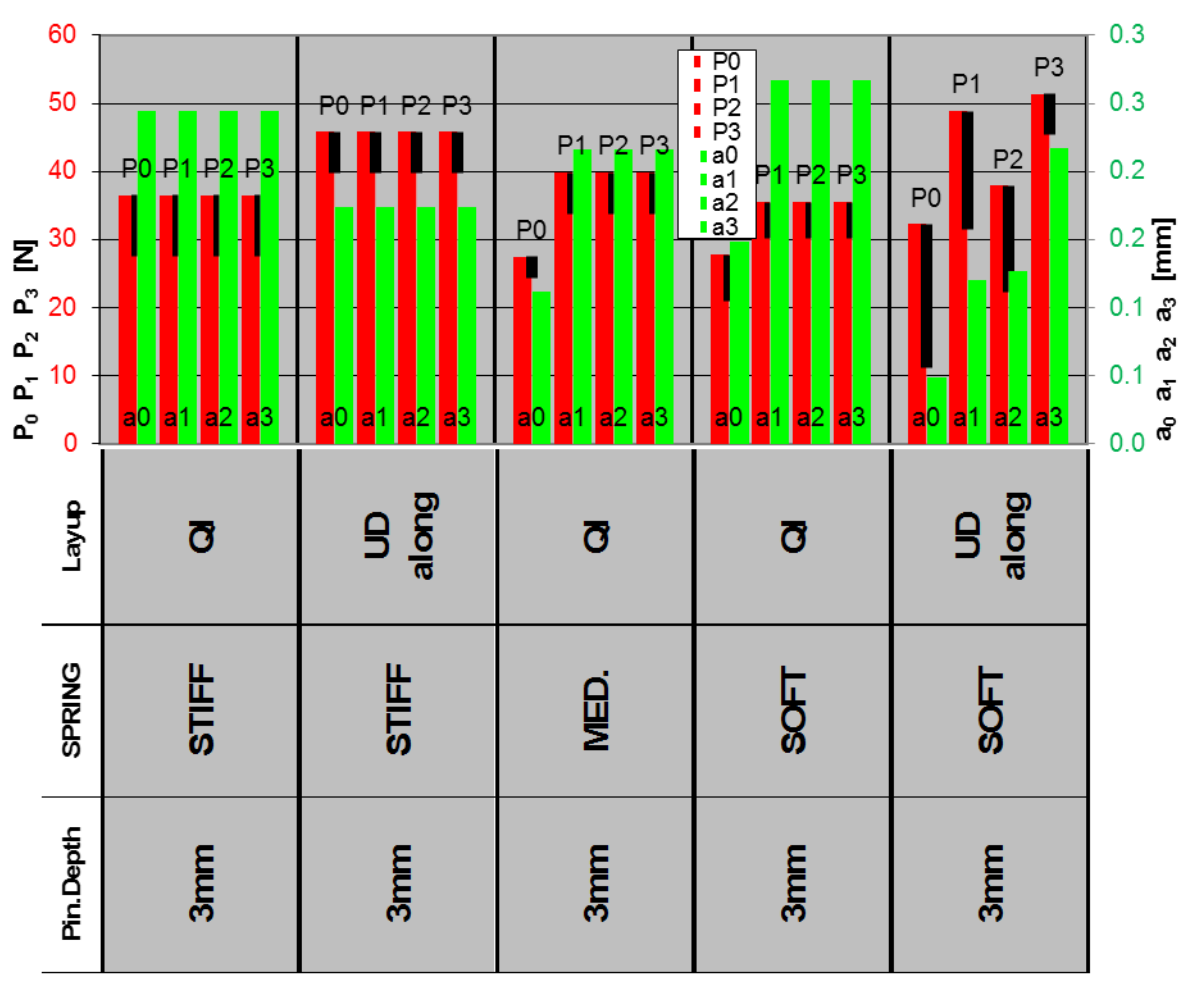


Figure 5.47 Shear-out force at specific points and corresponding displacement chart – Method C, single 0.28 mm Z-Pins (black lines indicate standard deviation)

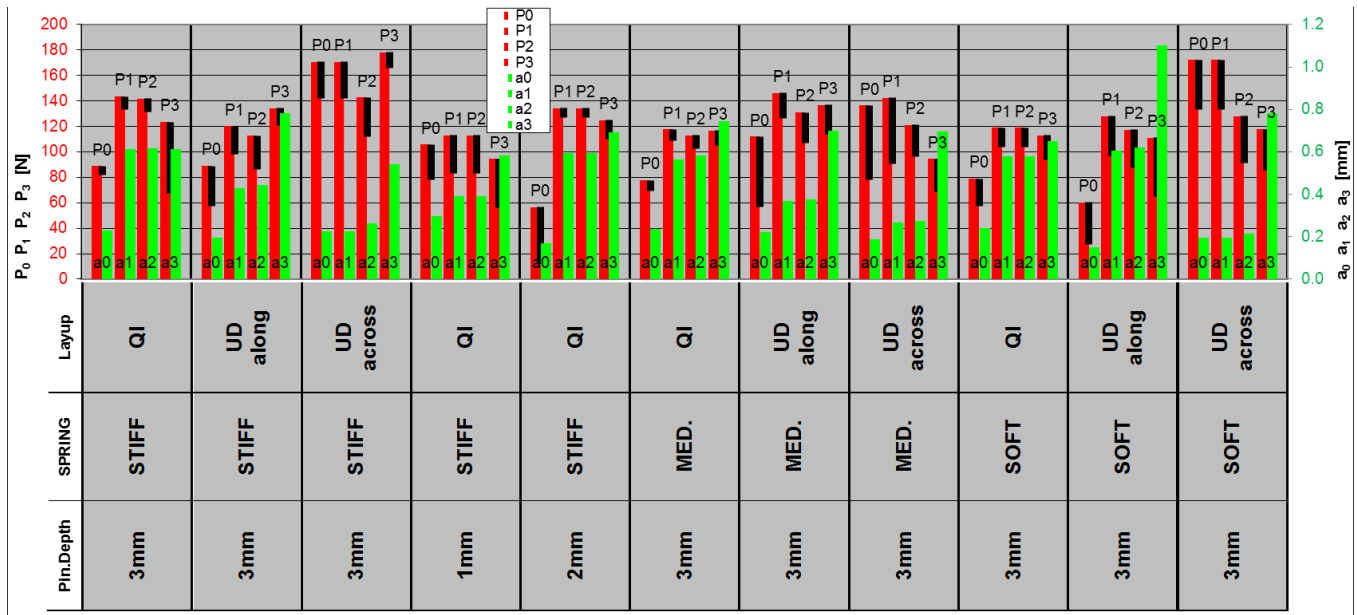


Figure 5.48 Shear-out force at specific points and corresponding displacement chart – Method C, single 0.51 mm Z-Pins (black lines indicate standard deviation)

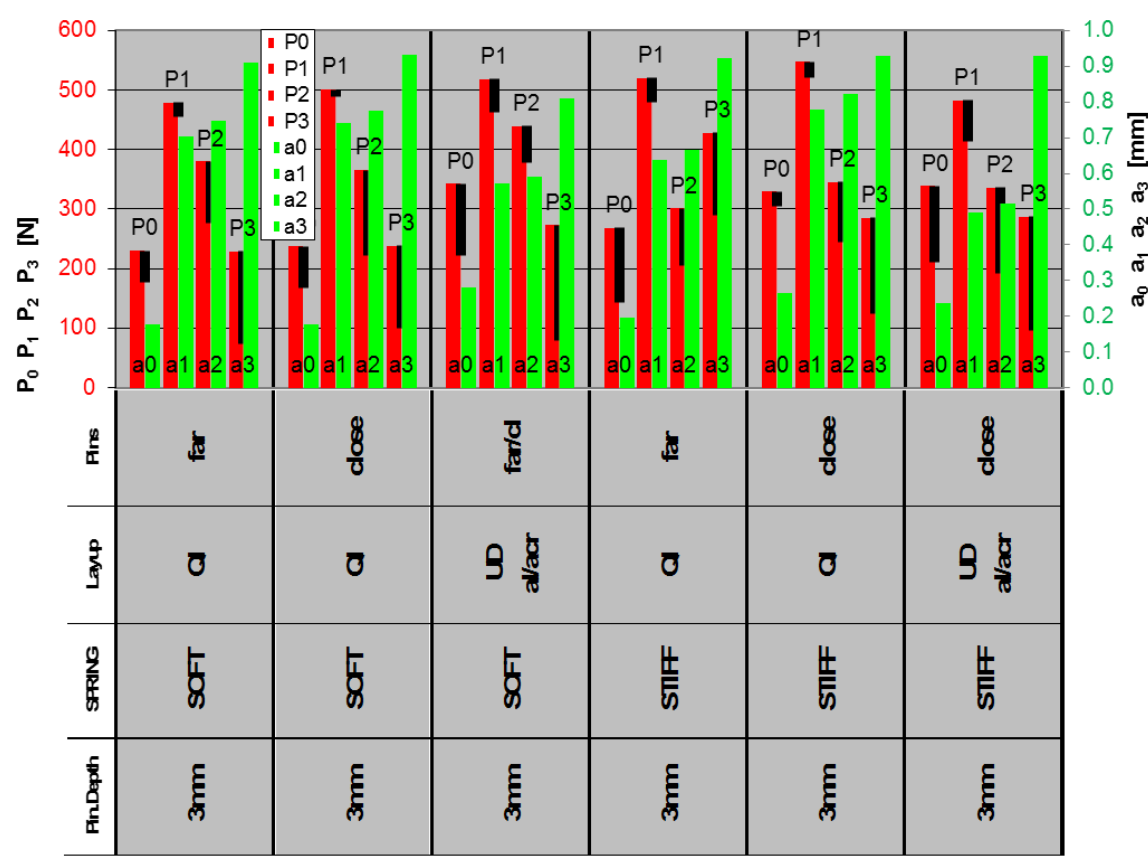


Figure 5.49 Shear-out force at specific points and corresponding displacement chart – Method C, group of four 0.51 mm Z-Pins (along and across grouped together in four Z-Pin specimens due to low number of specimens - black lines indicate standard deviation)

Scatter

Similar to the pull-out tests results, all the values, presented as an average of results of testing between 5 and 10 identical specimens, were characterised by high scatter. In Method B specimens the scatter could be attributed to the low quality of the specimens. However, in Method C specimens process of manufacturing could not be a significant source of variability, hence the scatter was likely to be due to imperfections in the Z-Pins themselves, e.g. air bubbles, twist, changes of the shape of the cross-section along the z axis. Also, the remarkably higher scatter in 0.28 mm Z-Pin specimens could be a result of brittleness of those specimens and any unnoticed damage due to the specimen handling.

Summary

During the shear-out process a gradual growth of the force was observed, usually steeper at the beginning and less steep later, ending with a rapid drop to zero at relatively small displacements, when the Z-Pin failed. The character of the curve seemed to be affected mainly by the direction of the shearing – across or along fibres of the laminate. Shearing in the direction along the fibres, so the Z-Pin was pushed into the resin pocket, showed “softer” character – less steep slopes of the force-displacement curves. This confirms findings reported in [67,48] indicating a difference between Z-Pin sheared in the “soft direction” (along fibres) and “hard direction” (across fibres).

In nearly all cases the Z-pin failed at the delamination surface and no noticeable “ploughing” or pull-out was observed.

The stiffness of the spring controlling the opening displacement did not seem to have a noticeable influence on the character of the shear-out process.

As the pull-out was not observed, the embedded length did not seem to influence the character of the process, with the exception of 1 mm when slight pull-out and “ploughing” occurred.

5.3.3 MICROMECHANICS OF SHEAR-OUT

Two phases of the shear-out process, explained in **Figure 5.51**, could be observed after the analysis of the results:

- **Linear phase**
- **Breaking phase**

Linear Phase

In this phase, believed to have elastic character, the linear increase of the force up to P_0 was observed. The displacement a_0 at the end of this phase oscillated between 0.1 mm and 0.2 mm in 0.51 mm Z-Pins – slightly higher for stiffer springs, lower in case of UD laminate sheared along the fibres, but similar for all Z-Pin embedded lengths. Based on observation of the shear-out curves, specimens of QI and UD laminate sheared along the laminate fibre direction seemed to behave similarly in this phase, reaching force of 70 N – 80 N. Specimens of UD laminate sheared across the laminate fibre direction reached a force of around 170 N. Due to the linear character of the curve it was assumed that no energy was dissipated.

The springs controlling the crack opening displacement indicated negligibly small or no movement in this phase.

This first phase seemed to be controlled by the conditions on the edge of the laminate surrounding the Z-Pin in the crack wake. A sharp, hard edge of fibres perpendicular to the Z-Pin movement could be expected in UD sheared across case, while a softer, resin dominated edge - in QI and UD sheared along cases.

Breaking Phase

In cases of QI and UD sheared along specimens the breaking phase began with a yield of the curve at a_0 of approximately 0.2 mm followed by a gradual increase of the force up to P_1 of 120 N to 140 N at $a_{\max}$ of 0.4 mm (UD sheared along) and 0.6 mm (QI), where the final drop of the force, and a Z-Pin breakage, usually occurred. In a number of cases, especially in cases of QI specimens, the process was continued with constant or slightly decreasing force until the final drop at $a_{\max}$ of approximately 0.7 mm to 1.0 mm.

In case of UD sheared across specimens the breaking phase began with a rapid drop of the force to the level of 120 N to 140 N. This was followed by a force staying approximately constant or slowly growing until $a_{\max}$ of 0.5 mm to 1.0 mm, where the final drop occurred. This second phase seemed to be controlled by breaking of the Z-Pin internal structure. It was assumed that during this phase the Z-Pin gets slowly broken by propagation of the micro-cracks along its fibres. Also a slight pull-out could be expected in this phase, as a rapid growth of the crack opening displacement was usually observed.

A number of specimens, especially those with 0.28 mm Z-Pins, did not develop the second phase, and broke at the end of the linear phase.

For a small amount of specimens of 0.51 mm Z-Pin with opening displacement controlled by soft springs, the breaking phase seemed to be prolonged, even up to 2 mm. The post mortem observation of remnants of the Z-Pin, revealed a “brush shape” structure. The microcracks between the fibres of the Z-Pin seemed to propagate along, instead of breaking, the Z-Pin in these cases.

After the final drop at $a_{\max}$ the recorded force was minimal, as the stump of the broken Z-Pin slid on the surface of the composite. A “ploughing” was expected, but even with the stiffest spring applied, only a small scratch on the surface could be observed.

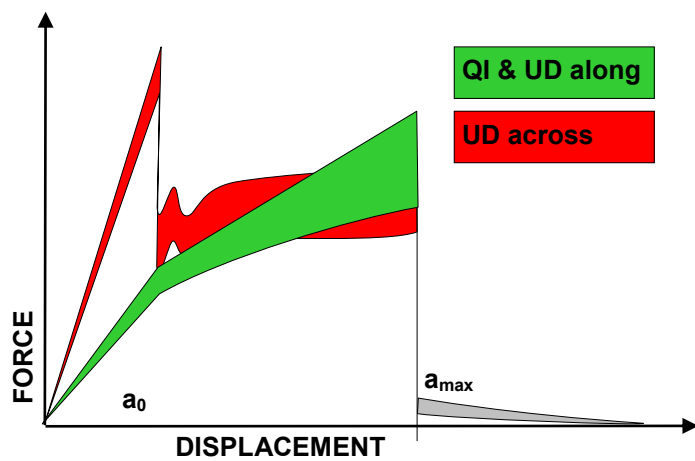


Figure 5.50 QI and UD sheared along versus UD sheared across (red and green zones indicate the range of curves recorded in tests).

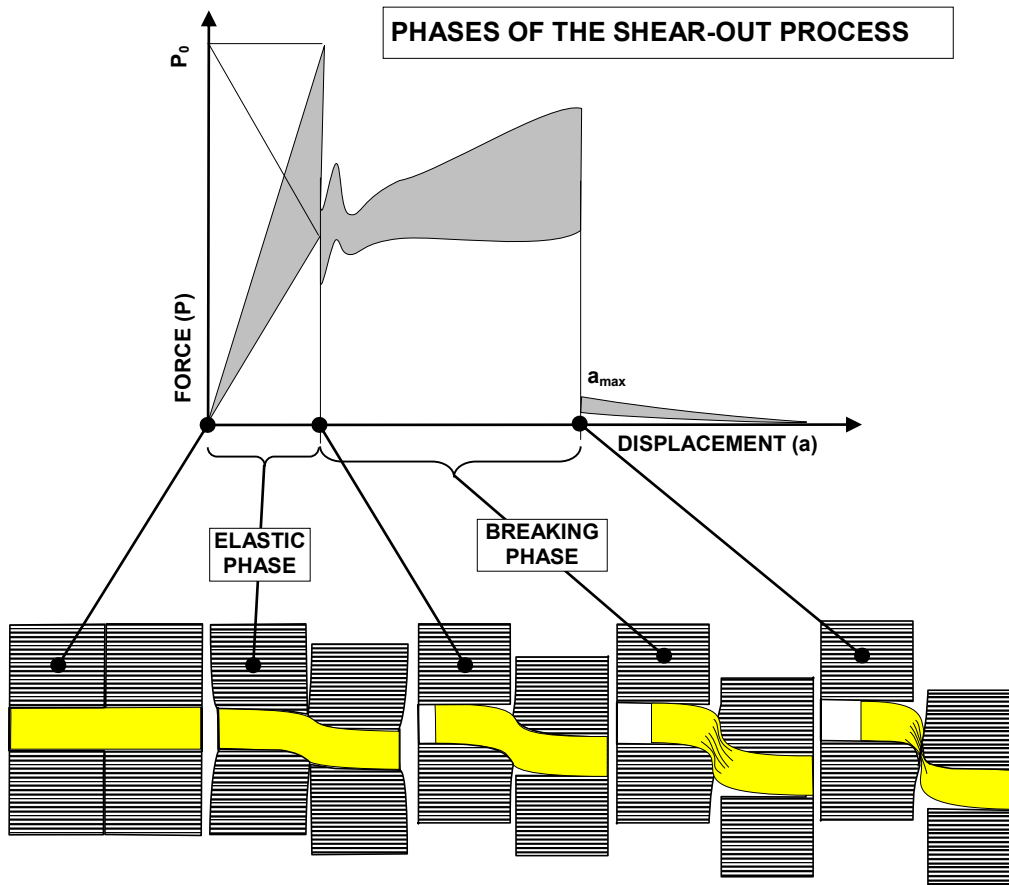


Figure 5.51 Phases of shear-out process.

5.4 MIXED MODE TESTS

5.4.1 RESULTS

Method C - Multi Mode Rig

Mixed mode test results of various angles can be divided into three groups:

- **Resembling pull-out tests – 30° and 45°**
- **Genuine mixed mode - 60° and 70°**
- **Resembling shear-out tests - 80°**

In general, the results of the mixed mode tests show exceptionally high scatter, with standard deviations being close to the average values in many cases, as can be seen in APPENDIX – TABLES OF RESULTS

The 0.51 mm Z-Pin tests for highest (80°) and lowest angles (30° - 45°) - had similar character to the shear-out and pull-out tests, respectively (see **Figure 5.52**). In case of 45° mixed mode tests of 0.51 mm Z-Pins the general character of the force-displacement curves resembled the curves from pull-out tests, as seen in **Figure 5.53**. However, the slopes at the beginning of the process were significantly less steep than in the pure pull-out: force reached level of 40 N to 120 N at the displacement of 0.1 mm to 0.4 mm. Unlike in the pure pull-out process, where only the longitudinal stiffness of the Z-Pin influenced the slope during the first linear phase, in case of a Z-Pin being pulled-out under an angle, the tangential stiffnesses of the Z-Pin had an influence on the initial slope.

In case of the angles of 60° and 70° the prolonged crack formation phase connected with pull-out could be observed, but not as prolonged as in pure pull-out. The initial growth of the force up to 60 N – 80 N at 0.2 mm – 0.4 mm was followed by the yield of the slope and further, slower growth of the force up to 80 N – 100 N at 1.1 mm – 1.5 mm. In most of these cases the brush shaped structure could be observed post mortem.

In case of 45° mixed mode tests of 0.28 mm Z-Pins the specimens seemed to be more brittle than 0.51 mm ones (see **Figure 5.54**) easily breaking after short growth of the force. However in case of QI laminate the prolonged pull-out could be observed.

Surprisingly, swivelling and rigid rig tests results did not seem to show any difference. However there were not enough specimens tested to prove this conclusively (see **Figure 5.55**).

The differences of the curves for 1 mm, 2 mm and 3 mm Z-Pin embedded lengths, tested at 45°, seemed to follow closely the pattern of the pull-out tests performed for the same embedded lengths (see **Figure 5.56**). Nearly pure pull-out behaviour at 45° seems to prove that Z-Pins are quite flexible and tend to bend rather than break during the pull-out from the composite.

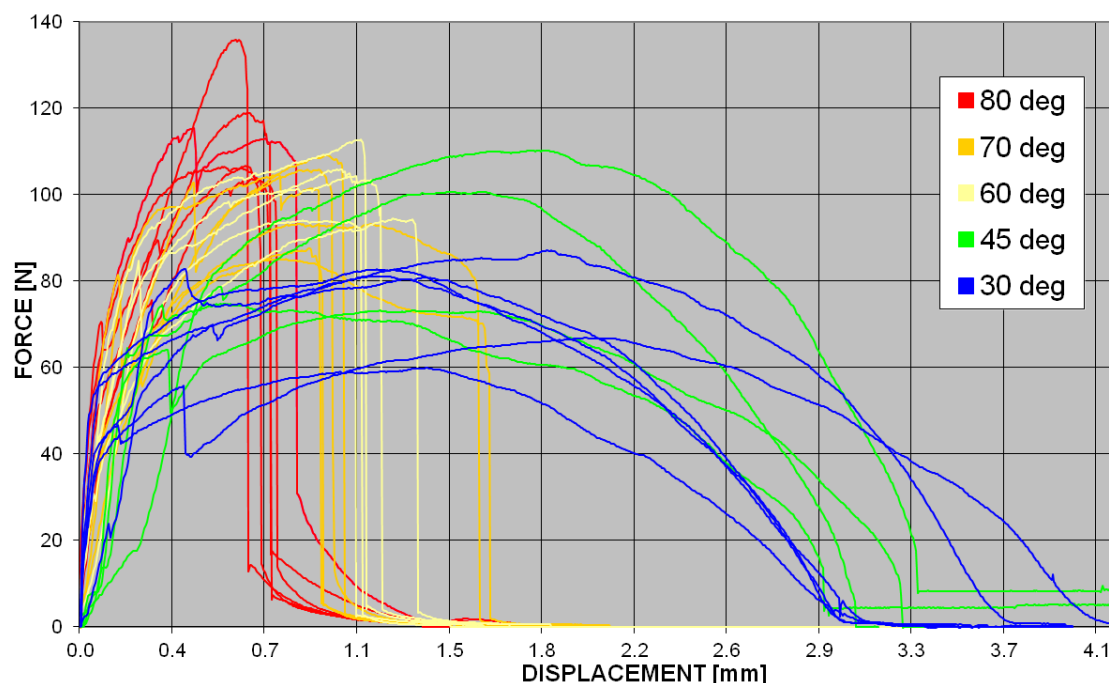


Figure 5.52 Mixed mode curves - Method C, single 0.51 mm Z-Pin, rigid rig: various testing angles

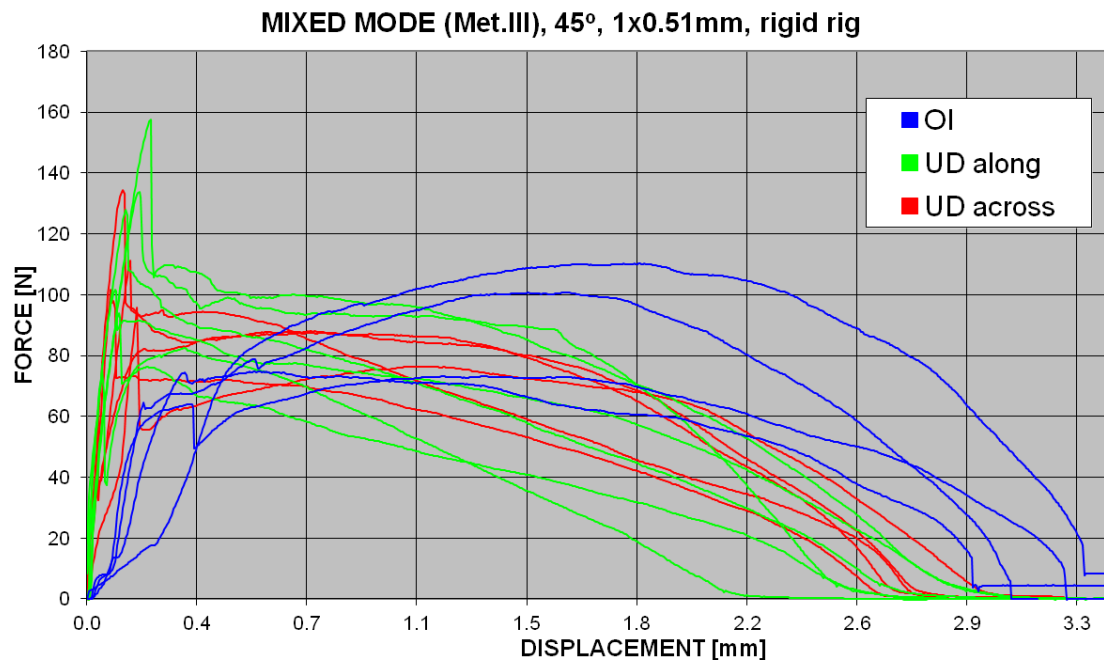


Figure 5.53 Mixed mode curves - 45° angle, Method C, 0.51 mm Z-Pin, rigid rig: QI vs. UD “along” and “across” laminate

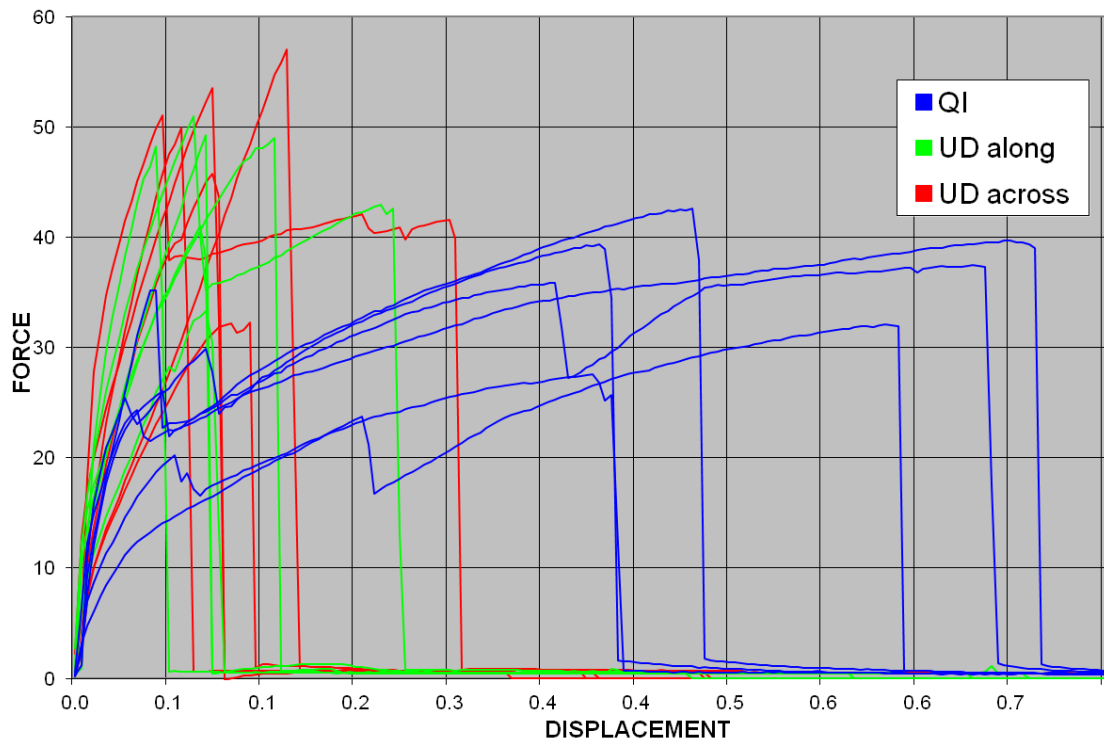


Figure 5.54 Mixed mode curves - 45° angle, Method C, 0.28 mm Z-Pin, rigid rig: QI vs. UD “along” and “across” laminate

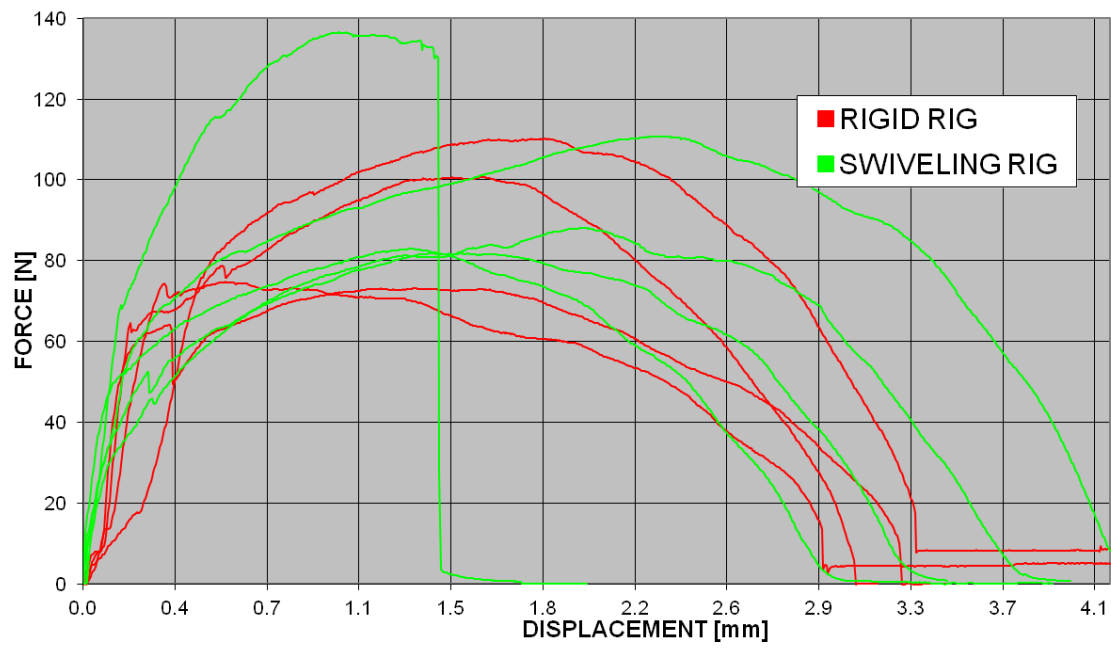


Figure 5.55 Mixed mode curves - 45° angle, Method C, 0.51 mm Z-Pin, QI laminate: rigid vs. swivelling rig

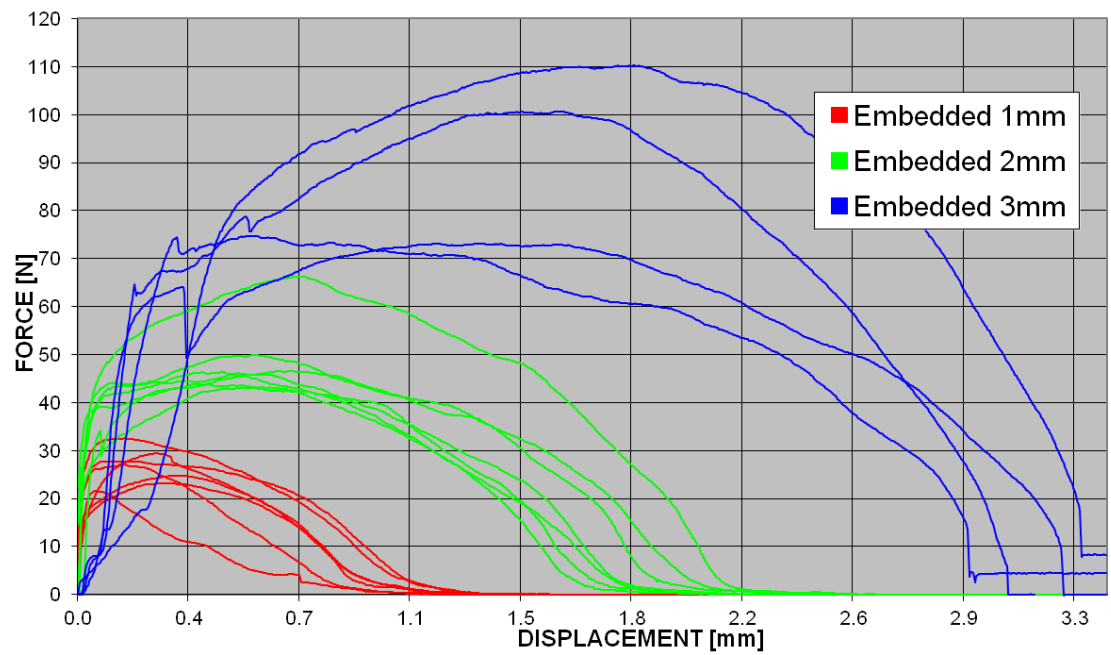


Figure 5.56 Mixed mode curves - 45° angle, Method C, 0.51 mm Z-Pin, QI laminate, rigid rig: various embedded lengths

5.4.2 DATA REDUCTION

The case of 45° mixed mode tests, similar to the shear-out tests, the value of U was highest for QI specimens, followed by lower values for UD specimens sheared across and along the fibres of the laminate for both 0.28 mm and 0.51 mm specimens – see **Figure 5.57**.

For the QI specimens in the rigid rig, which were tested for the whole range of the angles, the energy grew from the 0° (pure pull-out - $U=0.13$ J - see **Figure 5.14**) until 45° ($U=0.21$ J) and then significantly for drops 60°, 70°, 80° and 90° (pure shear-out – $U=0.05$ J for soft spring or 0.07 J for stiff spring - **Figure 5.46**). A similar energy distribution in a range of mode “mixities” was reported in [67,48]. However, the specimens in mode “mixities” above 40° seemed to behave more similarly to the pure shear-out and rupture at lower energies than reported in this thesis.

Also, for the QI specimens in the rigid rig at 45° the energy seemed to grow rapidly with the embedded length.

There is a noticeable difference between the values of U recorded in case of rigid or freely swivelling rig. Higher value of U in case of freely swivelling rig may be due to higher likeliness of prolonged pull-out with the formation of the brush shape in this case.

Summary

It was observed that mode “mixities” of 0° (pull-out), 30° and 45° showed similar character of the Z-Pin being pulled-out without internal breakage, with high energy consumption. In the range of mode “mixities” between 60° and 70° a pull-out with the brush shape formation was observed. Finally the mode “mixities” of 80° and 90° (shear-out) show similar character of Z-Pin breakage at low displacements without noticeable pull-out and low energy consumption.

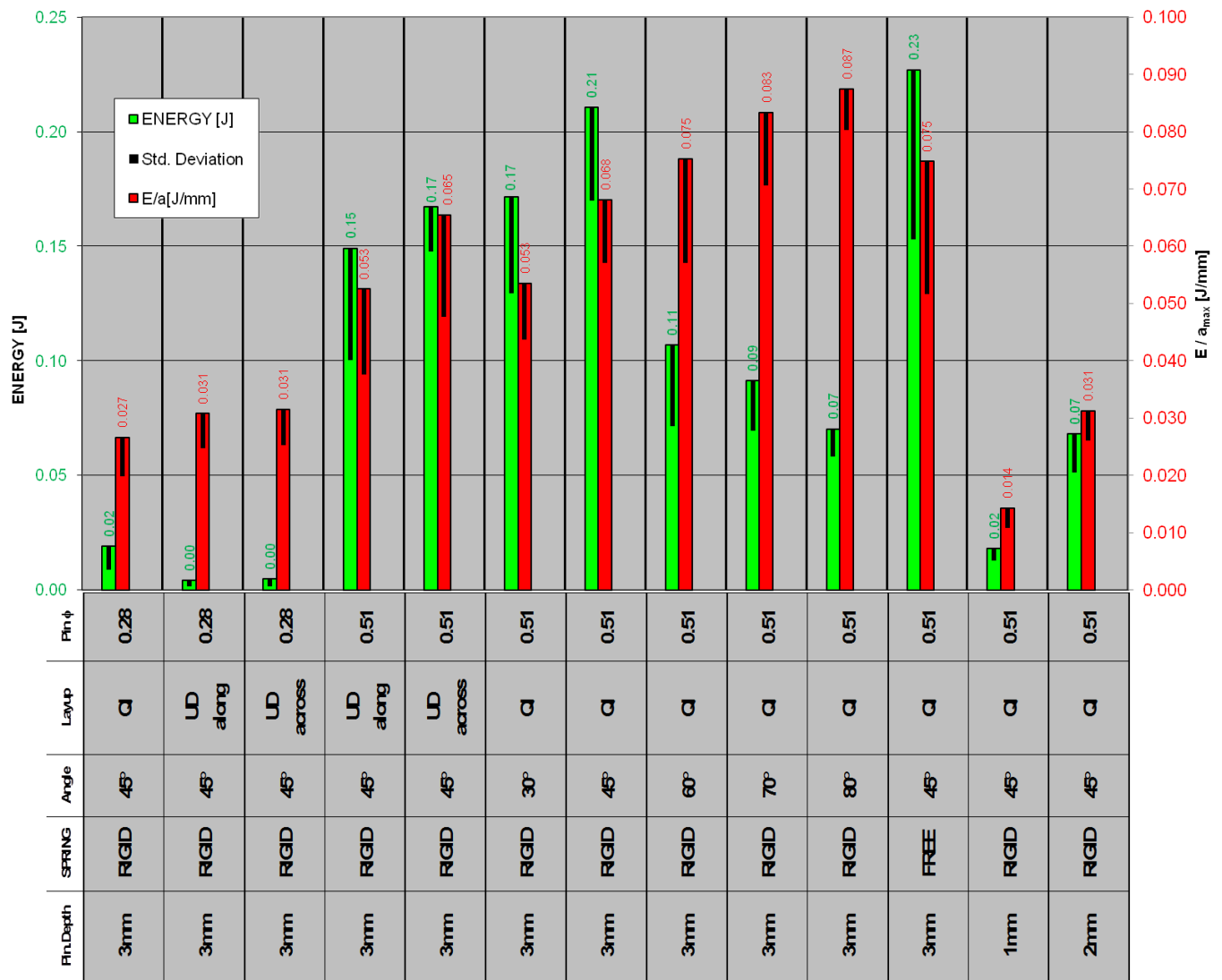


Figure 5.57 Mixed mode energy chart – Method C

5.5 MIXED MODE TESTS WITH OPENING DISPLACEMENT MEASUREMENT

Method C – Multi Mode Rig

This experiment, with the use of laser gauge measuring the displacement in the direction perpendicular to the acting force, was performed in order to investigate the mixed mode processes of a Z-Pin being pulled/sheared out of the composite at various angles in local coordinates, connected with the Z-Pin. For visualisation purposes a three-dimensional graph showing test results in local coordinates was created in order to show the force-displacement curves for various degrees of mixed mode, between pure pull-out and pure shear-out.

Unfortunately, the use of laser gauge was limited to the 45° case. This kind of measurement demanded two laser gauges connected symmetrically to both parts of the rig. The measurement could be improved by using a pair of laser gauges.

All of the tests results were recorded in global coordinates, connected with the testing machine. Vertical displacement was measured in the direction of acting force and cross-head movement and the horizontal displacement was measured in the direction perpendicular to the acting force, regardless of the Z-Pin angle. The transformation to the local coordinates, connected with the Z-Pin, can be seen on **Figure 5.58**.

As seen on both graphs (**Figure 5.59** for stiff spring case and **Figure 5.60** for soft spring case) the first moments, up to approximately 0.3 mm in both shear-out and pull-out directions, the shear-out and mixed mode tests coincide.

Examples of 45° mixed mode tests, with the record of the displacement in the direction perpendicular to the acting force, can be seen in **Figure 5.61**.

Summary

This experiment need repeating with more sophisticated measurement of the opening displacement. The results showed that at 45° the lateral opening grew until approximately 1 mm of the cross-head movement and then stabilised at approximately 0.3 mm. The moment of stabilisation was also marked by the yield of the acting force, which may suggest breakage of the Z-Pin and formation of the “brush shape”.

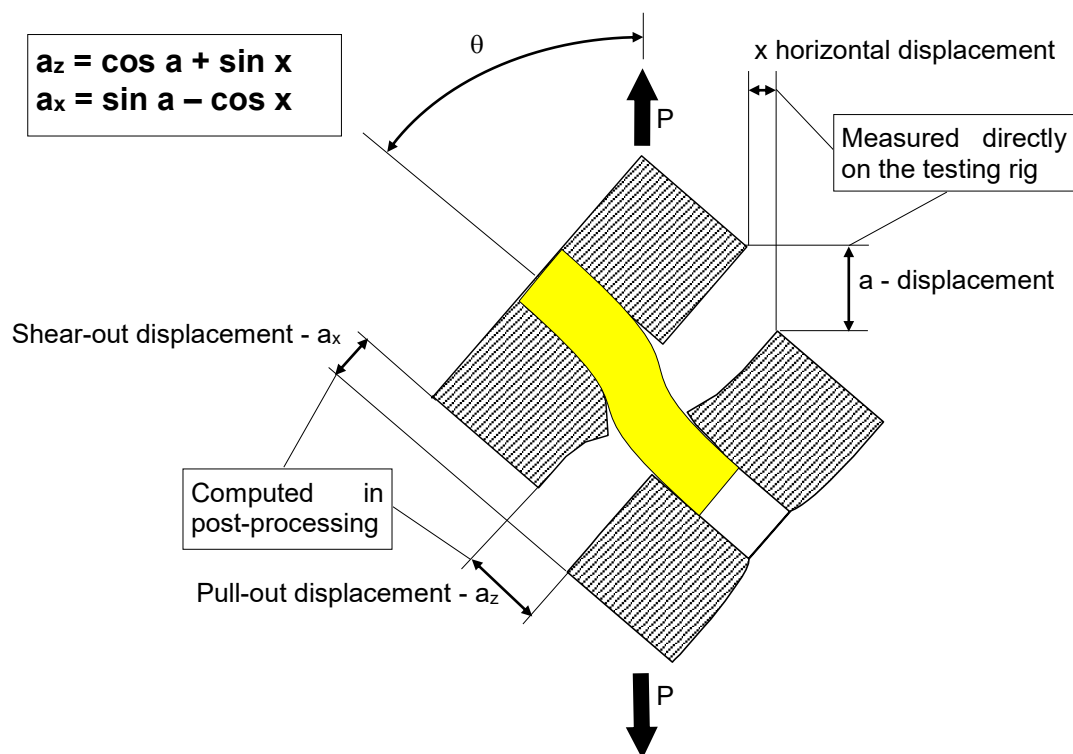


Figure 5.58 Displacements in mixed mode tests – global and local coordinates

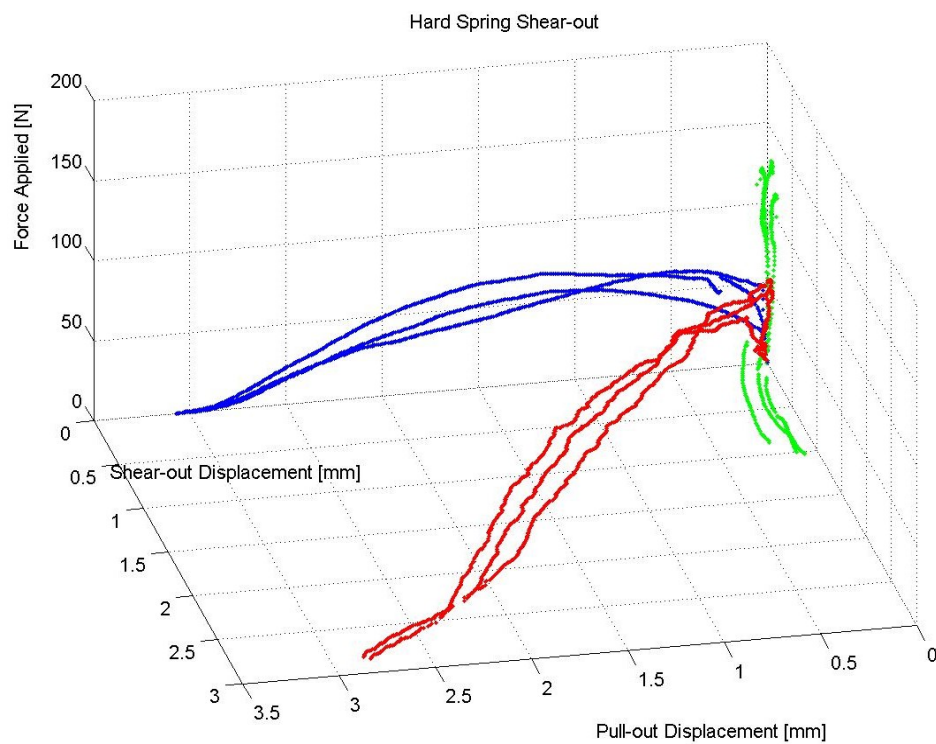
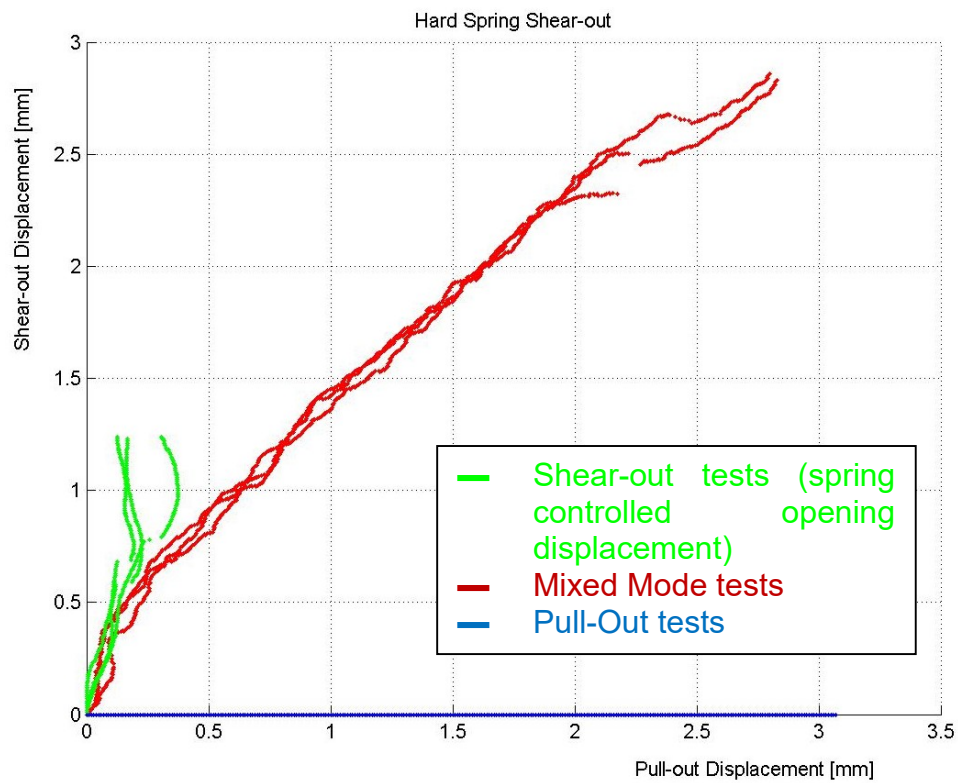


Figure 5.59 Pull-out, 45° mixed mode and shear-out processes in local coordinates – stiff spring

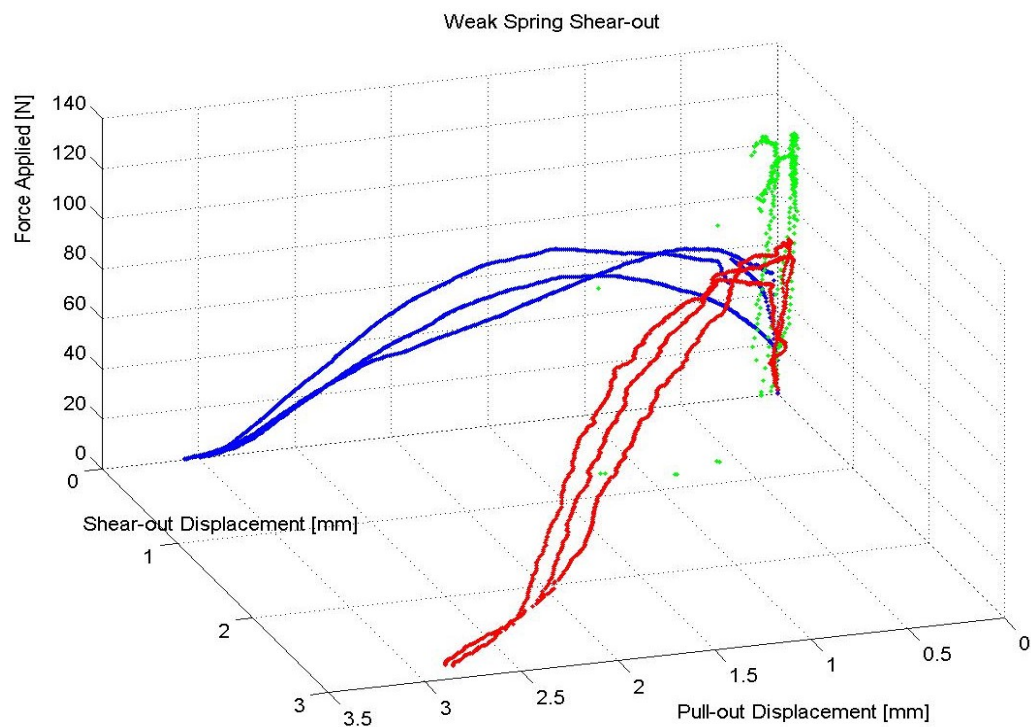
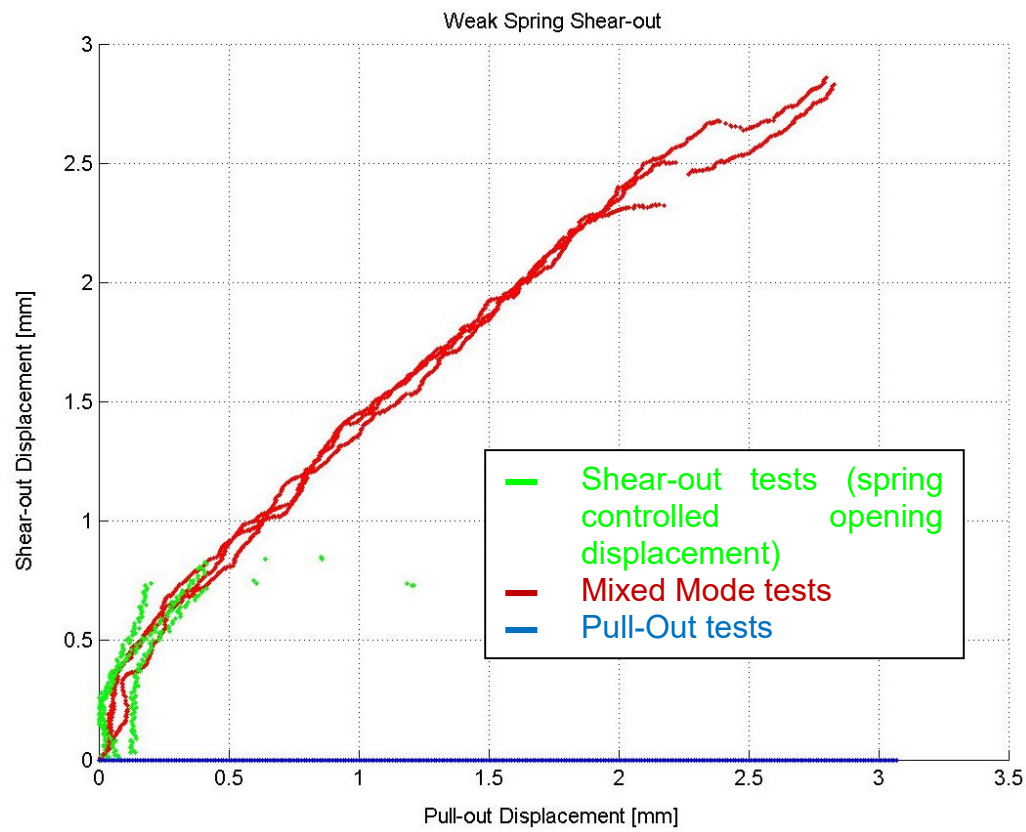


Figure 5.60 Pull-out, 45° mixed mode and shear-out processes in local coordinates – soft spring.

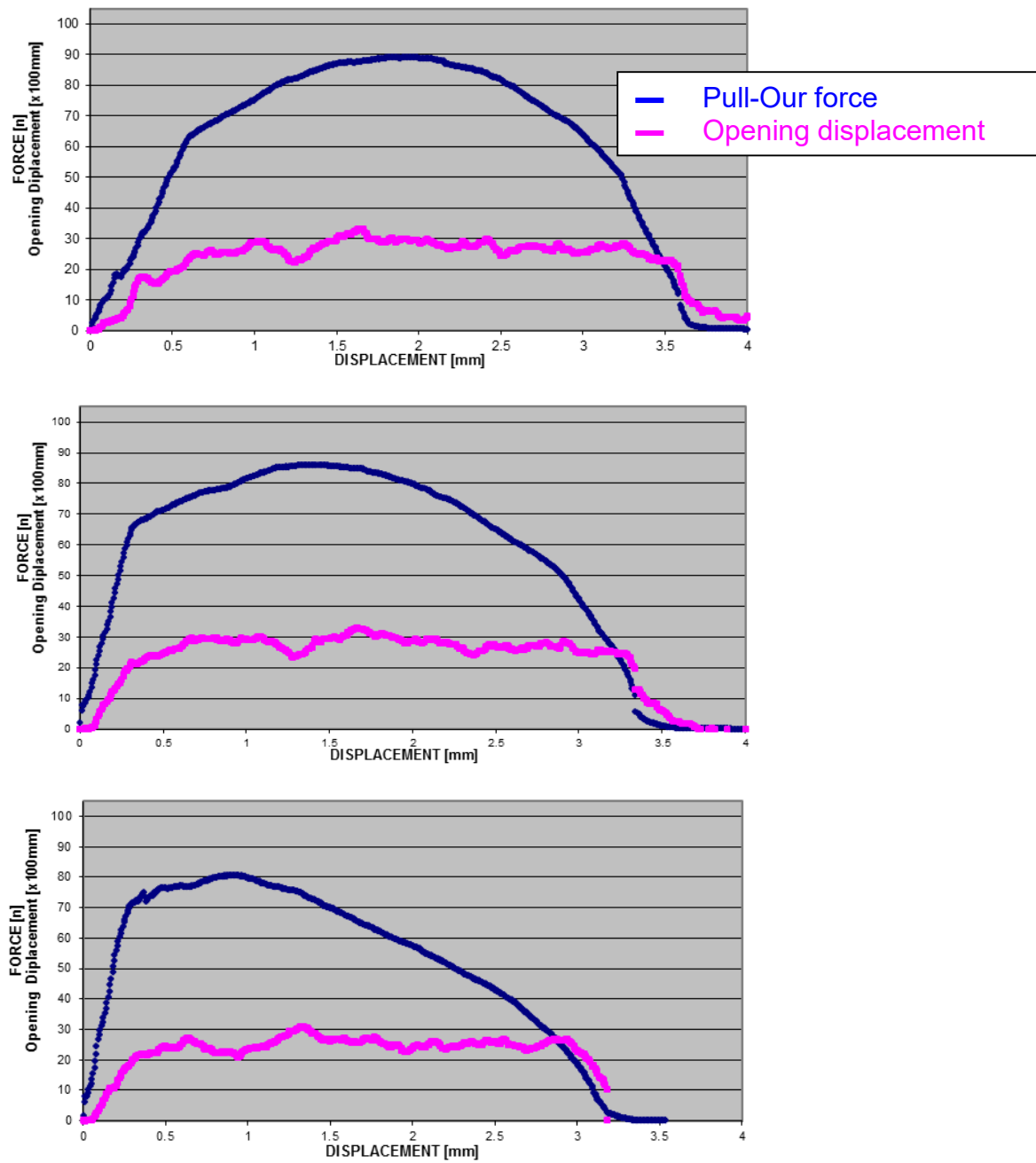


Figure 5.61 Examples of the 45° mixed mode curves along with the opening displacement recording.

5.6 PURE SHEAR AND SHEAR IN THE PRESENCE OF BENDING TESTS

5.6.1 OVERVIEW

The objectives of this test were identification and characterization of the behaviour of the single Z-Pin rod-stocks under pure shear and under shear in the presence of bending. The test was intended to be a simulation of the behaviour of a shear-loaded Z-Pin in the crack wake, with different levels of crack opening.

In this test, T650/35BMI Z-Pin rod-stock, 0.51 mm in the diameter, was used. Approximately 30 mm long pieces of the rod-stock were cut and installed in the testing rig, detailed in Chapter 3. No special treatment was applied to the rod-stock or specimens before test.

5.6.2 OBSERVATIONS AND RESULTS

In three different test cases, various behaviours of Z-Pin rod-stock were observed.

Shear tests with no bending

With no spacers inserted, simple cutting was observed. The force increased with growing relative displacement of the bars, to the value of about 200 N (in one case even 270 N), and then rapidly dropped to zero. The load-displacement curve of all three specimens showed very similar characteristics. Two stages of the force increase were observed (**Figure 5.62**):

- At the beginning, until approximately 0.4 mm displacement, slow growth could be seen.
- From this point force increases rapidly to its maximum value in an almost linear manner.

The effect observed in the first stage may be the result of sliding of the jaws of machine over the surface of relatively soft aluminium bars at the beginning of the process, before achieving a proper grip. Another explanation may lie in local crushing of the resin of the Z-Pin rod-stock. However, due to the displacement at the end of the first stage being 0.4 mm (80% of the Z-Pin diameter of 0.51 mm), this explanation is less probable.

The initial slow growth could be explained by the combination of elastic deformation of the aluminium bars and the Z-Pin followed by the initial plastic damage of the relatively soft resin of the Z-Pin. Further, more steep growth of the force the result of progressing damage to the harder fibres of the Z-Pin, continuing until breakage.

On inspection of the tested pins, the break at the test section was fairly clean and perpendicular to the pin axis. No pictures were taken.

In the case of tests with one spacer (0.33 mm gap)

No complete failure of the Z-Pin was observed in this case. The force increased rapidly in a linear manner to the first maximum, at about 40 N. Then the force dropped about 10 N and grew to another maximum, at about 45 N. The displacement of the bars between maxima was about 0.5 mm for all three specimens. After the second maximum the force remained at approximately the same value irrespective of the applied displacement (the tests were carried up to a maximum displacement of 2.8 mm) (**Figure 5.62**).

After the tests the specimens were taken out of the rig and the rod-stock was broken. The post mortem inspection of the specimens revealed an existence of brush-like structure along the pulled-out ends of rod-stock. The length of the “brush” corresponded to the length of the plateau visible on the graphs. The filaments in the “brush” seem to be perfectly separated. In fact, on visual inspection the rod-stock seemed intact, however bending it with a finger revealed fine separation of the fibres. Unfortunately, no pictures were taken.

It appears that under this loading condition, a mix of shear and bending, the shear stress causes the breakage of resin between the filaments (i.e. numerous longitudinal cracks running parallel to the filaments, making the “brush” shape). The filaments do not break at the first maximum load, when the initiation of the longitudinal cracks presumably occurs. Eventually a steady state is established: longitudinal cracks propagate as the thread is pulled out of the hole in the aluminium bar. (Note that in the pure shear tests the edges of the hole in aluminium bars became visibly blunt. This might have influenced the behaviour of the pin in the subsequent tests with spacers.)

In the case of tests with two spacers (0.66 mm gap)

In this case the force increased approximately linearly to the magnitude of from 20 N to 40 N at the displacement 0.25 mm approximately, and then slowly, linearly decreased to zero (see **Figure 5.62**). Slight drop and immediate rise in the value of the force was observed shortly after the first maximum, which was probably connected with breakage of the pin on each side of the cutting bar not occurring simultaneously. In this case the length of the pin in the gap probably allows bending failure to dominate. It is likely that the resulting cracks grow transversely across the pins in a stable manner. Behaviours of the all four tested specimens were closely comparable except for the magnitude of the force. The maximum value of the force varied from 20 N to 40 N. This may be due to an error in the “zeroing” of the force at the beginning of a test – a small tensile pre-load could cause the observed force variation between tests.

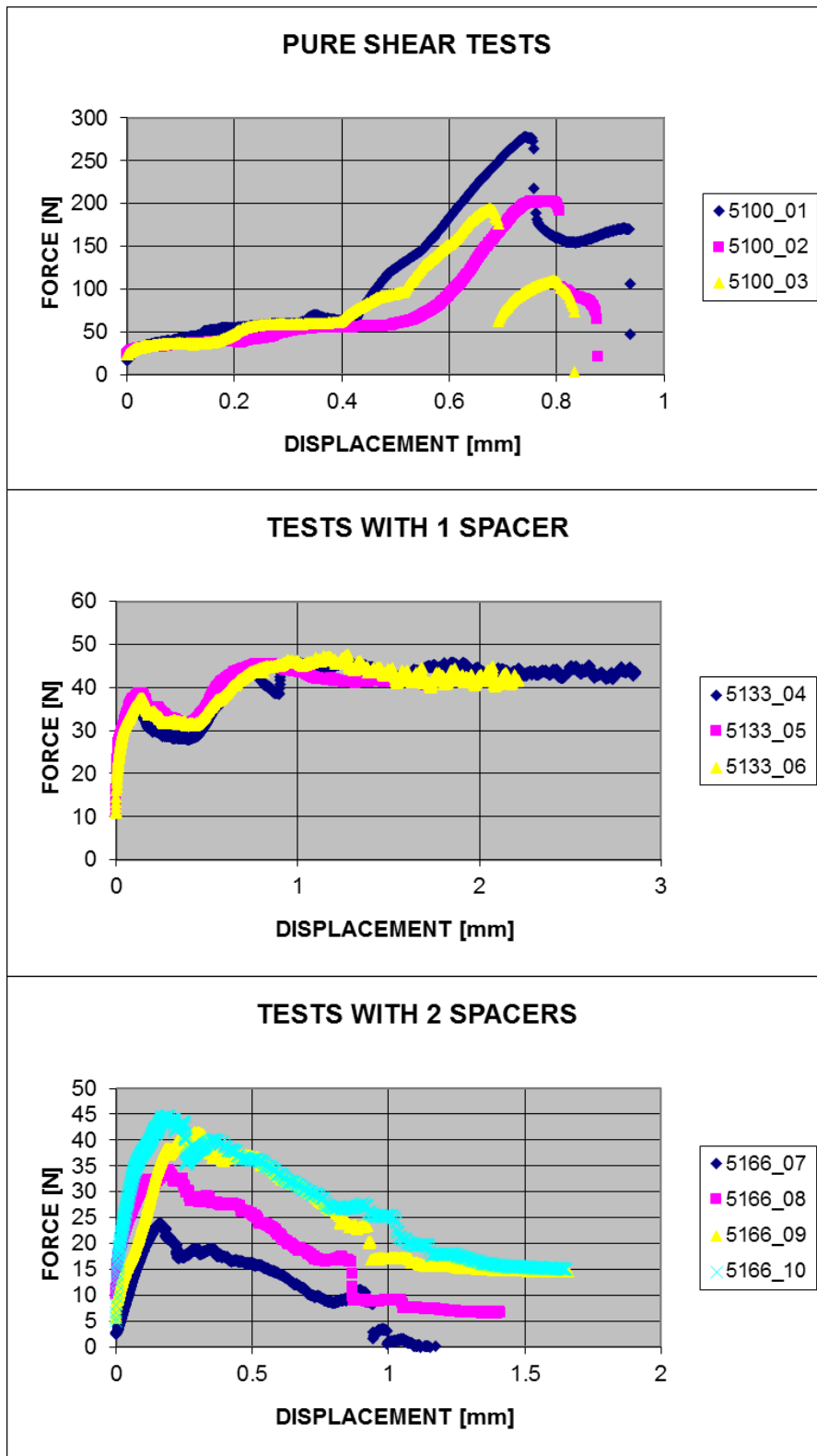


Figure 5.62 Results of the shear tests. The colours in each graph distinguish the specimens.

6 CONCLUSIONS AND FUTURE WORK

6.1 CONCLUDING REMARKS

In order to characterize the behaviour of Z-Pins bridging an existing delamination, tests of single Z-Pins and groups of Z-Pins under Mode I, mixed mode and Mode II loading conditions were carried out. In order to investigate the features, which may influence the behaviour of the Z-Pins, a variety tests were developed, namely:

- Z-Pins of two different diameters were tested – 0,28 mm and 0,51 mm
- Specimens were prepared using laminates of two distinct stacking sequences – QI and UD
- Specimens containing single Z-Pins and Z-Pins arranged in groups were tested
- The influence of controlling the opening displacement in Mode II was investigated
- The influence of the speed of pull-out was investigated

Observation of poor z-pinning quality achieved with the common UAZ insertion method, led to development of alternative methods. Among the four different preparation Z-Pinning methods used for the manufacture of Z-Pinned composite specimens, manual insertion was most promising. In this method the prepreg panels were perforated with a sharp steel needle either before or after preconsolidation and then the Z-Pins were inserted into the resulting holes. This method gave the highest quality of Z-Pinning, with all the Z-Pins being embedded through the thickness of the composite at the desired angle and causing lowest level of damage in the composite. In comparison the traditional UAZ method produced low quality specimens, with very variable insertion angles and insertion depths.

Extensive microscopic observations showed damage caused in the composite by the insertion of the Z-Pins, including resin pockets and fibre waviness (in-plane and also pushing the fibres across the plies, in the through-thickness direction) and air bubbles. They also showed faults in the structure of the Z-Pins, including cavities or resin-filled areas stretching along the fibres, as well as irregularity in the shape of Z-Pin cross-sections. Observation of the subsequent cross-sections proved that Z-Pin rodstock can be twisted by approximately 50° per 2.5 mm of the length.

Three phases were identified during the pull-out tests:

- Linear Phase - which is believed to be elastic stretch with no energy loss and with the Z-Pin interface bond staying intact
- Crack Formation - where Z-Pin separates from the surrounding composite during unstable crack propagation
- Frictional Sliding - friction-controlled pull-out of the Z-Pin from the composite

The stacking sequence of the composite, UD or QI, seemed to have the highest influence on the character of the pull out process. This was believed to be a result of tensile character of the curing stresses at the interface between the Z-Pin and the laminate in the QI composite (due to mismatch of the thermal coefficients of expansion of the resin and fibre), thus causing weaker bond between the Z-Pin and the composite in the QI laminate.

The substantial growth of the force during the Frictional Sliding phase was attributed to the irregularities of the Z-Pin surface along the z axis (due to features like irregular, non-circular cross-section combined with the twist of the Z-Pin, and irregular voids in the Z-Pin structure which collapse due the curing shrinkage of the laminate). This phenomenon of increasing pull-out force during the Frictional Sliding phase has been attributed in the literature to the “snubbing” effect causing “enhanced” friction between the edge of the laminate at the delamination and a Z-Pin inserted at non-zero (2° - 30°) angles [67,48] and this has been confirmed by the FE modelling [68]. However, due to application of the needle assisted manual insertion method, the insertion angles achieved in the research described in this thesis were lower than 2° and so “snubbing” would not have significant influence on the pull-out behaviour.

In the shear-out tests two phases were identified:

- Linear Phase (a short elastic stretch with no energy loss)
- Breaking Phase (where the fibrous structure of the Z-Pins is fractured, finally resulting in Z-Pin failure, with no or little pull-out.

It was observed that the shear-out process of QI and UD specimens sheared along fibres had similar character, while UD specimens sheared across fibres behaved in a significantly different manner. This was believed to be due to the “softer” character of the edge of the composite

around the Z-Pin in the crack wake in the QI and UD specimens sheared along the fibre direction.

In Mixed Mode test conditions, specimens exhibited a behaviour similar to pull-out for test angles up to and including 45° . For higher angles the behaviour was more similar to pure shear-out. A number of specimens tested at angles of 70° or 80° showed unusual behaviour, e.g. shear damage and pull-out occurring simultaneously. Similar behaviour was also reported in case of shear-loaded Z-Pins bridging an open crack, for a particular crack opening size (around 0.3 mm for 0.51 mm diameter Z-Pins). A brush-shaped structure was formed, which showed that cracks propagated along the fibres of the Z-Pin, causing no damage to the fibres.

6.2 FUTURE WORK

Knowledge of the behaviour of Z-Pins bridging a delamination in a composite structure will enable better assessment of the load bearing capacity of z-pinned composite structure after damage (e.g. after impact), and hence a better prediction of the damage tolerance of the structure. One way this could be achieved is by using the load-displacement curves derived in the tests reported in this thesis for development of link elements mimicking the action of Z-Pins in the structure for use in FE modelling.

Given the strong dependency of the Z-Pin pull-out response on the friction caused by the curing residual stresses, a further investigation of the influence of temperature and moisture on the Z-Pin behaviour should be performed.

A detailed investigation to establish the cause of the growth of the force, commonly observed during the Frictional Sliding pull-out phase should be carried out. An FE model of the Z-Pin including the irregularities of the Z-Pin along the z axis may also be needed to compare the influence of these irregularities to that of the “snubbing” action of inclined Z-Pins.

A further examination should be performed of the lateral (or opening) displacement during the shear-out and mixed mode loading conditions, with the application of more sophisticated methods of measurement.

The quality of the Z-Pin rod stock and pre-forms should be investigated further in detail. The differences between Z-Pins and pre-forms made by different manufacturers, and the influence of these differences on Z-Pinning quality requires more research.

Work on alternative Z-Pin insertion methods is also needed. As shown in this study the Z-Pinning quality using the standard UAZ method is rather low and the process is highly laborious. A possible industrial implementation of the manual insertion method, as developed in this thesis, could be considered. A proposal for an alternative pinning device, which would allow the use of Z-Pin rodstock directly, without the necessity to use preforms, is shown in **Figure 6.1**.

The elements of the alternative pinning device shown in **Figure 6.1** are as follows:

a – head of a hand held or gantry mounted pistol

b – moving part, which automatically cuts the Z-Pin rodstock when fully inserted and also pulls the new rodstock towards the needles

c – rodstock cutters (triggered by the moving part **b** when needles are fully inserted into the laminate)

d - plastic or rubber “funnels” which allow the rodstock to move freely in one direction, and blocks the movement in the other direction (when the moving part **b** travels up during the Z-Pin insertion, the funnels allow the Z-Pin to slide through; when the moving part travels down the funnels contract and the new rodstock is pulled down together with the moving part)

e - laminate

f – Z-Pin rodstock (depending on the pinning needle design, the rodstock can be in form of hardened rods or soft fibre)

A - pinning needle with an open cross-section – this solution allows for the tip of the needle to be smoothly tapered over a fairly long distance from the tip, however the tip of the Z-Pin may get “caught” at the edge of the hole in the laminate; to prevent this the end of the Z-Pin would have to be far above the tip of the needle, and enough space would have to be allowed under the laminate for the needle and Z-Pin to penetrate through the entire thickness of the laminate.

B – syringe type pinning needle – in this solution the sharp tip of the needle is non-symmetric, which may cause problems during the penetration into the laminate, however because the sharp tip is shorter, the end of the Z-Pin can be closer to the tip of the needle, hence much less space is needed under the composite in order for the Z-Pin to penetrate the laminate through the entire thickness. This type of needle allows to use soft rodstock as well as hardened one.

For shear-out testing, using the mixed mode rig, the opening displacement control feature needs to be explored further, to give a deeper insight into the behaviour of the Z-Pins under shear-out and mixed mode conditions, in which the opening displacement is constrained/measured.

The Mixed Mode behaviour needs in-depth research, as only general studies were carried out in this work - more detailed data reduction should be performed. This should include collecting more data to fully populate the 3D graph representing Z-Pin behaviour for various angles in the local coordinates.

A full Finite Element Z-Pin pull-out model could be created and investigated, for various stacking sequences of the composite. This should include a detailed numerical investigation of crack propagation during Z-Pin pull-out and the significance of residual stress. A numerical model of shear-out process, including the complicated process of Z-Pin damage (cracks propagating alongside the Z-Pin fibres) should also be investigated.

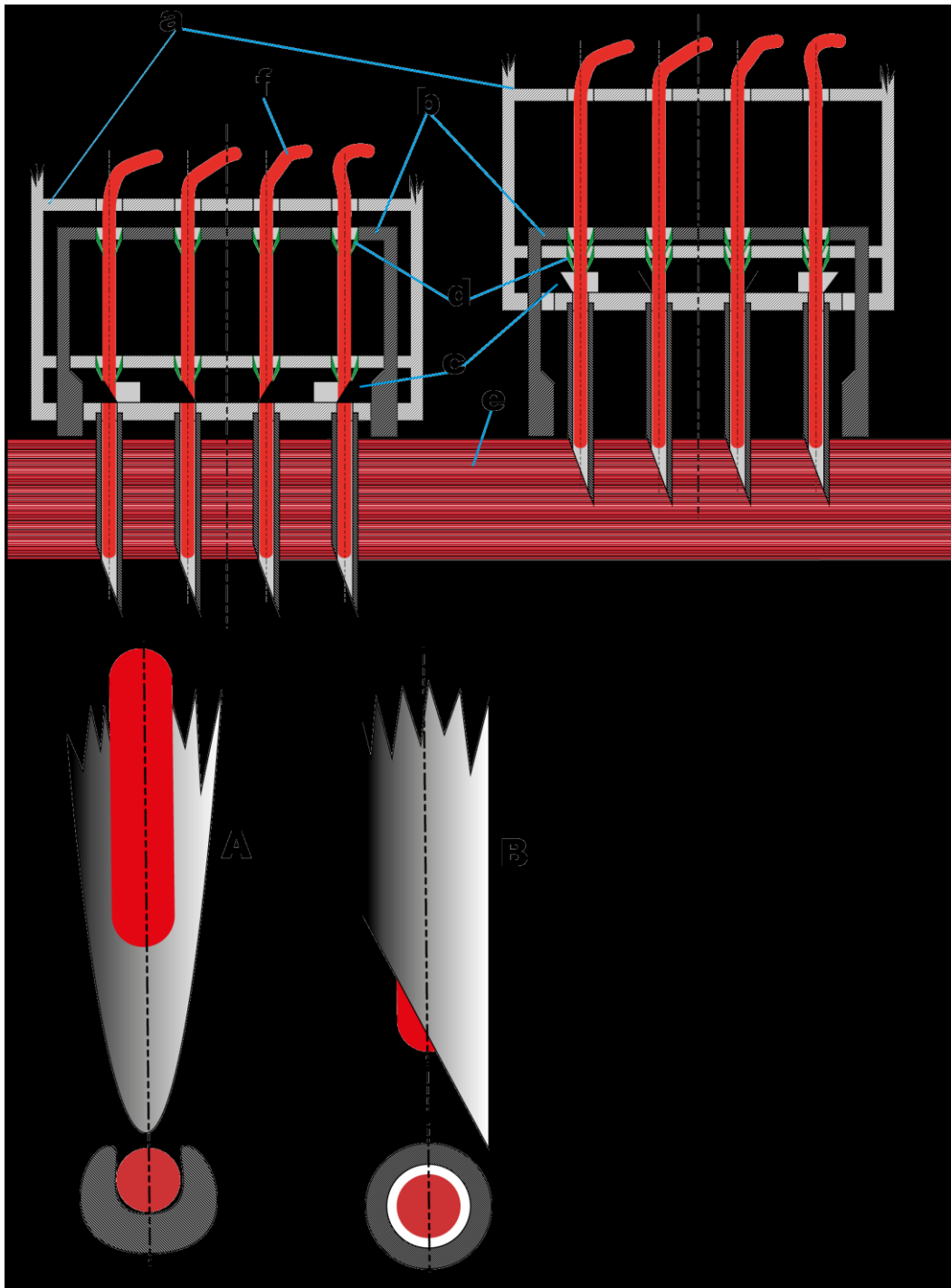


Figure 6.1 Proposition of an alternative pinning device

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APPENDIX – TABLES OF RESULTS

PULL-OUT Method A																						
	PIN DIAMETER [mm]	LAYUP	PINNING DEPTH		No OF SPEC's	ENRG. [J]	E/a _{max} [J/mm]	P _{max} [N]	a _{pmax} [mm]	a _{max} [mm]	τ _d [MPa]	τ _f [MPa]	P ₀ [N]	a ₀ [mm]	P ₁ [N]	a ₁ [mm]	P ₂ [N]	a ₂ [mm]	P ₃ [N]	a ₃ [mm]		
SINGLE	0.28	UD	3mm/4mm		1	0.013	0.012	53.02	0.05	1.13	53.34	23.55	53.02	0.05	53.02	0.05	19.05	0.06	19.05	0.06	Mean	
						N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	S.Dev	
						N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	C.of Var.	
	0.51	UD	3mm/4mm		6	0.147	0.049	177.39	0.24	2.83	39.81	20.27	173.70	0.21	175.67	0.24	84.33	0.27	87.22	0.37	Mean	
						0.096	0.018	21.72	0.09	0.65	8.71	3.77	24.01	0.03	20.69	0.10	25.06	0.11	29.40	0.29	S.Dev	
						0.657	0.372	0.12	0.40	0.23	0.22	0.19	0.14	0.17	0.12	0.41	0.30	0.40	0.34	0.79	C.of Var.	
	0.51	QI	2mm/5mm		7	0.141	0.052	90.43	0.32	2.57	20.15	25.17	82.44	0.12	89.38	0.22	87.02	0.23	89.79	0.39	Mean	
						0.082	0.017	27.67	0.20	0.58	3.52	5.57	20.04	0.02	28.15	0.14	26.51	0.15	27.09	0.24	S.Dev	
						0.580	0.324	0.31	0.61	0.23	0.17	0.22	0.24	0.19	0.31	0.63	0.30	0.65	0.30	0.61	C.of Var.	
	0.51	QI	3mm/4mm		7	0.167	0.046	112.56	0.61	3.54	21.55	17.01	106.14	0.16	110.59	0.21	82.15	0.23	86.85	0.67	Mean	
						0.073	0.015	34.29	0.54	1.13	12.32	4.67	39.51	0.08	35.82	0.08	16.78	0.10	18.97	0.51	S.Dev	
						0.439	0.319	0.30	0.89	0.32	0.57	0.27	0.37	0.49	0.32	0.40	0.20	0.44	0.22	0.75	C.of Var.	
FOUR	0.51	QI (close)	3mm/4mm		5	0.605	0.046	257.38	0.91	4.06											Mean	
						0.116	0.006	16.69	0.44	0.58												S.Dev
						0.191	0.131	0.06	0.49	0.14												C.of Var.
	0.51	QI (far)	3mm/4mm		2	0.825	0.091	451.91	0.56	4.05											Mean	
						0.154	0.022	0.09	0.29	0.35												S.Dev
						0.187	0.245	0.00	0.52	0.09												
	0.51	UD (close)	2mm/5mm		5	0.320	0.041	328.06	0.24	2.21											Mean	
						0.078	0.010	75.01	0.04	0.09												S.Dev
						0.243	0.253	0.23	0.16	0.04												C.of Var.
	0.51	UD (far)	2mm/5mm		4	0.336	0.094	417.29	0.54	2.69											Mean	
						0.072	0.033	24.65	0.13	0.16												S.Dev
						0.213	0.352	0.06	0.23	0.06												C.of Var.

PULL-OUT Method C																						
RIG	PIN DIAMETER [mm]	LAYUP	SPEED mm/min	PINNING DEPTH	No OF SPEC'S	ENRG. [J]	E/a _{max} [J/mm]	P _{max} [N]	a _{pmax} [mm]	a _{max} [mm]	τ _d [MPa]	τ _f [MPa]	P ₀ [N]	a ₀ [mm]	P ₁ [N]	a ₁ [mm]	P ₂ [N]	a ₂ [mm]	P ₃ [N]	a ₃ [mm]		
SINGLE	rigid	0.28	UD	0.5	3mm	6	0.059	0.022	49.25	0.11	2.69	20.33	18.16	48.40	0.03	48.40	0.03	36.04	0.05	40.94	0.28	Mean
							0.013	0.004	13.42	0.11	0.10	5.44	3.24	14.06	0.00	14.06	0.00	5.63	0.01	7.26	0.06	S.Dev
							0.225	0.201	0.27	0.97	0.04	0.27	0.18	0.29	0.14	0.29	0.14	0.16	0.16	0.18	0.23	C.of Var.
		0.28	QI	0.5	3mm	7	0.057	0.019	30.31	0.51	2.91	10.09	14.44	25.23	0.03	26.38	0.06	22.14	0.08	30.01	0.61	Mean
							0.023	0.006	5.98	0.57	0.43	2.38	3.78	3.81	0.02	3.21	0.07	4.79	0.07	6.38	0.53	S.Dev
							0.406	0.313	0.20	1.12	0.15	0.24	0.26	0.15	0.55	0.12	1.08	0.22	0.92	0.21	0.87	C.of Var.
		0.51	UD	0.5	3mm	7	0.134	0.046	105.46	0.28	2.92	22.21	19.27	103.55	0.04	103.55	0.04	63.83	0.08	68.38	0.57	Mean
							0.049	0.013	13.65	0.56	0.24	2.46	4.34	11.06	0.03	11.06	0.03	11.06	0.03	13.65	0.56	S.Dev
							0.367	0.288	0.13	2.04	0.08	0.11	0.23	0.11	0.72	0.11	0.72	0.17	0.35	0.20	1.00	C.of Var.
		0.51	QI	0.5	3mm	7	0.132	0.043	66.25	0.98	3.01	8.97	17.44	42.98	0.06	42.98	0.06	42.98	0.06	66.25	0.98	Mean
							0.027	0.009	34.49	0.40	0.15	8.16	4.34	37.50	0.01	37.50	0.01	12.70	0.02	12.72	0.23	S.Dev
							0.208	0.220	0.52	0.41	0.05	0.91	0.25	0.87	0.22	0.87	0.22	0.30	0.32	0.19	0.24	C.of Var.
	0.51	QI	0.5	2mm	5	0.046	0.022	36.11	0.45	2.07	9.33	12.11	31.05	0.07	31.05	0.07	30.95	0.07	36.11	0.45	Mean	
						0.019	0.008	8.74	0.24	0.29	2.39	3.57	9.29	0.03	9.29	0.03	9.24	0.04	8.74	0.24	S.Dev	
						0.415	0.363	0.24	0.53	0.14	0.26	0.29	0.30	0.48	0.30	0.48	0.30	0.49	0.24	0.53	C.of Var.	
	0.51	QI	0.5	1mm	7	0.015	0.013	32.04	0.12	1.14	15.65	13.62	28.42	0.03	28.71	0.03	30.68	0.04	25.31	0.12	Mean	
						0.005	0.004	23.29	0.14	0.08	10.08	4.15	19.21	0.01	19.11	0.01	24.11	0.02	7.15	0.14	S.Dev	
						0.324	0.315	0.73	1.21	0.07	0.64	0.31	0.68	0.39	0.67	0.41	0.79	0.56	0.28	1.18	C.of Var.	
	0.51	QI	5	3mm	6	0.138	0.043	63.44	1.13	3.21	9.79	15.98	50.47	0.14	50.47	0.14	44.79	0.16	63.44	1.13	Mean	
						0.019	0.005	7.11	0.18	0.17	1.42	1.89	8.75	0.10	8.75	0.10	3.61	0.12	7.11	0.18	S.Dev	
						0.134	0.109	0.11	0.16	0.05	0.15	0.12	0.17	0.74	0.17	0.74	0.08	0.78	0.11	0.16	C.of Var.	
0.51	QI	0.05	3mm	6	0.129	0.041	60.72	0.97	3.11	9.71	16.49	48.17	0.03	48.17	0.03	40.85	0.05	59.76	1.04	Mean		
					0.041	0.011	15.29	0.57	0.26	3.93	4.20	19.49	0.01	19.49	0.01	14.24	0.01	14.93	0.44	S.Dev		
					0.316	0.267	0.25	0.59	0.08	0.40	0.25	0.40	0.31	0.40	0.31	0.35	0.26	0.25	0.42	C.of Var.		
FOUR	4 x 0.51	UD (close)	0.5	3mm	7	0.441	0.035	338.42	0.10	3.13	16.83	13.34	338.42	0.10	338.42	0.10	216.29	0.12	235.08	0.48	Mean	
						0.093	0.007	84.77	0.02	0.12	4.15	2.50	84.77	0.02	84.77	0.02	24.45	0.01	34.68	0.13	S.Dev	
						0.210	0.197	0.25	0.21	0.04	0.25	0.19	0.25	0.21	0.25	0.21	0.11	0.10	0.15	0.28	C.of Var.	
	4 x 0.51	UD (far)	0.5	3mm	7	0.466	0.037	320.32	0.09	3.13	15.99	14.11	320.32	0.09	320.32	0.09	216.77	0.12	244.07	0.54	Mean	
						0.111	0.007	54.17	0.02	0.13	2.76	2.40	54.17	0.02	54.17	0.02	25.27	0.01	35.36	0.17	S.Dev	
						0.237	0.201	0.17	0.26	0.04	0.17	0.17	0.17	0.26	0.17	0.26	0.12	0.13	0.14	0.32	C.of Var.	
	4 x 0.51	QI (close)	0.5	3mm	7	0.560	0.041	259.60	0.83	3.38	9.43	15.22	203.34	0.05	215.81	0.13	187.19	0.16	254.85	0.86	Mean	
						0.069	0.005	31.74	0.23	0.25	0.88	2.07	16.35	0.01	19.65	0.20	18.78	0.22	34.51	0.20	S.Dev	
						0.124	0.109	0.12	0.28	0.08	0.09	0.14	0.08	0.18	0.09	0.15	0.10	1.34	0.14	0.24	C.of Var.	
	4 x 0.51	QI (far)	0.5	3mm	7	0.571	0.040	259.04	0.76	3.56	8.43	13.95	191.15	0.08	206.31	0.12	192.15	0.17	255.79	0.87	Mean	
						0.117	0.005	38.24	0.30	0.49	1.83	2.21	41.87	0.03	55.73	0.09	42.46	0.12	34.80	0.20	S.Dev	
						0.206	0.129	0.15	0.39	0.14	0.22	0.16	0.22	0.33	0.27	0.69	0.22	0.72	0.14	0.23	C.of Var.	

SHEAR-OUT Method B																						
	PIN DIAMETER [mm]	SPRING	LAYUP	SPECIM EN ORIENT ATION	PINNING DEPTH	No OF SPEC's	ENRG. [J]	E/a _{max} [J/mm]	P _{max} [N]	a _{Pmax} [mm]	a _{max} [mm]	τ _d [MPa]	τ _r [MPa]	P ₀ [N]	a ₀ [mm]	P ₁ [N]	a ₁ [mm]	P ₂ [N]	a ₂ [mm]	P ₃ [N]	a ₃ [mm]	
SINGLE	0.28	MEDIUM	QI	-	3mm	9	0.027	0.060	102.80	0.33	0.45	130.52	44.53	77.72	0.20	102.80	0.33	71.01	0.34	44.92	0.44	Mean
							0.013	0.025	43.53	0.06	0.09	61.27	26.03	30.03	0.12	43.53	0.06	39.14	0.06	12.17	0.09	S.Dev
							0.467	0.421	0.42	0.20	0.20	0.47	0.58	0.39	0.59	0.42	0.20	0.55	0.18	0.27	0.20	C.of Var.
	0.28	MEDIUM	UD	across	3mm	5	0.009	0.037	69.47	0.22	0.25	162.10	27.39	21.23	0.08	69.47	0.22	65.20	0.22	62.86	0.24	Mean
							0.005	0.013	19.01	0.03	0.05	25.32	37.88	27.08	0.07	19.01	0.03	10.20	0.03	6.38	0.05	S.Dev
							0.543	0.339	0.27	0.14	0.20	0.16	1.38	1.28	0.95	0.27	0.14	0.16	0.14	0.10	0.21	C.of Var.
	0.28	MEDIUM	UD	along	3mm	5	0.006	0.026	59.57	0.23	0.26	163.75	17.63	6.26	0.04	59.57	0.23	40.69	0.23	41.99	0.24	Mean
							0.002	0.014	42.21	0.08	0.05	156.64	28.98	3.85	0.02	42.21	0.08	5.31	0.07	5.89	0.05	S.Dev
							0.323	0.547	0.71	0.35	0.21	0.96	1.64	0.61	0.40	0.71	0.35	0.13	0.31	0.14	0.21	C.of Var.
	0.28	SOFT	QI	-	2.5mm	5	0.022	0.043	88.16	0.33	0.50	95.05	34.54	10.41	0.08	88.16	0.33	40.61	0.37	39.39	0.48	Mean
							0.010	0.011	36.73	0.09	0.14	38.97	20.40	0.74	0.08	36.73	0.09	8.19	0.11	9.03	0.14	S.Dev
							0.464	0.254	0.42	0.28	0.29	0.41	0.59	0.07	1.03	0.42	0.28	0.20	0.29	0.23	0.29	C.of Var.
	0.28	SOFT	QI	-	2.0mm	4	0.032	0.048	99.03	0.35	0.43	105.71	30.10	8.97	0.09	98.60	0.33	56.17	0.34	45.76	0.42	Mean
							0.026	0.041	100.19	0.04	0.09	101.44	18.43	0.50	0.05	100.87	0.05	46.88	0.05	49.16	0.08	S.Dev
							0.824	0.843	1.01	0.11	0.20	0.96	0.61	0.06	0.53	1.02	0.15	0.83	0.14	1.07	0.20	C.of Var.
	0.28	SOFT	QI	-	1.5mm	3	0.014	0.022	41.69	0.51	0.60	36.36	13.58	6.71	0.11	40.49	0.46	26.98	0.47	24.18	0.60	Mean
							0.014	0.019	33.46	0.04	0.08	23.19	14.63	4.85	0.05	34.16	0.09	11.81	0.08	7.32	0.08	S.Dev
							0.955	0.854	0.80	0.07	0.12	0.64	1.08	0.72	0.45	0.84	0.20	0.44	0.17	0.30	0.14	C.of Var.
	0.51	MEDIUM	QI	-	3mm	12	0.084	0.102	156.32	0.63	0.83	107.86	62.19	120.82	0.24	156.24	0.63	129.99	0.65	125.68	0.77	Mean
							0.055	0.055	84.86	0.29	0.30	107.83	29.87	95.28	0.13	84.91	0.29	67.42	0.29	65.96	0.23	S.Dev
							0.654	0.540	0.54	0.46	0.35	1.00	0.48	0.79	0.52	0.54	0.47	0.52	0.44	0.52	0.30	C.of Var.
	0.51	MEDIUM	UD	across	3mm	6	0.057	0.117	181.16	0.30	0.48	194.13	111.54	158.29	0.22	181.16	0.30	155.78	0.31	155.85	0.46	Mean
							0.014	0.015	17.02	0.09	0.08	52.94	26.24	40.66	0.07	17.02	0.09	25.57	0.08	27.96	0.09	S.Dev
							0.246	0.129	0.09	0.30	0.17	0.27	0.24	0.26	0.30	0.09	0.30	0.16	0.25	0.18	0.19	C.of Var.
0.51	MEDIUM	UD	along	3mm	6	0.071	0.120	181.05	0.39	0.58	204.01	71.46	40.54	0.08	176.13	0.33	151.55	0.36	166.11	0.55	Mean	
						0.022	0.008	11.82	0.16	0.17	99.66	12.07	71.31	0.09	18.16	0.06	10.95	0.07	9.46	0.17	S.Dev	
						0.318	0.065	0.07	0.43	0.30	0.49	0.17	1.76	1.15	0.10	0.19	0.07	0.20	0.06	0.31	C.of Var.	
0.51	SOFT	QI	-	1.5mm	5	0.066	0.065	106.11	0.35	1.06	58.66	37.32	17.41	0.06	105.31	0.35	87.45	0.40	40.43	1.04	Mean	
						0.012	0.020	28.40	0.30	0.23	40.62	19.27	14.79	0.04	27.07	0.30	21.71	0.27	33.92	0.23	S.Dev	
						0.185	0.306	0.27	0.85	0.22	0.69	0.52	0.85	0.61	0.26	0.86	0.25	0.67	0.84	0.22	C.of Var.	
0.51	SOFT	UD	across	1.5mm	3	0.077	0.048	175.27	0.20	1.61	72.12	14.15	10.94	0.05	175.27	0.20	71.95	0.26	11.83	1.52	Mean	
						0.012	0.002	128.05	0.05	0.22	61.31	2.69	0.54	0.01	128.05	0.05	13.27	0.04	1.22	0.33	S.Dev	
						0.156	0.048	0.73	0.23	0.13	0.85	0.19	0.05	0.22	0.73	0.23	0.18	0.14	0.10	0.22	C.of Var.	
0.51	SOFT	UD	along	1.5mm	1	0.123	0.062	122.81	0.42	2.00	28.92	17.86	9.40	0.08	122.81	0.42	95.70	0.44	9.40	1.88	Mean	
						N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	S.Dev
						N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	C.of Var.
0.51	SOFT	QI	-	2.0mm	4	0.116	0.081	140.64	0.30	1.58	92.33	40.28	11.01	0.06	136.21	0.20	114.85	0.34	50.44	1.50	Mean	
						0.050	0.027	53.30	0.17	0.86	96.17	34.02	2.21	0.02	58.70	0.07	34.98	0.14	47.30	0.78	S.Dev	
						0.434	0.327	0.38	0.57	0.54	1.04	0.84	0.20	0.27	0.43	0.34	0.30	0.42	0.94	0.52	C.of Var.	
0.51	SOFT	QI	-	2.5mm	2	0.130	0.119	315.95	0.22	1.19	184.65	47.57	12.19	0.05	315.95	0.22	174.31	0.35	69.51	1.13	Mean	
						0.084	0.096	262.37	0.16	0.25	177.11	37.66	1.83	0.04	262.37	0.16	149.52	0.00	81.45	0.18	S.Dev	
						0.648	0.806	0.83	0.71	0.21	0.96	0.79	0.15	0.79	0.83	0.71	0.86	0.00	1.17	0.16	C.of Var.	
FOUR	0.51	MEDIUM	QI (close)	-	3mm	5	0.346	0.339	645.01	0.39	1.09	338.39	200.72	562.56	0.19	580.27	0.21	483.18	0.23	154.62	1.08	Mean
							0.150	0.110	228.86	0.20	0.56	96.56	91.51	246.30	0.11	228.01	0.09	189.00	0.12	119.72	0.56	S.Dev
							0.436	0.324	0.35	0.52	0.51	0.29	0.46	0.44	0.58	0.39	0.45	0.39	0.49	0.77	0.52	C.of Var.
	0.51	MEDIUM	UD (close)	across	3mm	3	0.287	0.432	876.52	0.33	0.69	823.53	224.73	592.20	0.26	876.52	0.33	500.94	0.36	341.73	0.67	Mean
							0.030	0.099	272.04	0.03	0.18	387.46	90.98	221.57	0.14	272.04	0.03	58.45	0.04	210.72	0.18	S.Dev
							0.106	0.228	0.31	0.08	0.26	0.47	0.40	0.37	0.54	0.31	0.08	0.12	0.12	0.62	0.27	C.of Var.
	0.51	MEDIUM	UD (close)	along	3mm	4	0.326	0.417	646.84	0.42	0.80	412.14	268.64	611.99	0.29	626.64	0.32	533.74	0.35	209.94	0.79	Mean
							0.024	0.074	98.99	0.16	0.11	152.74	104.31	125.64	0.15	119.37	0.21	110.14	0.21	119.32	0.12	S.Dev
							0.073	0.177	0.15	0.39	0.14	0.37	0.39	0.21	0.52	0.19	0.65	0.21	0.60	0.57	0.15	C.of Var.
	0.51	MEDIUM	QI (far)	-	3mm	7	0.345	0.325	562.39	0.51	1.06	277.09	164.31	457.18	0.25	545.84	0.37	474.27	0.40	137.53	1.06	Mean
							0.089	0.031	122.32	0.16	0.27	122.71	53.48	225.28	0.11	132.86	0.12	75.55	0.11	45.42	0.28	S.Dev
							0.258	0.095	0.22	0.32	0.26	0.44	0.33	0.49	0.43	0.24	0.31	0.16	0.29	0.33	0.26	C.of Var.
	0.51	MEDIUM	UD (far)	across	3mm	4	0.283	0.352	696.14	0.35	0.82	554.70	153.03	696.13	0.35	696.13	0.35	453.20	0.38	157.26	0.82	Mean
							0.034	0.056	86.95	0.02	0.18	179.64	48.65	86.97	0.02	86.97	0.02	97.63	0.03	78.79	0.18	S.Dev
							0.119	0.160	0.12	0.05	0.22	0.32	0.32	0.12	0.06	0.12	0.06	0.22	0.08	0.50	0.22	C.of Var.
	0.51	MEDIUM	UD (far)	along	3mm	4	0.365	0.254	635.38	0.46	1.62	293.07	70.44	632.74	0.43	632.74	0.43	513.66	0.46	100.37	1.12	Mean
							0.106	0.068	58.01	0.14	0.94	135.20	30.44	63.20	0.08	63.20	0.08	128.93	0.07	32.35	0.41	S.Dev
							0.289	0.270	0.09	0.30	0.58	0.46	0.43	0.10	0.18	0.10	0.18	0.25	0.16	0.32	0.37	C.of Var.

SHEAR-OUT Method C																										
	PIN DIAMETER [mm]	SPRING	LAYUP	SPECIM EN ORIENT ATION	PINNING DEPTH	No OF SPEC's	ENRG. [J]	E/a _{max} [J/mm]	P _{max} [N]	a _{Pmax} [mm]	a _{max} [mm]	τ _d [MPa]	τ _f [MPa]	P ₀ [N]	a ₀ [mm]	P ₁ [N]	a ₁ [mm]	P ₂ [N]	a ₂ [mm]	P ₃ [N]	a ₃ [mm]					
SINGLE	0.28	STIFF	QI	-	3mm	6	0.007	0.023	36.49	0.24	0.28	151.73	22.23	36.49	0.24	36.49	0.24	36.49	0.24	36.49	0.24	36.49	0.24	Mean		
							0.002	0.008	8.96	0.08	0.06	42.87	39.72	8.96	0.08	8.96	0.08	8.96	0.08	8.96	0.08	S.Dev				
							0.376	0.327	0.25	0.34	0.21	0.28	1.79	0.25	0.34	0.25	0.34	0.25	0.34	0.25	0.34	C.of Var.				
	0.28	STIFF	UD	along	3mm	5	0.008	0.033	48.81	0.21	0.24	231.31	67.87	45.79	0.17	45.79	0.17	45.79	0.17	45.79	0.17	45.79	0.17	Mean		
							0.002	0.006	1.94	0.12	0.09	93.09	79.84	6.09	0.08	6.09	0.08	6.09	0.08	6.09	0.08	S.Dev				
							0.271	0.185	0.04	0.58	0.35	0.40	1.18	0.13	0.46	0.13	0.46	0.13	0.46	0.13	0.46	C.of Var.				
	0.28	MEDIUM	QI	-	3mm	5	0.005	0.024	39.97	0.22	0.23	152.14	65.25	27.51	0.11	39.83	0.22	39.83	0.22	39.83	0.22	39.83	0.22	Mean		
							0.001	0.005	6.20	0.04	0.04	54.20	36.93	3.26	0.04	6.05	0.04	6.05	0.04	6.05	0.04	S.Dev				
							0.255	0.230	0.16	0.17	0.15	0.36	0.57	0.12	0.32	0.15	0.17	0.15	0.17	0.15	0.17	C.of Var.				
	0.28	SOFT	QI	-	3mm	5	0.006	0.022	35.50	0.27	0.29	128.20	47.35	27.77	0.15	35.50	0.27	35.50	0.27	35.50	0.27	35.50	0.27	Mean		
							0.003	0.005	5.40	0.09	0.11	75.42	34.71	6.77	0.06	5.40	0.09	5.40	0.09	5.40	0.09	S.Dev				
							0.449	0.254	0.15	0.35	0.37	0.59	0.73	0.24	0.38	0.15	0.35	0.15	0.35	0.15	0.35	C.of Var.				
	0.28	SOFT	UD	along	3mm	5	0.008	0.033	55.93	0.18	0.23	264.96	69.39	32.25	0.05	48.87	0.12	37.91	0.13	51.40	0.22	51.40	0.22	Mean		
							0.003	0.007	10.81	0.07	0.07	130.62	70.93	21.16	0.02	17.37	0.09	15.65	0.08	6.02	0.07	S.Dev				
							0.432	0.226	0.19	0.38	0.29	0.49	1.02	0.66	0.40	0.36	0.71	0.41	0.64	0.12	0.32	C.of Var.				
	0.51	STIFF	QI	-	3mm	7	0.071	0.099	146.69	0.68	0.72	69.77	76.67	88.67	0.23	143.40	0.61	141.90	0.62	123.41	0.61	123.41	0.61	Mean		
							0.011	0.014	12.53	0.07	0.08	25.46	13.84	6.89	0.13	9.97	0.08	10.55	0.08	56.13	0.28	S.Dev				
							0.157	0.143	0.09	0.11	0.11	0.36	0.18	0.08	0.56	0.07	0.14	0.07	0.14	0.45	0.46	C.of Var.				
	0.51	STIFF	UD	along	3mm	6	0.078	0.098	137.09	0.74	0.80	86.52	54.77	88.92	0.20	120.17	0.43	112.68	0.45	134.28	0.78	134.28	0.78	Mean		
							0.015	0.010	11.24	0.12	0.15	35.02	24.48	31.44	0.09	21.96	0.21	26.73	0.20	13.38	0.15	S.Dev				
							0.190	0.098	0.08	0.17	0.19	0.40	0.45	0.35	0.48	0.18	0.49	0.24	0.45	0.10	0.19	C.of Var.				
	0.51	STIFF	UD	across	3mm	6	0.073	0.131	181.88	0.50	0.56	195.25	100.12	170.46	0.23	170.46	0.23	142.72	0.26	177.97	0.54	177.97	0.54	Mean		
							0.012	0.013	16.93	0.12	0.07	48.02	9.97	28.67	0.06	28.67	0.06	30.90	0.07	12.50	0.07	S.Dev				
							0.170	0.096	0.09	0.24	0.13	0.25	0.10	0.17	0.27	0.17	0.27	0.22	0.26	0.07	0.14	C.of Var.				
	0.51	STIFF	QI	-	1mm	5	0.079	0.065	112.91	0.39	1.20	59.46	23.72	105.70	0.30	112.86	0.39	112.86	0.39	94.32	0.58	94.32	0.58	Mean		
							0.030	0.010	29.79	0.11	0.34	15.93	4.96	27.75	0.10	29.71	0.11	29.71	0.11	38.37	0.18	S.Dev				
							0.381	0.157	0.26	0.28	0.28	0.27	0.21	0.26	0.32	0.26	0.27	0.26	0.27	0.41	0.30	C.of Var.				
	0.51	STIFF	QI	-	2mm	5	0.063	0.089	134.29	0.60	0.70	115.92	38.62	56.61	0.17	134.21	0.59	134.21	0.59	124.79	0.69	124.79	0.69	Mean		
0.017							0.002	7.51	0.16	0.19	37.00	25.24	44.34	0.13	7.57	0.16	7.57	0.16	14.65	0.19	S.Dev					
0.268							0.023	0.06	0.27	0.27	0.32	0.65	0.78	0.76	0.06	0.27	0.06	0.27	0.12	0.28	C.of Var.					
0.51	MEDIUM	QI	-	3mm	6	0.066	0.087	121.25	0.66	0.76	64.34	60.02	77.63	0.24	117.51	0.57	112.85	0.58	116.82	0.74	116.82	0.74	Mean			
						0.009	0.009	10.73	0.07	0.09	9.96	16.74	8.45	0.08	8.65	0.09	10.20	0.08	11.64	0.09	S.Dev					
						0.140	0.102	0.09	0.11	0.11	0.15	0.28	0.11	0.33	0.07	0.15	0.09	0.14	0.10	0.12	C.of Var.					
0.51	MEDIUM	UD	along	3mm	6	0.076	0.106	146.91	0.49	0.71	121.08	60.82	111.96	0.22	146.21	0.37	130.93	0.38	136.86	0.70	136.86	0.70	Mean			
						0.025	0.016	19.74	0.13	0.20	60.07	23.81	55.32	0.13	19.84	0.12	24.03	0.12	23.08	0.20	S.Dev					
						0.327	0.147	0.13	0.27	0.28	0.50	0.39	0.49	0.60	0.14	0.34	0.18	0.32	0.17	0.28	C.of Var.					
0.51	MEDIUM	UD	across	3mm	5	0.066	0.094	142.44	0.27	0.72	132.36	69.57	136.29	0.19	142.44	0.27	121.09	0.28	94.37	0.70	94.37	0.70	Mean			
						0.017	0.021	52.16	0.17	0.23	85.71	26.96	58.46	0.06	52.16	0.17	24.74	0.17	25.93	0.21	S.Dev					
						0.256	0.220	0.37	0.64	0.32	0.65	0.39	0.43	0.30	0.37	0.64	0.20	0.60	0.27	0.30	C.of Var.					
0.51	SOFT	QI	-	3mm	7	0.054	0.080	118.91	0.57	0.66	74.84	59.72	78.85	0.24	118.86	0.58	118.86	0.58	113.08	0.65	113.08	0.65	Mean			
						0.016	0.009	15.34	0.11	0.13	21.14	13.23	21.75	0.11	15.34	0.11	15.34	0.11	19.42	0.13	S.Dev					
						0.289	0.112	0.13	0.19	0.19	0.28	0.22	0.28	0.44	0.13	0.19	0.13	0.19	0.17	0.20	C.of Var.					
0.51	SOFT	UD	along	3mm	8	0.087	0.087	128.14	0.65	1.16	56.79	51.69	60.38	0.15	127.86	0.60	117.17	0.62	111.05	1.10	111.05	1.10	Mean			
						0.023	0.022	31.15	0.30	0.82	41.66	25.68	33.15	0.11	31.02	0.32	29.60	0.30	46.01	0.71	S.Dev					
						0.265	0.253	0.24	0.47	0.71	0.73	0.50	0.55	0.77	0.24	0.52	0.25	0.49	0.41	0.65	C.of Var.					
0.51	SOFT	UD	across	3mm	6	0.083	0.110	172.09	0.20	0.80	157.88	74.52	172.00	0.20	172.00	0.20	127.86	0.21	117.79	0.78	117.79	0.78	Mean			
						0.028	0.020	39.24	0.07	0.42	61.44	28.10	39.05	0.07	39.05	0.07	36.89	0.06	32.56	0.41	S.Dev					
						0.334	0.183	0.23	0.34	0.53	0.39	0.38	0.23	0.34	0.23	0.34	0.29	0.29	0.28	0.52	C.of Var.					
FOUR	4 x 0.51	SOFT	QI (far)	-	3mm	5	0.297	0.321	482.09	0.74	0.93	258.49	141.88	230.01	0.18	478.66	0.70	379.83	0.75	228.56	0.91	228.56	0.91	Mean		
							0.030	0.017	18.67	0.07	0.12	59.35	80.35	52.54	0.07	23.95	0.04	103.08	0.06	155.40	0.12	S.Dev				
	4 x 0.51	SOFT	QI (close)	-	3mm	6	0.311	0.330	500.82	0.74	0.95	158.29	202.83	237.30	0.18	500.63	0.74	365.51	0.78	238.04	0.93	238.04	0.93	Mean		
							0.025	0.022	11.52	0.14	0.08	60.27	22.45	69.56	0.05	11.74	0.14	142.82	0.14	138.18	0.08	S.Dev				
	4 x 0.51	SOFT	UD (far/clos al/acr	3mm	6	0.081	0.066	0.02	0.18	0.08	0.38	0.11	0.29	0.28	0.02	0.19	0.39	0.18	0.58	0.08	0.58	0.08	C.of Var.			
						0.261	0.321	535.41	0.67	0.82	331.38	164.52	342.36	0.28	518.28	0.57	439.51	0.59	273.07	0.81	Mean					
	4 x 0.51	STIFF	QI (far)	-	3mm	5	0.336	0.354	543.32	0.78	0.95	299.16	142.09	267.93	0.20	520.16	0.64	300.91	0.67	428.02	0.92	428.02	0.92	Mean		
							0.043	0.019	45.69	0.18	0.09	34.71	52.46	125.71	0.08	40.29	0.08	95.36	0.07	139.13	0.09	S.Dev				
	4 x 0.51	STIFF	QI (close)	-	3mm	6	0.340	0.364	548.21	0.77	0.94	294.24	151.52	329.13	0.26	547.55	0.78	345.74	0.82	285.18	0.93	285.18	0.93	Mean		
							0.047	0.015	26.05	0.12	0.13	75.06	104.34	24.71	0.08	26.05	0.12	102.17	0.11	160.77	0.13	S.Dev				
	4 x 0.51	STIFF	UD (close) al/acr	3mm	6	0.137	0.042	0.05	0.15	0.14	0.26	0.69	0.08	0.31	0.05	0.15	0.30	0.14	0.56	0.14	0.56	0.14	C.of Var.			
						0.297	0.319	510.23	0.63	0.95	278.56	160.93	338.43	0.24	482.36	0.49	336.24	0.52	287.09	0.93	Mean					
	4 x 0.51	STIFF	UD (close) al/acr	3mm	6	0.059	0.083	91.59	0.17	0.13	107.92	52.93	127.47	0.09	68.72	0.12	143.76	0.11	191.15	0.13	191.15	0.13	S.Dev			
						0.200	0.261	0.18	0.27	0.13	0.39	0.33	0.38	0.38	0.14	0.25	0.43	0.22	0.67	0.13	C.of Var.					

MIXED MODE Method C																	
	PIN DIAMETER [mm]	ANGLE	RIG	LAYUP	SPECIM EN ORIENT ATION	PINNING DEPTH	No OF SPEC's	ENRG. [J]	E./a _{max} [J/mm]	P ₀ [N]	P _{max} [N]	a _{p0} [mm]	a _{pmax} [mm]	a _{max} [mm]	τ _d [MPa]	τ _f [MPa]	
SINGLE	0.28	45	rigid	QI	-	3mm	7	0.019	0.027	23.32	34.47	0.06	0.52	0.83	45.85	102.33	Mean
								0.010	0.007	6.85	7.35	0.02	0.13	0.78	22.11	48.61	S.Dev
								0.539	0.253	0.29	0.21	0.44	0.25	0.94	0.48	0.48	C.of Var.
	0.28	45	rigid	UD	along	3mm	6	0.004	0.031	45.34	45.34	0.09	0.09	0.13	483.19	96.88	Mean
								0.003	0.006	6.80	6.80	0.03	0.03	0.06	237.21	99.43	S.Dev
								0.652	0.195	0.15	0.15	0.34	0.34	0.49	0.49	1.03	C.of Var.
	0.28	45	rigid	UD	across	3mm	6	0.005	0.031	48.28	48.28	0.10	0.10	0.15	434.66	73.23	Mean
								0.003	0.006	8.69	8.69	0.04	0.04	0.07	184.00	101.78	S.Dev
								0.675	0.200	0.18	0.18	0.35	0.35	0.49	0.42	1.39	C.of Var.
	0.51	45	rigid	UD	along	3mm	7	0.149	0.053	106.41	107.39	0.12	0.17	2.82	23.42	21.92	Mean
								0.049	0.015	35.59	34.68	0.05	0.08	0.30	6.88	6.00	S.Dev
								0.327	0.285	0.33	0.32	0.43	0.50	0.11	0.29	0.27	C.of Var.
	0.51	45	rigid	UD	across	3mm	6	0.167	0.065	106.36	108.33	0.12	0.26	2.66	26.40	32.43	Mean
								0.019	0.018	18.37	16.87	0.06	0.27	0.51	9.51	19.50	S.Dev
								0.116	0.271	0.17	0.16	0.55	1.05	0.19	0.36	0.60	C.of Var.
	0.51	30	rigid	QI	-	3mm	8	0.171	0.053	66.81	78.00	0.28	1.06	3.21	13.69	19.16	Mean
								0.042	0.010	17.18	13.53	0.19	0.70	0.52	5.87	3.85	S.Dev
								0.246	0.182	0.26	0.17	0.68	0.66	0.16	0.43	0.20	C.of Var.
	0.51	45	rigid	QI	-	3mm	5	0.211	0.068	68.09	89.16	0.31	1.36	3.09	13.73	26.16	Mean
								0.041	0.011	10.46	16.16	0.15	0.49	0.22	1.65	4.87	S.Dev
								0.194	0.162	0.15	0.18	0.48	0.36	0.07	0.12	0.19	C.of Var.
	0.51	60	rigid	QI	-	3mm	8	0.107	0.075	94.82	95.98	0.89	0.97	1.60	49.45	17.08	Mean
								0.035	0.018	17.50	17.03	0.33	0.21	0.93	27.58	23.96	S.Dev
								0.332	0.241	0.18	0.18	0.38	0.22	0.58	0.56	1.40	C.of Var.
	0.51	70	rigid	QI	-	3mm	7	0.091	0.083	74.09	101.96	0.22	0.83	1.13	46.77	89.69	Mean
								0.022	0.013	23.08	14.99	0.11	0.14	0.35	27.41	38.26	S.Dev
								0.238	0.152	0.31	0.15	0.50	0.17	0.31	0.59	0.43	C.of Var.
	0.51	80	rigid	QI	-	3mm	7	0.070	0.087	67.27	112.49	0.13	0.62	0.80	51.96	126.50	Mean
								0.012	0.007	18.04	12.11	0.08	0.08	0.12	9.93	26.63	S.Dev
								0.171	0.082	0.27	0.11	0.62	0.14	0.15	0.19	0.21	C.of Var.
	0.51	45	free	QI	-	3mm	5	0.227	0.075	57.97	100.05	0.24	1.62	3.23	13.61	36.21	Mean
								0.074	0.023	10.55	23.52	0.08	0.52	1.11	9.49	33.51	S.Dev
								0.326	0.309	0.18	0.24	0.32	0.32	0.34	0.70	0.93	C.of Var.
	0.51	45	rigid	QI	-	1mm	7	0.018	0.014	21.68	26.65	0.04	0.20	1.24	10.89	13.79	Mean
								0.005	0.003	5.66	3.77	0.02	0.10	0.12	2.70	3.22	S.Dev
								0.293	0.243	0.26	0.14	0.46	0.52	0.09	0.25	0.23	C.of Var.
	0.51	45	rigid	QI	-	2mm	7	0.068	0.031	38.89	48.91	0.07	0.57	2.16	11.24	17.32	Mean
								0.017	0.005	6.38	7.93	0.03	0.11	0.18	1.66	1.76	S.Dev
								0.249	0.165	0.16	0.16	0.39	0.20	0.08	0.15	0.10	C.of Var.