APPENDIX B

Fractographic Aspects of Fatigue Failure in Complex Composites
given by

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GROUP FOR AERONAUTICAL RESEARCH AND TECHNOLOGY IN EUROPE
FRANCE•GERMANY•ITALY•THE NETHERLANDS•SPAIN•SWEDEN•UNITED KINGDOM

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25th April 2003

GARTEUR - AG27

Fractographic Aspects of Fatigue Failure in Complex Laminates and Structures

Current Status

Prepared by Matthew Hiley (chairman)

Presented by Charlotte Meeks

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Membership AG27

• **Mr M. Hiley**	**QinetiQ (UK)**	**Chairman**
• **Mr R. Muskett**	**BAE Systems (UK)**	
• **Mr T. Jollivet**	**CETIM (France)**	**(replaces A . Lemasçon)**
• **Mr U. Begström**	**CSM Materialteknik (Sweden)**	**(replaces P. Granstam)**
• **Dr A. Sjögren**	**SICOMP (Sweden)**	**(new member)**
• **Ms L. Papaix**	**DGA/CEAT (France)**	**(replaces T. Ansart)**
• **Mr M. Hogendoorn**	**NLR (Netherlands)**	**(replaces J-P Steyaert)**
• **Dr H. Franz**	**EADS (Germany)**	
• **Mr W. Förtsch**	**EADS (Germany)**	**(new secretary)**
• **Dr J.M Pintado**	**INTA (Spain)**	
• **Dr S. Nilsson**	**FOI (Sweden)**	**(replaces A Skontorp)**
• **Mr E. Ollivier**	**EADS (France)**	**(replaces M. Vancon)**

There has been a considerable turnover in staff over the last year!

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Objectives

1) Establish the extent to which the findings of fatigue studies in AG20 can be applied to the analysis of failures in multi-directional and woven laminates.
2) Identify macroscopical and microscopical features associated with static and fatigue damage growth in multi-directional and woven/NCF laminates.
3) Establish the relationship between fractographic features in multi-directional and woven laminates and the direction of crack delamination.
4) Establish microscopical mechanisms by which the features in (2) occur under different loading modes.
5) Establish the material dependency, in particular the effect of brittle and tough matrices, on the fractographic features identified in (2)
6) Establish the read across between the fatigue failure processes occurring in coupons with those observed in structural components.

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Plan - Specimen Exchange

- Aim to address objectives by conducting four round robin exercises involving the blind assessment of failed specimens.
- RR1 - Assessment of FATIGUE fractures in multidirectional laminates based on U.D prepreg. (T800/AS4) /8552, 0°/45° interface tested in mode I and mode II.
- RR2a - As RR1, but investigate 2 levels of G in mode II and 2 R-ratios (0.5 and -1). In mode I conduct tests at 2 levels of G, but a different R-ratio to RR1.

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Plan - Specimen Exchange

- RR2b - Evaluation of STATIC fractures in two materials manufactured from woven fabric. Modes I, II and (I+II). Materials AS4/8552 (5-harness satin) and IM/920 (2:2 Twill). Fracture between 90°/90° (weft to weft) interface.
- RR3 - Evaluate FATIGUE test specimens with 90°/90° (weft to weft) interface.

  Assess STATIC fractures in woven specimens with +45°/-45° interface (weft to weft). Mode I, mode II and (I+II).

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Plan - Specimen Exchange

- RR4 - Evaluate STATIC and FATIGUE fractures in woven laminates based on woven fabric AS4/8552 (5-Harness) and IM/920 (2:2 Twill). Fracture between 0°/90 ° (warp to weft) interface.
- All fatigue testing within the round robins will be conducted at 5Hz using an R ratio = 0.1.
- Where available case studies, involving structural elements subject to fatigue, will be examined to corroborate the findings of coupons tests.

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Progress

- RR1 - Fatigue fracture in multidirectional laminates - completed
- RR2a - Fatigue in multidirectional laminates under different R-ratios/strain energy levels G - Incomplete.
- RR2b - Assessment of static fracture in woven laminates (complete).
- RR3 and RR4 Ongoing.

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Plan versus Progress

- RR2a studying R-ratio effects and influence of strain energy level not completed due problems with test apparatus and material supply. Task set aside so as to concentrate on woven materials.
- Start of RR2b delayed due to testing problems. Specimens tended to failed in flexure rather by interlaminar fracture. Specimens redesigned and tests repeated.
- Delay in starting RR3 caused by delay in procuring materials. Laminates currently being manufactured for both RR3 and RR4 and should be distributed in May 2003.
- Lost time to be regained by running RR3 and RR4 in parallel, rather than sequentially.

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Plan versus Progress

- Group lost some momentum following the unexpected death of the AG27 secretary Dr Arne Skontörp. He made a significant contribution to group and will be greatly missed!
- There has been a substantial turnover in the AG27 membership, due to retirement or long-standing members moving on to new positions. This has further reduced the pace of progress as new members become familiar with the groups activities.
- 1st meeting of group held 1/2 Oct 2001, DGA/CEAT
- 2nd meeting held 13/14 Jan 2003, NLR
- 3rd meeting schedules for Oct 2003, INTA

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Plan versus Progress

Date / Objective	03/2001	06/2001	09/2001	12/2001	03/2001	06/2002	09/2002	12/2002	03/2002	06/2003	09/2003	12/2003	03/2004
Proposal													
Literature review													
Manufacture RR1 specimens (Multi-directional)													
Examine Specimens													
Review RR1 (Meeting 1)			**09/2001**										
Manufacture RR2 specimens (Multi-directional – mixed mode)													
Examine Specimens													
Review RR2 (Meeting 2)					**03/2002**								
Manufacture RR3 specimens (Woven)													
Examine Specimens													
Review RR3 (Meeting 3)							**09/2002**						
Manufacture RR4 specimens (Woven)													
Examine Specimens													
Review RR4 (Meeting 4)									**03/2003**				
Preparation of final Report													
Final Review **(Meeting 5)**											**09/2003**		
Report Distribution													

Start of RR3 and RR4 delayed by approximately 6 months. Although still aim to complete project by March 2004

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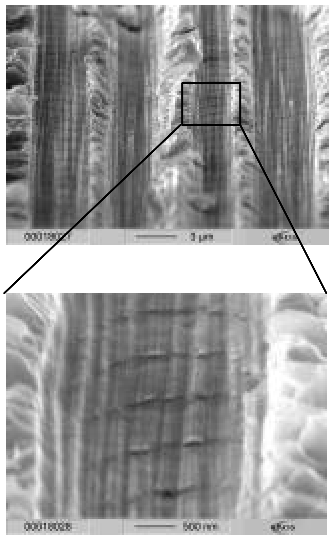
Findings RR1 - Multidirectional Fatigue 0°/45°



- Characteristic features associated with fatigue (indentified in AG20) also found to occur at 0°/45° interfaces.
- Striations reported in mode I and mode II fractures, but much more abundant in the shear specimens.
- Fibre bridging may be responsible for striations in the mode I specimens; localised mode II stresses promoting striation formation. (Globally striations not thought to be a genuine feature of mode I).

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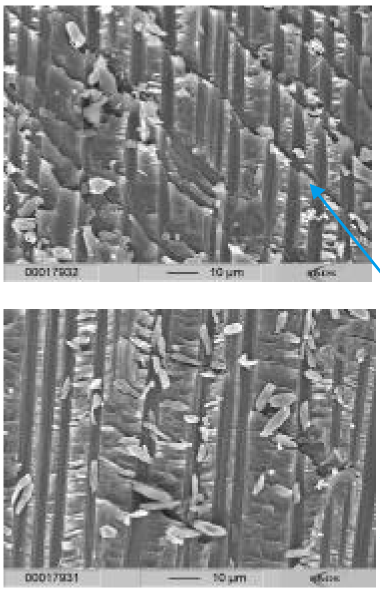
Findings RR1 - Multidirectional Fatigue 0°/45°



Under shear loading (3 pt bend) crack front had a tendency to grow upwards towards compressive surface. To stop crack migration through the plies, tests always performed with 0° ply on top. Surface contained mainly fibres.

Lower surface (tensile) surfaces showed much more microcracking and was resin rich. Surface also contained mainly fibre imprints.

Matrix rollers also observed.

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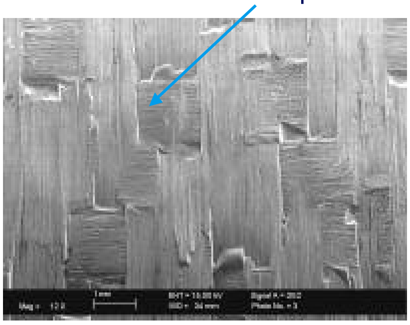
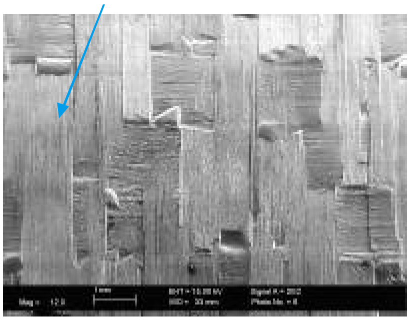
Findings RR2b - Static Fracture in Woven Laminates Mode I - AS4/8552 5HS

Warp tows

Weft tows





Crack growth R ⇒L

Both upper and lower surfaces were similar. Resin rich pockets between tows contain information as to the direction of crack growth.

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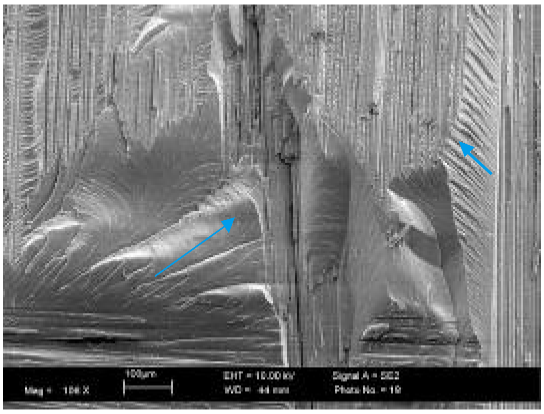
Findings RR2b - Static Fracture in Woven Laminates Mode I - AS4/8552 5HS



Crack growth R ⇒L

In general river lines and scarps, in the resin rich regions, could be used to determine C.G.D

Care was needed, however, as features indicating an opposing direction were sometimes observed.

Mode I generally characterised by rough fracture.

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Findings RR2b - Static Fracture in Woven Laminates Mode I - AS4/8552 5HS

Mode I (opening) fractures could be distinguished optically and in the SEM. This was confirmed by the presence of river lines, scarps and ribbons and absence of any cusps.

The direction of fracture could be determined by examining the local directions of fracture at the ‘cross over’ points (resin rich regions) in the weave.

It was noted that locally the CGD could run in both directions and care was needed in assessing the general global growth direction.

With the 920 material parabolic cusps, visible in the resin, also aided crack growth determination.

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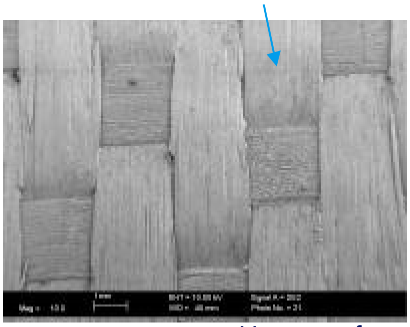
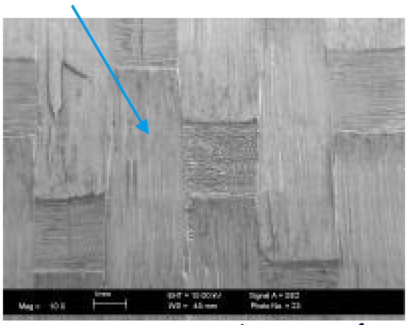
Findings RR2b - Static Fracture in Woven Laminates Mode II - AS4/8552 5HS

Warp tows

Weft tows



Upper surface



Lower surface

Upper surface dominated by tows (fibres). Lower surface matrix/fibre imprint rich.

Crack growth R ⇒L

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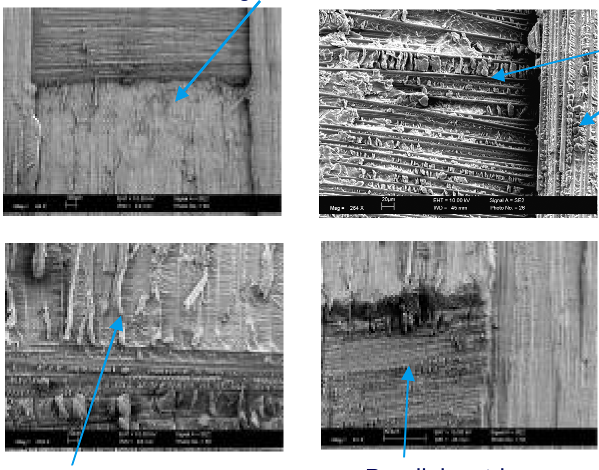
Findings RR2b - Static Fracture in Woven Laminates Mode II - AS4/8552 5HS

Fibre fracture at edge of weft tows

Shear cusps in warp and weft fibre

Upper

Lower



Matrix ribbons

Parallel matrix cracking

Multiple fracture features made mode II surface difficult to interpret especially C.G.D

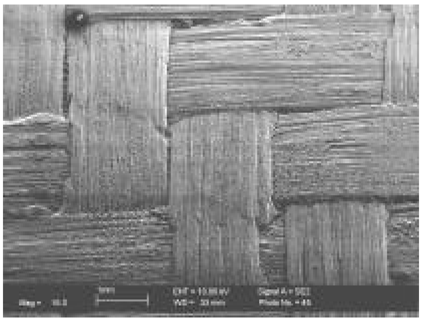
Findings RR2b - Static Fracture in Woven Laminates Mode II

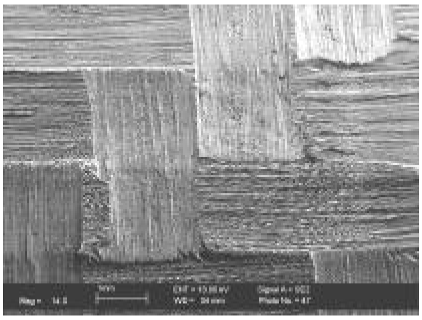
Mode II (shear) fractures could be identified visually and in the SEM was due to their dull appearance and the presence of cusps, particularly in the short (warp) tows. Evidence of mode I fracture in the long (weft) tows, however, created some uncertainty.

Visual and optical examination showed the upper compressive surface tended to be fibre rich, whilst the bottom surface was imprint/resin rich.

Although cusps were mainly oriented parallel to the axis of crack growth (in the warp fibres), at the junction with the weft fibre the cusps often ran perpendicular to this axis.

Findings RR2b - Static Fracture in Woven Laminates Mode I +II





In common with mode II fracture, mixed-mode surfaces show resin rich and fibre (tow) rich surfaces - attributable to shear component

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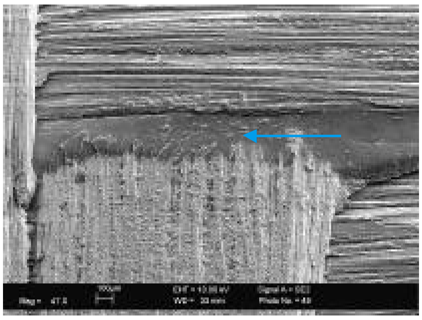
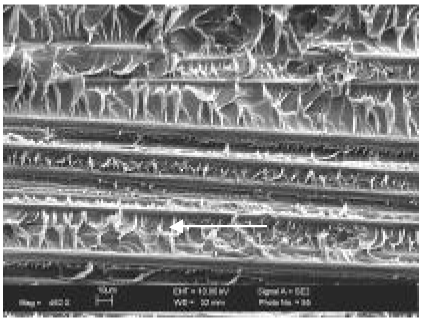
Findings RR2b - Static Fracture in Woven Laminates Mode I + II

Upper surfaces





Surfaces of 920 resin show parabolic cusps which indicate C.G.D. shallow cusps indicate that fracture is mixed mode.

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Findings RR2b - Static Fracture in Woven Laminates Mode I + II

Visually dull appearance of mixed mode fractures, and partition into fibre rich and resin rich surfaces, indicate mode II fracture.

SEM needed to reveal shallow cusps that confirm mixed-mode fracture.

River lines in resin rich regions were most useful for determining CGD, although thse were sometimes contradictory. In the 920 resin the presence of parabolic cusps helped in the determination of C.G.D.

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