Imperial College London

The Composites Centre

for research, modelling, testing and training in advanced composites

MICROMECHANICS OF Z-PIN REINFORCED LAMINATES

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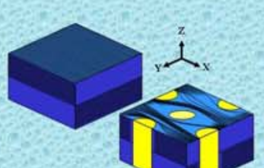
INTRODUCTION

ADVANTAGES OF COMPOSITE MATERIALS:
- High strength-to-weight ratio
- Corrosion resistance

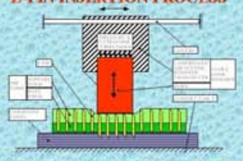
DISADVANTAGES OF COMPOSITE MATERIALS:
- relatively poor inter-laminar properties
- susceptibility to damage
- lack of acceptable joining methods
- poor through-thickness thermal conductivity

Most of these disadvantages can be solved by the application of Z-PINS:

Tiny, 5 – 20mm long, 0,25 – 2mm diameter pins, made of various fibre-epoxy compounds or metals, like Titanium (there are no restrictions for size and material used for Z-PINS), which inserted through the thickness of laminate hold the plies together. They can be also used as fasteners. They notably improve through-thickness strength of laminate and, hence, the delamination resistance.



Z-PIN INSERTION PROCESS



Z-PINS, before insertion, are kept in PREFORMS:

sheets of double-density foams which support the pins during the insertion and prevent them from buckling under the load applied by ULTRASONIC HAMMER.

Ultrasonic vibrations of hammer head heats up the Z-PINS and prepreg assembly making the insertion easier. The Z-PINS are pushed with the hammer head and, as the foam collapses, they are driven into the laminate.

ALTERNATIVE INSERTION METHOD was also used in this study, in order to decrease the number of wasted Z-Pins and to avoid using costly ultrasonic insertion process. Z-Pins were manually inserted in the holes made in the prepreg assemblies with a steel needle. The method seems to increase pinning quality and decrease the damage of the composite cased by the insertion. There is also no need of preforms in this method.

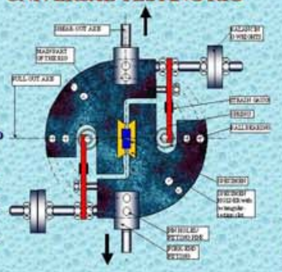
EXPERIMENT

Two Z-Pin insertion methods has been applied:
- Standard ULTRASONIC HAMMER INSTERTION
- Manual insertion of the Z-Pins into the perforated prepreg assembly

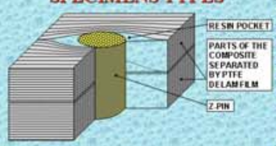
Unique TESTING RIG has been designed for Z-PIN TESTS:
- PULL-OUT tests (MODE I)
- SHEAR-OUT tests (MODE II), with opening force control
- MIXED MODE tests (10°, 20°, 30° and 45°), with off-axis displacement control

System of springs with strain gauges allows OPENING FORCE & DISPLACEMNET CONTROL during SHEAR-OUT tests. Springs of various thicknesses can be applied to survey the influence of the laminate stiffness on the pull-out/shear-out behaviour.

UNIVERSAL TESTING RIG



SPECIMENS TYPES

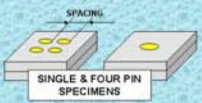


Bricks of carbon-epoxy laminate, 15mm x 15mm and 6mm thick, with a delam film in the middle of the thickness producing a crack in the laminate, containing one or four Z-PINS inserted through the whole thickness were used as specimens.
- UNIDIRECTIONAL layup specimens
- QUASI-ISOTROPIC layup specimens

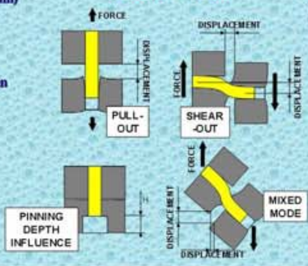
- SINGLE Z-Pin specimens
- GROUP of 4 Z-PINS specimens (two different spacings: 1.75mm & 3.2mm)

- 0.28mm ϕ Z-Pin specimens
- 0.51mm ϕ Z-Pin specimens

Every combination of the above has been tested.



TEST TYPES

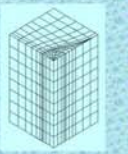


To understand the mechanics of the sliding phase the also the following tests were performed:
- PINNING DEPTH tests (PULL-OUT & SHEAR-OUT) where part of the Z-PIN was drilled out, shortening the insertion depth of the pin
- PULL-OUT SPEED tests (0.05mm/min, 0.5mm/min, 5.0mm/min)
- Repetitive PULL-OUT & PUSH-IN tests
- PURE RESIN PULL-OUT tests

DESCRIPTION

MODELLING

MESH

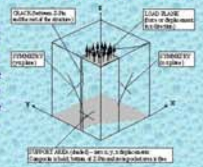


3D FINITE ELEMENT model of the single Z-PIN embedded in the composite structure was built. The model consists of three parts:
- Z-PIN
- RESIN POCKET (resin-filled eye-shaped space around the Z-PIN)
- SURROUNDING LAMINATE

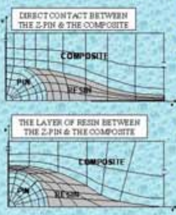
1000 element models (featuring 3mmx3mmx3mm piece of composite with a Z-PIN in the middle) were analysed

BOUNDARY CONDITIONS

Thanks to the two planes of symmetry only one-quarter part of the model was meshed. PULL-OUT FORCE was applied as a uniformly distributed pressure over the top of the pin. According to the observations of he real specimens behaviour only the "laminate" part of the model was held on the opposite surface of the model.



CASES ANALYSED



Two separate cases were modelled:
- Direct contact between the Z-PN and the LAMINATE
- LAYER OF RESIN between the Z-PIN and the LAMINATE

STEADY STATE analysis was used to solve the stress and strain field in the vicinity of the Z-PIN under the applied load.

STEADY STATE ANALYSIS IN STEPS was used to simulate the pull out process. The ENERGY RELEASE RATE during the process was evaluated.

RESULTS

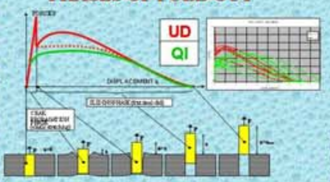
Two phases of the PULL-OUT process could be identified:

CRACK PROPAGATION PHASE, when the fracture between the Z-PIN and composite is formed, and all the structure is stretched elastically

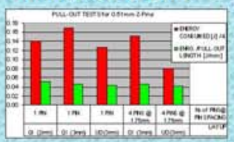
SLIDING PHASE, which begins when the crack reaches the bottom of the Z-PIN, when the Z-PIN is actually pulled out of the composite.

The growth of the force during the sliding phase is possibly caused by roughness of the surfaces of the pins. Detailed microscopic observations revealed also 20° to 40° "twist" angle of the Z-Pins (measured on 3mm distance).

PHASES OF PULL-OUT



PULL-OUT ENERGY

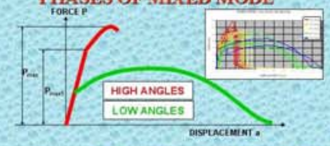


PHASES OF SHEAR-OUT

During the SHEAR-OUT process the following behaviour was observed:

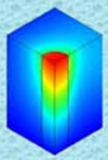
LINEAR FORCE GROWTH, when the structure is distorted elastically, is followed by the rapid DROP OF THE FORCE, when the structure of the Z-PIN is damaged, however without the complete fracture. Remaining loose fibres of the Z-PIN, still able to carry the load, cause the growth of the force until the total Z-PIN fracture, when the force drops rapidly to zero.

PHASES OF MIXED MODE



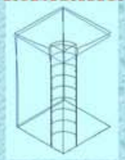
STEADY STATE ANALYSIS

Typical DISPLACEMENT DISTRIBUTION over the model

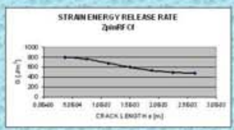


The distortion of the composite in the beginning phase of the pull-out process. Mixed mode fracture visible at the top of the model.

CRACK PROPAGATION



STRAIN ENERGY RELEASE RATE CURVE



Strain energy release rate curves suggest stable character of the propagation of the crack between Z-PIN and and composite (or resin).

CONCLUSIONS

The Z-PINS considerably improve the interlaminar performance of the laminate, which is one of the main weaknesses of laminates in general. They have drawbacks too:
- negative influence on in-plane properties of the laminate (fibre waviness)
- cost
- problems with proper insertion

WHAT'S LEFT TO INVESTIGATE?
- The detailed description and mathematical model of the PULL-OUT and SHEAR-OUT processes
- more sophisticated FE model of the single Z-PIN with interface elements for crack propagation simulation
- Development of the numerical tool featuring behaviour of Z-PIN in laminate