OPTIMAT BLADES
Task Group 5
Residual Strength & Condition Assessment

Task Group Leader: Dr Geoff Dutton
Energy Research Unit, CCLRC Rutherford Appleton Laboratory

Participants: WMC, UP, VUB, CRES, CCLRC

EC Contract No.  NNE5-2001-00174
Objectives

Work Package 13 : Residual Strength and Condition Assessment

To establish engineering models to account for residual static strength reduction of reference material induced by cyclic loading.

To define and validate condition monitoring strategies for blade materials subjected to fatigue loading, by adapting NDT techniques, in order to assess residual strength/life.

Work Package 14 : Residual Strength of Alternative Materials

To validate the predictive engineering model for residual strength and life, established for the reference material in WP13, by comparing theoretical predictions and experimental data from the alternative materials.
Task breakdown

Work Package 13 : Residual Strength and Condition Assessment

13.1. Review of residual strength assessment concepts
13.2. Experimental evaluation of residual strength after fatigue
13.3. Development of condition monitoring techniques
13.4. Establishment of predictive engineering model

Work Package 14 : Residual Strength of Alternative Materials

14.1. Selection of alternative materials and test plan
14.2. Residual strength of alternative materials
14.3. Condition monitoring applied to alternative materials
14.4. Final evaluation of predictive engineering model
Residual strength tests – characterisation (1)
Task 13.1/13.4

• The in-plane static strength of an orthotropic lamina under a biaxial state of loading can be characterised by 5 strength values related to the principal material directions:

• The resultant residual strengths $X_R$, $X'_R$, $Y_R$, $Y'_R$, and $S_R$ after a certain number of cycles, $N$, at a stress ratio $R_i = \sigma_{imin}/\sigma_{imax}$ can be expressed as:

$$X_R = f_{XR} (X, \sigma_{xmax}, \sigma_{ymax}, \sigma_{smax}, R_x, R_y, R_s, N) \quad \text{tensile strength dir}^n \text{ 1}$$

$$Y_R = f_{YR} (Y, \sigma_{xmax}, \sigma_{ymax}, \sigma_{smax}, R_x, R_y, R_s, N) \quad \text{tensile strength dir}^n \text{ 2}$$

$$X'_R = f_{XR'} (X', \sigma_{xmax}, \sigma_{ymax}, \sigma_{smax}, R_x, R_y, R_s, N) \quad \text{compr. strength dir}^n \text{ 1}$$

$$Y'_R = f_{YR'} (Y', \sigma_{xmax}, \sigma_{ymax}, \sigma_{smax}, R_x, R_y, R_s, N) \quad \text{compr. strength dir}^n \text{ 2}$$

$$S_R = f_{SR} (S, \sigma_{xmax}, \sigma_{ymax}, \sigma_{smax}, R_x, R_y, R_s, N) \quad \text{shear strength pl. 1-2}$$
Residual strength tests – characterisation (2)
Task 13.1/13.4

- A more simplified approach is possible if each strength component is reduced to a function of load cycling in the same direction.

\[ X_R = f_{XR} (X, \sigma_{x_{max}}, R_x, N) \] tensile strength dir\(^n\) 1

\[ Y_R = f_{YR} (Y, \sigma_{y_{max}}, R_y, N) \] tensile strength dir\(^n\) 2

\[ X'_{R} = f_{XR'} (X', \sigma_{x_{max}}, R_x, N) \] compressive strength dir\(^n\) 1

\[ Y'_{R} = f_{XR'} (Y', \sigma_{y_{max}}, R_y, N) \] compressive strength dir\(^n\) 2

\[ S_R = f_{SR} (S, \sigma_{s_{max}}, R_s, N) \] shear strength pl. 1-2
Residual Strength Test procedure

- Initial static “proof” load (or AE proof test) for stiffness evaluation
- Constant amplitude fatigue loading
- Final static “proof” load (or AE proof test) for stiffness evaluation
- Residual strength test to failure
Residual Strength Test procedure

- Fatigue Cycles to 20/50/80% of expected life
- Residual Strength Tests to failure
- Tensile
- Compressive

Load vs. Time on test

- R = 0.1
- R = -1
- R = 10
# Test programme – overall (Task 13.2)

## Residual Strength Tests

<table>
<thead>
<tr>
<th>Partner</th>
<th>Lay-up</th>
<th>Type of test</th>
<th>Remarks</th>
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<td>Standard Optimat Specimens</td>
<td>0.1</td>
<td>20/50/80%</td>
<td>36 36 36 36 36 36</td>
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<td>20/50/80%</td>
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<td>long life</td>
<td>3 3 3 3 3 3</td>
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<tr>
<td>Transverse (⊥)</td>
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<td>20/50/80%</td>
<td>36 36</td>
</tr>
<tr>
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<td>-1</td>
<td>20/50/80%</td>
<td>36 36</td>
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<tr>
<td></td>
<td>10</td>
<td>20/50/80%</td>
<td>36 36</td>
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### Test programme – overall (Task 13.2)

#### Residual Strength tests - finer resolution test test breakdown

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<th>Lifetime R</th>
<th>Axial (I/J)</th>
<th>Transverse</th>
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<td>12 12 12 12 12 12</td>
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<tr>
<td>CCLRC</td>
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<td>12 12 12 12</td>
<td>12 12</td>
</tr>
<tr>
<td>CRES</td>
<td>10 1.00E+03</td>
<td>12 12 12 12</td>
<td>12 12</td>
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<tr>
<td>VUB</td>
<td>0.1 5.00E+04</td>
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<tr>
<td>UP</td>
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<td>12 12</td>
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<tr>
<td>UP</td>
<td>10 1.00E+07</td>
<td>3 3 3 3</td>
<td>12</td>
</tr>
</tbody>
</table>

- **Axial (I/J)** indicates tests deferred to Phase 2
- **Transverse** indicates tests for which priority must be decided
Test programme – overall (Task 13.2)

Residual Strength Tests

<table>
<thead>
<tr>
<th>Partner</th>
<th>lay-up</th>
<th>R</th>
<th>Type of test</th>
<th>Remarks</th>
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<td>36</td>
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<tr>
<td></td>
<td>-1</td>
<td>20/50/80%</td>
<td>36</td>
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<tr>
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</tr>
<tr>
<td></td>
<td>0.1</td>
<td>long life</td>
<td>3</td>
<td>3</td>
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<td></td>
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<tr>
<td>Transverse (⊥)</td>
<td>0.1</td>
<td>20/50/80%</td>
<td>36</td>
<td>36</td>
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Test programme – current status
(Task 13.2/14.2)

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<th>WMC</th>
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<th>CRES</th>
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<tr>
<td>Axial (//)</td>
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<td>20/50/80%</td>
<td>42%</td>
<td>128%</td>
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<td>78%</td>
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<td>0%</td>
<td>100%</td>
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<td></td>
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Progress (January 2005)

• Progress with testing (results reported to Optidat) by 12 January 2005 was as follows:
  • CCLRC : 48 reported (32 valid RST; 16 prem.) of 144
  • CRES : 0 reported (0 valid RST) of 108
  • UP : 72 reported (64 valid RST; 8 prem.) of 144
  • VUB : 93 reported (62 valid RST; 31 prem.) of 108
  • WMC : 51 reported (39 valid RST; 12 prem.) of 144
Residual strength tests – sample results

MD (R = 0.1 & R = -1) : results from VUB, WMC & CCLRC
UD (R = 0.1 & R = -1) : results from VUB, WMC & CCLRC
Residual strength tests – characterisation (3)
Task 13.1/13.4


• Linear degradation model (Broutman & Sahu, 1972)

\[ X_R = X - \left( X - \sigma_{\text{max}} \right) \left[ \frac{n}{N} \right] \]

• Power law degradation model (Schaff & Davidson, 1997)

\[ X_R = X - \left( X - \sigma_{\text{max}} \right) \left[ \frac{n}{N} \right]^m \]
OPTIMAT TG5-CCLRC/VUB UD (R=0.1) - 02-Feb-2005

OPTIMAT BLADES

CCLRC
Rutherford Appleton Laboratory
A key issue is the ability of the model(s) to accurately predict the statistical distribution of residual strength at specific \{load level, life fraction\}.

Typically, static strength and fatigue life distribution are fitted by two-parameter Weibull distributions

- Residual static strength:
  \[
P_x(X) = \exp\left[-\left(\frac{X}{\beta}\right)^\alpha\right]
  \]

- Lifetime:
  \[
P_N(n) = \exp\left[-\left(\frac{n}{N}\right)^\alpha_f\right]
  \]
OPTIMAT MD static compressive strength

No. samples = 44
\[ k_{\text{Weibull}} = 15.946 \]
\[ c_{\text{Weibull}} = 473.0566 \]
OPTIMAT MD static tensile strength

No. samples = 36

\[ k_{\text{Weibull}} = 32.8501 \]

\[ c_{\text{Weibull}} = 535.4064 \]
OPTIMAT UD static compressive strength

No. samples = 63

\[ k_{\text{Weibull}} = 12.717 \]
\[ c_{\text{Weibull}} = 529.5332 \]
OPTIMAT UD static tensile strength

No. samples = 70

\[ k_{\text{Weibull}} = 24.175 \]

\[ c_{\text{Weibull}} = 811.9168 \]
Residual strength tests (Task 13.3) – NDT techniques (preliminary results)

AE testing:

- MD (R = 0.1) : tests 154, 156 (CCLRC)
- MD (R = -1) : test 394 (CCLRC)
- UD (R = 0.1) : test 637 (CCLRC)
- ISO 14129 geometry [+45/-45]s (UP)
Residual Strength Test procedure

Fatigue Cycles to 20/50/80% of expected life

Residual Strength Tests to failure

Load

Time on test

R = 0.1
R = -1
R = 10

Tensile

Compressive
Residual Strength Test procedure
AE Counts during RST (UPatras)

Normalized RS vs. Counts [till nominal AEL]

R² = 0.8877
R² = 0.9301
R² = 0.8838

0.65 0.70 0.75 0.80 0.85 0.90 0.95 1.00 1.05

0 2000 4000 6000 8000 10000 12000 14000 16000 18000 20000

AE Counts

Normalized Residual Strength

R² = 0.9301
R² = 0.8877
R² = 0.8838
Residual strength tests (Task 13.3) – NDT techniques (preliminary results)

Thermoelastic stress analysis:

- MD (R = 0.1) : tests 154, 164, 165, 166 (CCLRC)
- UD (R = 0.1) : test 384 (CCLRC)

Initial findings:

- Cross-ply structure of MD surface layer visible on first fatigue loading
- Early failure of surface plies reduces signal (MD)
- Surface temperature distribution shows higher T than expected
Residual strength tests – NDT techniques (preliminary results)

First fatigue (OP)  Middle fatigue (IP)  Temperature (deg. C)
<table>
<thead>
<tr>
<th>No.</th>
<th>Deliverable / Milestone</th>
<th>Project month</th>
<th>Revised</th>
<th>% DONE</th>
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<tr>
<td>6</td>
<td>Review of existing residual strength predictive models</td>
<td>Report 05 (CO)</td>
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<tr>
<td>M8</td>
<td>DPA on condition monitoring and residual life and strength</td>
<td>05</td>
<td>-</td>
<td>100</td>
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<td>24</td>
<td>Experimental database from residual strength tests</td>
<td>Report/CD 26 (PU)</td>
<td>48</td>
<td>50</td>
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<td>25</td>
<td>Validated engineering model for residual strength evaluation</td>
<td>Report 26 (PU)</td>
<td>48</td>
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<tr>
<td>26</td>
<td>Validated engineering model for residual life evaluation and strategy for condition assessment</td>
<td>Report 26 (PU)</td>
<td>48</td>
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<td>M20</td>
<td>Validated engineering model for residual life and strength</td>
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<td>M21</td>
<td>DPA for residual strength programme (phase 2)</td>
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<td>48</td>
<td>90</td>
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<td>31</td>
<td>Experimental database from residual strength tests on alternative materials (note enlarged extent of D24)</td>
<td>Report/CD 42 (PU)</td>
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<td>39</td>
<td>Validated engineering model for residual strength and life prediction using condition assessment (alternative materials) (modify to MD, UD, +/-45 shear)</td>
<td>Report 43 (PU)</td>
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Conclusions - TG5
Residual strength and condition assessment

- Phase I test matrix was comprehensive, over-ambitious, and contained 2 specimen lay-ups (where only 1 was envisaged in the DoW)
- Phase 1 testing is more than 50% complete but will now extend to end 2005 (D24)
- Potential engineering models have been identified and are being evaluated (D25)
- NDT evaluation of residual strength has achieved only limited success – some re-evaluation necessary (D26)
- The most important deliverable is a validated engineering model for residual strength degradation (D25/D39)
- Phase II tests on alternative materials (14.1-14.3) limited to WMC in WP5 / other partners to complete Phase I tests (additional model validation in 14.4 based on UD/MD comparison)