DETAILED PLAN OF ACTION WP13 AND WP14 (TG5)

Version 4 (27-06-2003)

Geoff Dutton

Change record

Issue/revision	date	pages	Summary of changes
V0 draft	10-06-02	9	
V1 DPA submission to SC	17-09-02	16	Major revision to document format and inclusion of test tables
V2 DPA revision after comments by SC	11-12-02	17	Minor changes in text
V3 DPA revision following TG5 meeting in Stuttgart, updated to May 2003	06-05-03	15	Modification to test duration estimates (section 2.3.5) Correction of table printing errors by replacement of section 5 Revision of Residual Strength testing allocations (TUDT, VUB, UP) (section 5) Revised time schedule (section 6)
V4 DPA revision prior to TG5 meeting at VUB	27-06-03	15	Revision of Residual Strength testing allocations (VUB, UP) (section 5)

1 INTRODUCTION

The main objectives of work package 13 is:

(i) to develop one or more predictive engineering models of residual strength reduction in wind turbine blade laminates due to cyclic fatigue loading,

(ii) to define and validate condition monitoring strategies for wind turbine blade laminates subjected to fatigue loading and to relate these, if possible, to residual life and strength.

These objectives will be fulfilled by fatigue testing of the basic OB materials at three constant amplitude load levels (intended to result in nominal lifetimes 10^3, $5x10^4$, 10^6 cycles) within the three R-ratio values (0.1, 1.0, -1.0) and periodically extracting a set of test coupons at given fractions (e.g. 20%, 50%, 80%) of the nominal lifetime for proof-testing and subsequent testing to failure (i.e. residual strength test). Additional testing will be carried out up to 10^7 cycles for a limited number of test coupons.

For the UD material equal number of tests will be carried out in the axial and transverse (except 10^7 cycles) directions. For the MD material only the nominal axial direction will be required.

For the OPTIMAT Blades project, Philippidis and Passipoularidis [1] have reviewed the pertinent literature and observed that 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:

X : tensile strength in material direction 1 (fibre-direction),
X' : compressive strength in material direction 1 (fibre-direction),
Y : tensile strength in material direction 2 (transverse-direction),
Y' : compressive strength in material direction 2 (transverse-direction),
S : shear strength in plane 1-2.

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:

$$
\begin{aligned}
X_R &= f_{XR} (X, \sigma_{xmax}, \sigma_{ymax}, \sigma_{smax}, R_x, R_y, R_s, N) \\
Y_R &= f_{YR} (Y, \sigma_{xmax}, \sigma_{ymax}, \sigma_{smax}, R_x, R_y, R_s, N) \\
X_{R'} &= f_{XR'} (X', \sigma_{xmax}, \sigma_{ymax}, \sigma_{smax}, R_x, R_y, R_s, N) \qquad (1) \\
Y_{R'} &= f_{XR'} (Y, \sigma_{xmax}, \sigma_{ymax}, \sigma_{smax}, R_x, R_y, R_s, N) \\
S_R &= f_{SR} (S, \sigma_{xmax}, \sigma_{ymax}, \sigma_{smax}, R_x, R_y, R_s, N)
\end{aligned}
$$

Experimental evaluation of this model is impossible, due to the overlarge parameter set and complexity of the experiments required. A more simplified approach is possible if each strength component is reduced to a function of load cycling in the same direction. Philippidis and Passipoularidis [1] have found that such a model represents the current state of the art in residual strength modelling[1]:

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1 See: Diao, X., Lessard, L.B., Shokrieh, M.M., *Statistical model for multiaxial fatigue behaviour of unidirectional plies*, Comp. Sci. Tech. 59, 1999, p. 2025-2035
Yang, J.N., *Fatigue and residual strength degradation for graphite/epoxy composites under tension-compression cyclic loadings*, J. Comp. Mat. 12, 1978, p. 19-39
Shokrieh, M.M., Lessard, L.B., *Multiaxial fatigue behaviour of unidirectional plies based on uniaxial fatigue experimental: Part I. Modelling*, Int. J. Fatigue 19(3), 1997, p. 201-7

$$
\begin{aligned}
X_R &= f_{XR}\,(X,\ \sigma_{xmax},\ R_x,\ N)\\
Y_R &= f_{YR}\,(Y,\ \sigma_{ymax},\ R_y,\ N)\\
X_{R'} &= f_{XR'}\,(X',\ \sigma_{xmax},\ R_x,\ N)\\
Y_{R'} &= f_{XR'}\,(Y',\ \sigma_{ymax},\ R_y,\ N)\\
S_R &= f_{SR}\,(S,\ \sigma_{smax},\ R_s,\ N)
\end{aligned}
\qquad (2)
$$

Once the basic characterisation has been made, it will be evaluated by testing against different materials and lay-ups within WP14 (OPTIMAT BLADES Phase 2).

Shokrieh, M.M., Lessard, L.B., *Multiaxial fatigue behaviour of unidirectional plies based on uniaxial fatigue experimental: Part II. Experimental evaluation*, Int. J. Fatigue 19(3), 1997, p. 209-17

2 DPA FOR WP 13

2.1 Description of work

A matrix of residual strength tests (compression and tension) will be carried out at various combinations of fibre direction, R-ratio, and nominal lifetime. The test specimens will be fatigued in standard material test rigs at constant maximum strain rate. Batches of specimens will be removed at various nominal lifetime fractions and strength tested in uni-axial tension and compression. Selected fatigue tests will be monitored using thermoelastic stress analysis. The ultimate strength tests will be monitored using strain gauges and AE sensors (if space restrictions permit). Additional NDT tests (ultrasonics, acousto-ultrasonics, and visual inspection) will be employed between the fatigue and residual strength tests, in order to facilitate later characterisation of the residual strength.

Based on the results of the residual strength tests, a predictive engineering model for residual strength reduction due to cyclic loading will be devised.

2.1.1 Modifications to the annex

The above description of work complies in principle with Annex I of the contract; however, the shape of the test matrix has changed in that the tests will now be carried out for three values of R-ratio and the number of lifetime fractions has been reduced to three. The maximum lifetime has also now been defined to be 10^7 cycles, which would require many years of testing time to evaluate across the complete matrix of stress conditions. This lifetime has been introduced as a fourth stress level and a limited number of tests will be performed at this condition, as the rest of the test programme allows.

Some additional "benchmark characterisation" static tension/compression and fatigue tests have been added to the work of the Task Group in order that all laboratories can be compared in a benchmark exercise.

Note, also, that the (small) specimen geometry may impede the application of NDT techniques to the characterisation of residual strength.

2.2 Laminate and specimen definition

Laminate UD : $[0]_4$ E-glass/epoxy
Laminate MD : $[[\pm 45,0]_4; [\pm 45]]$ E-glass/epoxy

The final specimen gauge length will be determined following the evaluation of the second preliminary test series, but it is likely that this will severely limit the application of NDT techniques for characterising residual strength. For shear, a coupon geometry as specified by ISO 14129 (1997) and detailed in DPA of TG2 (OB document #10050) will be used.

2.3 Test Plan

2.3.1 Types of test, instrumentation and reporting

The test laminates will be produced (under industrial quality) on basis of the laminate definition above.

In order to measure the strains, all specimens will have either strain gauges or clip gauges, mounted singly (tension tests) or back to back (compression tests) during the residual strength tests. To facilitate the application of NDT techniques (and to avoid degradation), the gauges may not be applied until after completion of the fatigue testing stages.

All tests will be reported in OptiDat as soon as the tests are accomplished. Test reports, including data, figures and photographs will be prepared after a complete set of tests has been finished.

2.3.2 Static strength parameters, basic S-N curve, and residual strength testing

The material needs to be characterised in detail, to allow the appropriate lifetime fractions to be calculated and various material parameters required by thermoelastic stress analysis. In a change to the original programme, TG5 will now participate in the measurement of the initial static strength parameters (tension and compression) and basic S-N curves, in collaboration with TG1. This exercise will then be used as a benchmark to compare results across the different partners involved in the project.

In addition to basic strength parameters, thermal (specific heat capacity and thermal expansion coefficient) properties of the UD and the MD material are required to assist in interpretation of thermoelastic stress results. The thermal expansion coefficients in the principal material directions will be measured by TG4. The specific heat capacity will be independently measured.

For partners using AE, a standard static proof loading will be applied before any static, residual strength, or fatigue test. Acoustic emission will be continuously monitored during this static load test (which should be up to the maximum stress that will be encountered in the next experimental stage). A clip-gauge or strain gauges will be mounted to determine axial stiffness.

The final part of each test will be a residual strength test, carried out to failure; a clip-gauge or strain gauges will be mounted to measure axial stiffness; where available, AE transducers will continuously monitor the specimen up to fracture.

2.3.3 Fatigue testing

Fatigue testing will be carried out at the R-values: 10, -1 and 0.1 at life cycle levels of log(N)=3, 4.65 and 6. For each combination of fibre direction, R-value, and stress level 72 reliable results are needed. Acoustic emission is monitored either continuously at low sensitivity or with regular sensitivity but at discrete time intervals. A clip-gauge or strain gauges will be used in specific life fraction intervals to monitor stiffness degradation during the test.

2.3.4 Additional testing

Additional condition monitoring will be carried out during both the fatigue and static strength test phases. Some of these tests will be carried out as a matter of procedure on all tests, others may only be applied to specifically selected tests. These will include:

(i) proof test with acoustic emission (AE) monitoring (applied before start of fatigue cycles and before final residual strength test) (CLRC-RAL, CRES, UPAT),

(ii) AE monitoring during fatigue cycles (CLRC-RAL, CRES, UPAT)

(iii) thermoelastic stress measurement (and possibly also infra red thermography measurements) during fatigue cycling (restricted by availability of equipment) (CLRC-RAL),

(iv) ultrasonics testing (UPAT, VUB),

(v) acousto-ultrasonics (CLRC-RAL, CRES, UPAT) - two or three transducers will be placed on the coupon surface, at least two of them remaining fixed through all test stages.

2.3.5 Test time per partner

The time schedule for Phase 1 of the project is shown in Section 5. Due to the length of time consumed in preliminary testing and establishment of the basic coupon design, the test schedule is compressed. The approximate test time per partner is presented below, based on the assumption of 5 Hz fatigue loading, 24 hours per day fatigue testing (where intermittent proof tests permit), and 1 hour setup/0.25 hours proof test/0.5 hours residual strength test (maximum 4 specimens per day). Note that within each main test block, 4 coupons are tested to 20% lifetime, 4 to 50% nominal lifetime, and 4 to 80% nominal lifetime; within the VL test blocks, 1 coupon is tested to each lifetime fraction. The correlation between test hours and man-months in the task must be reviewed in the context that several partners will be carrying out non-destructive testing, the performance and analysis of which can be very man power intensive. On this basis:

A block of 12 residual strength tests to a nominal lifetime of 10^3 cycles takes:	5.0 days
A block of 12 residual strength tests to a nominal lifetime of $5x10^4$ cycles takes:	8.0 days
A block of 12 residual strength tests to a nominal lifetime of 10^6 cycles takes:	24.0 days
A block of 3 residual strength tests to a nominal lifetime of 10^7 cycles takes:	36.0 days

Based on the above estimates and the test blocks per partner, the required number of testing days can be estimated as:

Partner	Short	Medium	Long	VL	Test days
TUDT	4	4	4	2	220
CLRC	4	4	4	3	256
CRES	3	3	3	2	183
VUB	3	3	3	2	183
UP	5	5	5	3	293
TOTALS	19	19	19	12	1135

(NB the VL test blocks to a nominal lifetime of 10^7 cycles will be carried out last and may be curtailed if there is insufficient time; these test blocks constitute 40%-50% of most partners test load):

2.4 Establishment of predictive engineering model

2.4.1 Analysis of test results

Experimental results to be produced in the course of this task group, will be subjected to usual data analysis, to provide an accurate knowledge on the statistical behaviour of the UD and MD material response under fatigue and static loading. Specifically, the static strength, fatigue life and residual strength data will be fitted by the appropriate statistical distributions, performing hypothesis validity tests such as Kolmogorov-Smirnov, confidence level definitions and so on.

2.4.2 Development of predictive engineering model

Establishment of a predictive engineering model will be done gradually, depending on the experimental results. The first step is the evaluation of already existing residual strength degradation models, which are presented in [2]. Detailed implementation procedures for the experimental data from Optimat Blades project will be presented. Specifically, for data from axial tests on UD material, transverse tests on UD and shear tests, different degradation functions are expected as a result from fitting various models to the data. The main result of the first step will be the knowledge of which residual strength degradation model is best applied to OB material data. In the second step, the procedure will be repeated and the MD laminate data set will be processed this time by fitting various residual strength models and comparing with those from UD. Based on the outcome of the comparison, additional data analyses and model modifications will be performed.

The third step, which is mostly a remote basic research target for Univ. of Patras, is the combination of axial, transverse and shear residual strength data on the UD material, in order to predict the residual strength degradation of any MD laminate subjected to multi-axial loading. The evaluation of this attempt will be made possible only after the second phase of experiments in Optimat Blades project. Initial comparisons, however, of model predictions to axial test results from the $[[\pm45,0]_4; [\pm45]]$ laminate will be performed as soon as theoretical background and experimental data are available.

2.5 Evaluation

Based on the results of Tasks 13.1, 13.2, and 13.3 a predictive engineering model will have been developed, based on nominal lifetime and partial safety factors. Where possible, these will be associated with selected NDT measurement criteria.

3 DPA FOR WP14

To be added for Phase II of the project.

4 REFERENCES

[1] Philippidis, T.P., Passipoularidis, V.A., *Residual strength characterisation of orthotropic ply material*, OB_TG2_003_UP, April 2002

5 TEST TABLES

Static Tests on Optimat Blades specimens

Partner			ECN	TUDT	DLR	DEWI	CCLRC	RISOE	CRES	VUB	UP	VTT	ECN	TUDT	DLR	DEWI	CCLRC	RISOE	CRES	VUB	UP	VTT	ECN	TUDT	DLR	DEWI	CCLRC	RISOE	CRES	VUB	UP	VTT	
lay-up	Test	Type of test																															Remarks
Axial (//)	T						5			5							5			5													Benchmark with TG1
	C						5			5							5			5													Benchmark with TG1
Transverse (⊥)	T																																
	C																																
10°	T																																
	C																																
60°	T																																
	C																																
30°	T																																
Axial (//)	T	40°/-60°/100%																															
	C	40°/-60°/100%																															
30°	T	40°/-60°/100%																															
Transverse (⊥)	T	40°/-60°/100%																															
	C	40°/-60°/100%																															

Constant Amplitude Fatigue Tests

Partner			ECN	TUDT	DLR	DEWI	CCLRC	RISOE	CRES	VUB	UP	VTT	ECN	TUDT	DLR	DEWI	CCLRC	RISOE	CRES	VUB	UP	VTT	ECN	TUDT	DLR	DEWI	CCLRC	RISOE	CRES	VUB	UP	VTT	
lay-up	R	Type of test																															Remarks
Standard Optimat Specimens																																	
Axial (//)	0.1	shear on long test																															
	0.5																																
	-0.4																																
	-1						10			10																							Benchmark with TG1
	-2.5																																
	10																																
	2																																
Transverse (⊥)	0.1																																
	-1																																
	10																																
10°	0.1																																
60°	0.1																																
10°	-1																																
60°	-1																																
Axial (//)	0.1	40°/-60°/100%																															
	0.1	submersed																															
	-1	40°/-60°/100%																															
	10	40°/-60°/100%																															

Residual Strength Tests

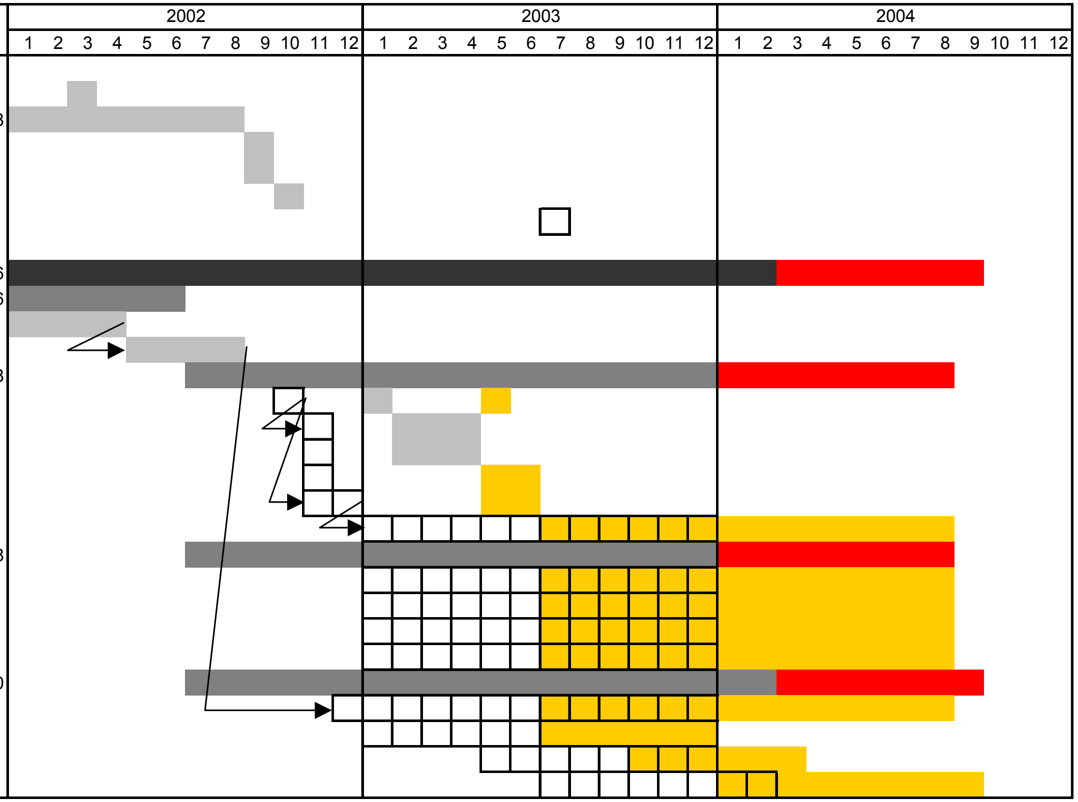
Partner			EC	TU	DL	DE	CC	RIS	CR	VU	UP	VT	EC	TU	DL	DE	CC	RIS	CR	VU	UP	VT	EC	TU	DL	DE	CC	RIS	CR	VU	UP	VT	
lay-up	R	Type of test																															Remarks
Standard Optimat Specimens																																	
Axial (//)	0.1	20/50/80%					36			36							36			36											36		
	-1	20/50/80%		36			36							36			36																
	10	20/50/80%		36							36			36					36														
	0.1	long life		3			3										3			3													
	-1	long life		3			3												3	3													
	10	long life							3		3										6												
Transverse (⊥)	0.1	20/50/80%								36	36																						
	-1	20/50/80%							36		36																						
	10	20/50/80%							36		36																						

Residual Strength tests - finer resolution test breakdown

Partner			ECN	TUDT	DLR	DEWI	CCLRC	RISOE	CRES	VUB	UP	VTT	ECN	TUDT	DLR	DEWI	CCLRC	RISOE	CRES	VUB	UP	VTT	ECN	TUDT	DLR	DEWI	CCLRC	RISOE	CRES	VUB	UP	VTT	
lay-up	Lifetime	R	UD										MD										Shear (UP to specify design)										Total spec
Standard Optimat Specimens																																	
Axial (//)	1.00E+03	0.1					12			12							12			12											12		60
		-1		12			12							12			12																48
		10		12							12			12					12														48
	5.00E+04	0.1					12			12							12			12											12		60
		-1		12			12							12			12																48
		10		12							12			12					12														48
	1.00E+06	0.1					12			12							12			12											12		60
		-1		12			12							12			12																48
		10		12							12			12					12														48
	1.00E+07	0.1		3			3										3			3													12
		-1		3			3												3	3													12
		10							3		3										6												12
Transverse	1.00E+03	0.1								12	12																						24
		-1							12		12																						24
		10							12	12																							24
	5.00E+04	0.1								12	12																						24
		-1							12		12																						24
		10							12	12																							24
	1.00E+06	0.1								12	12																						24
		-1							12		12																						24
		10							12	12																							24

6 TIME SCHEDULE

Task Name	Who	Duration (months)
MANAGEMENT AND PRELIMINARY TESTING		
PROJECT KICK-OFF		
Task 2.3. Proposal for reference material	TC	8
Task 1.2. Approval of reference material	SC	
Task 2.4. Reporting DPA for Phase I	TG5	
Task 1.3. Approval of DPA for Phase I	SC	
FIRST ASSESSMENT		
WP13: RESIDUAL STRENGTH AND CONDITION ASSSESSMENT		26
Task 13.1. Review of residual strength assessment		6
Literature review	UP	
Report	UP	
Task 13.2. Residual strength after fatigue		18
Production of specimens	LM	
Measurement of basic properties	TG3	
Baseline static tests	CCLRC/VUB	
Baseline fatigue tests	CCLRC/VUB	
Measurement of basic S-N curves	TG1/TG5	
Residual strength testing	TG5	
Task 13.3. Condition monitoring techniques		18
Thermoelastic stress analysis	CLRC-RAL	
Acoustic emission / Acousto-ultrasonics		
Visual inspection (microscopy)		
Ultrasonics		
Task 13.4. Predictive engineering model		20
Database		
Initial modelling		
Test and evaluation		
Final model		



Original DPA time schedule (September 2002)
Revised DPA time schedule (May 2003)
Completed
Over-run due to late specimen delivery