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4th semester progress report TG2 (01.07 to 31.12.2003)

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OPTIMAT BLADES

TG 2

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Change record

Issue/revision	date	pages	Summary of changes
1st version	11/02/2004	7	na

DETAILED REPORT FOR TASK GROUP 2

In the following, detailed information can be found regarding the activities for Task Group 2: 'Investigation of blade material behavior under complex stress states ' (WP6 and WP7).

Short description of TG2 WP's

Phase I of TG2 consists of WP6 "Complex Loading" in which the objective is to investigate the effect of complex stress states, e.g. plane stress conditions, on failure prediction both under static or cyclic loading. The combined action of all three in-plane stress tensor components will be taken into account in defining failure in contrast to one-dimensional approaches where only a normal and shear stress components are considered separately. To meet the objective, extensive testing for material characterization of basic UD ply is foreseen accompanied by uni- and multi-axial tests on MD laminates of various stacking sequences. Test results will be used to implement validated failure theories in conventional and FE large blade models and derive, in cooperation with certifying organizations, design guidelines for large rotor blades.

Specific objectives for this period

Specific objectives for the 4th semester (01.07.2003 to 31.12.2003) were:

- Testing of OPTIMAT coupons and special specimens for multi-axial loading (static and fatigue loading) planned for the 1st phase of the project
- Build FE and conventional blade models for theoretical analysis and assessment of complex stress state effect
- Review and validation of failure theories for static and CA cyclic loading, FE models

Overview of technical achievements

Phase I tests

Static tests of OB standard coupons

104 static tests using OB standard coupons were performed in the frame of the main testing program, phase I, accounted for WP6: 26 UD tensile, 26 UD compressive, 26 Transverse tensile and 26 Transverse compressive. Static tests were performed for the determination of in-plane elastic properties and strengths. According to the test plan, 26 coupons were scheduled for each case to define the respective elastic property and static strength distribution characteristics. Results from all coupons were uploaded to OPTIDAT and also presented in [1]. Thorough statistical evaluation and definition of probabilistic property distributions, e.g. see Fig.1, were performed for the tensile, E_1, and transverse Young modulus, E_2, major, v_{12}, and minor v_{21} Poisson ratios, tensile, X, and compressive strength, X', along the fiber and in the transverse direction, Y and Y' respectively.

CA cyclic tests of OB standard coupons

120 CA fatigue tests were performed on standard OB UD coupons. In the fiber direction, OB UD 0^o: 29 cyclic tests @ R=-1, 19 cyclic tests @ R=0.1, 9 cyclic tests @ R=10 (overlap with WP3, TG1), 2 cyclic tests @ R=∞. In the transverse to the fiber direction, OB UD 90^o: 27 cyclic tests @ R=-1, 8 cyclic tests @ R=0.1, 26 cyclic tests @ R=10. The number of coupons tested per loading condition, R, is some times greater than planned due to problems arising from details in testing

procedure, e.g. see Fig.2, or power grid failures. Test results were uploaded to OPTIDAT and also presented in [1]. Fatigue tests were performed to determine S-N curves under different loading conditions (R=-1, 0.1 and 10) of UD OPTIMAT coupons along the fiber and in the transverse direction. Load was introduced as a sinusoidal waveform at frequencies ranging from 0.84 to 6.70 Hz depending on max stress level. Test frequency for the first coupon tested was determined such as to avoid temperatures higher than 35^{o}C on coupon surface, near the tab region. To satisfy the aforementioned criterion, the laboratory was continuously air-conditioned and a fan was used to direct cool air on coupons surface. Surface temperature was monitored for a number of coupons using a PT100 thermo resistance. All coupons tested under CA cyclic stress were instrumented with two 6-mm single strain gauges, placed back to back to measure longitudinal strains at the first two cycles of each test, which were performed always, regardless of the cyclic stress level, at a frequency of 0.02 Hz.

Statistics	X	E1	v12	e1T_max%
Min	695.03	36.74	0.24	1.898
Max	836.03	41.38	0.3459	2.355
Sum	22518.42	1132.21	8.4267	60.647
Mean	776.4972	39.04172	0.290576	2.091275862
Median	781.34	39.03	0.2853	2.08
Variance	1306.319	1.065715	0.000736	0.009185064
Std. Dev.	36.14304	1.032335	0.027137	0.09583874
Std. Err.	6.711594	0.1917	0.005039	0.017796807
Valid Obs.	29	29	29	29
Total Obs.	29	29	29	29
95 Conf Int	13.74808	0.392679	0.010322	0.036455107
COV%	4.654625	2.644183	9.339083	4.582788024

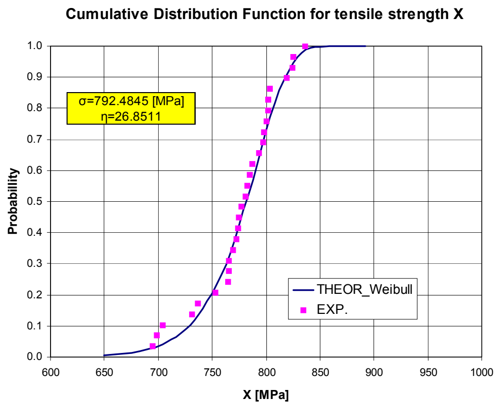

Fig.1 Data format for statistical property distributions from static tests on UD material

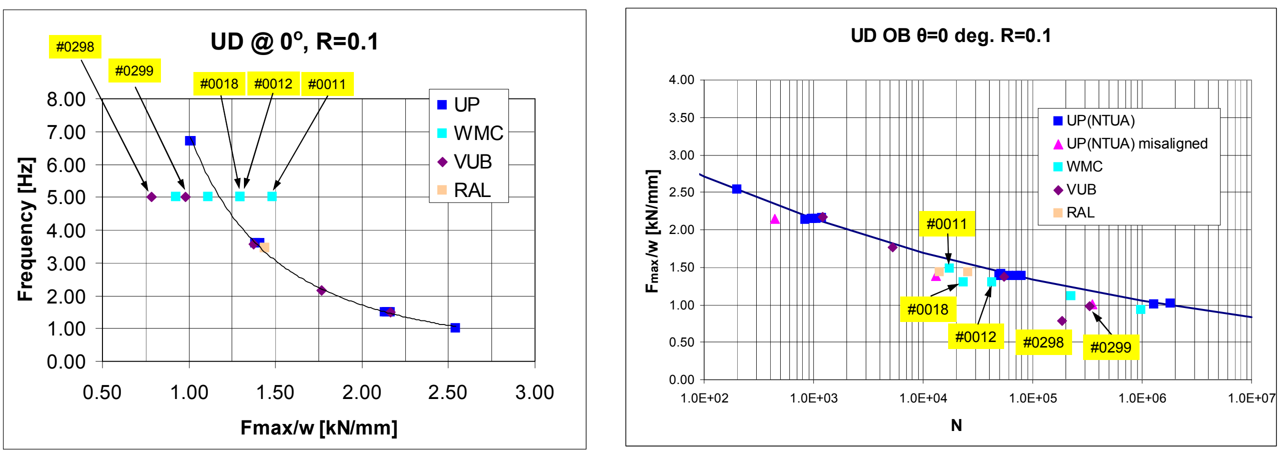

Fig.2 Sensitivity investigation of CA test results on frequency, coupon clamping & alignment, etc.

Biaxial static tests of cruciform coupons

25 preliminary biaxial tests, 5 experiments for 5 different specimen geometries, were performed on cruciform specimens to investigate candidate geometries of reduced stress concentration, which in combination with the available test frame at VUB should produce acceptable failure modes. The geometries tested were assigned the numbers 2, 3, 4, 5 and 7. A technical report with test results

was written and uploaded to the OPTIMAT site [2]. Cruciform coupons, prepared by LM, are made of MD lay-up, albeit of different thickness for the various geometries: $[(\pm45/0)_4/\pm45]$ for geometries 3, 4, 5 and 7, $[(\pm45/0)_3/\pm45]$ for geometry 2. In the middle of the specimens of geometries 3, 4, 5 and 7 a set of (0/±45) layers is milled away at each side of the specimen resulting in $[(\pm45/0)_2/\pm45]$ lay-up. All specimens were tested in biaxial tension using a servo-hydraulic biaxial test bench with a loading capacity of 100kN in both directions. In the gauge area of each specimen, a three element rosette strain gauge was bonded on both sides. Strain measurements were obtained in 0° direction (direction of UD fibers), 90° direction (perpendicular to UD fibres) and in 45° direction. The strain gauge type is FRA-6 from Tokyo Sokki Kenkyujo Co., Ltd. The gauge length is 6 mm and the gauge width is 2.4 mm. A digital video camera is used during testing to allow for specimen failure visualization. The test speed was 5kN/minute in the direction of the 0° fibres, and was adapted in transverse direction depending on the loading-ratio. Most of the specimens were loaded with a ratio F_x/F_y of 3.85, which is the strength ratio between 0°- and 90°- directions of the MD lay-up. One specimen per geometry was tested at a load ratio of 5.775/1, which is one and a half times the ratio of the strengths and some specimens were tested with a ratio 2.57/1, which is the ratio of the strengths divided by 1.5. Highest stresses at failure in the 0°-direction were obtained for geometry 5, see Fig.3, whereas, the highest obtained failure stresses in the transverse direction were from geometry 7. Highest failure strains are obtained for geometry 5 and 4. Looking at the failure modes for the load ratio 5.775/1, particularly good results were mostly obtained for geometry 5, see Fig.4. These facts considered together, lead to the conclusion to continue the main tests of phase I with geometry 5.

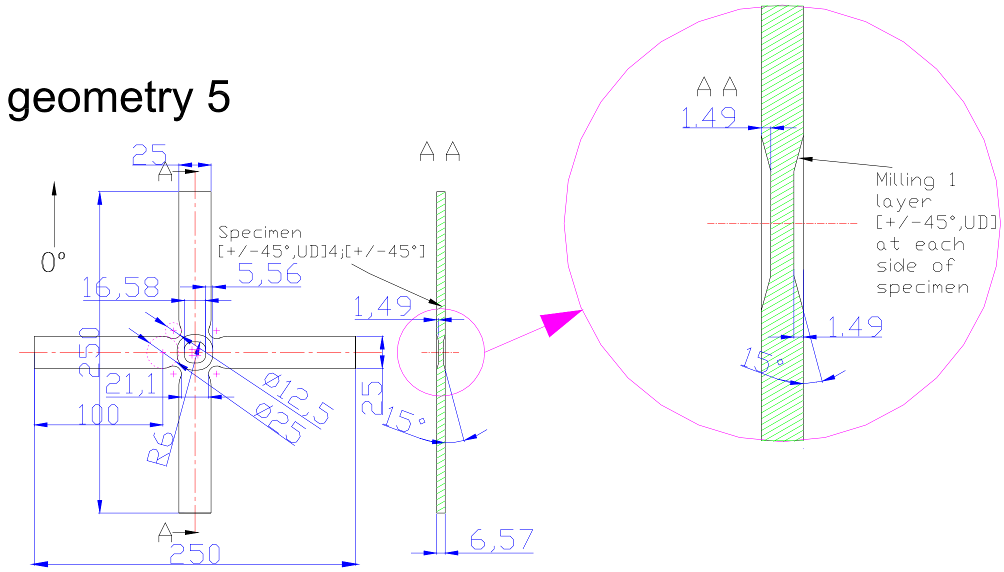

Fig.3 Preferred cruciform specimen geometry

Optimized stress analysis

Conventional (one-dimensional) and 3D shell-FE models of a Gl/Ep blade of 35 m were developed by TUDT and ECN and calculations for comparison of stress and strain between the two modeling philosophies were performed. A technical report entitled “Comparison between uni-axial and bi-axial stresses”, OB_TG2_R015, was prepared by ECN, and is to be uploaded at the OPTIMAT site. Objective of the exercise is to compare failure indices from both analyses and calibrate safety factors for each case so as to reach the same safety margin. So far, the task was not completed due to some difficulties in exchanging data (proprietary rights) between UP and WMC, but a settlement was reached and the work is expected to be done in the 1st semester of 2004.

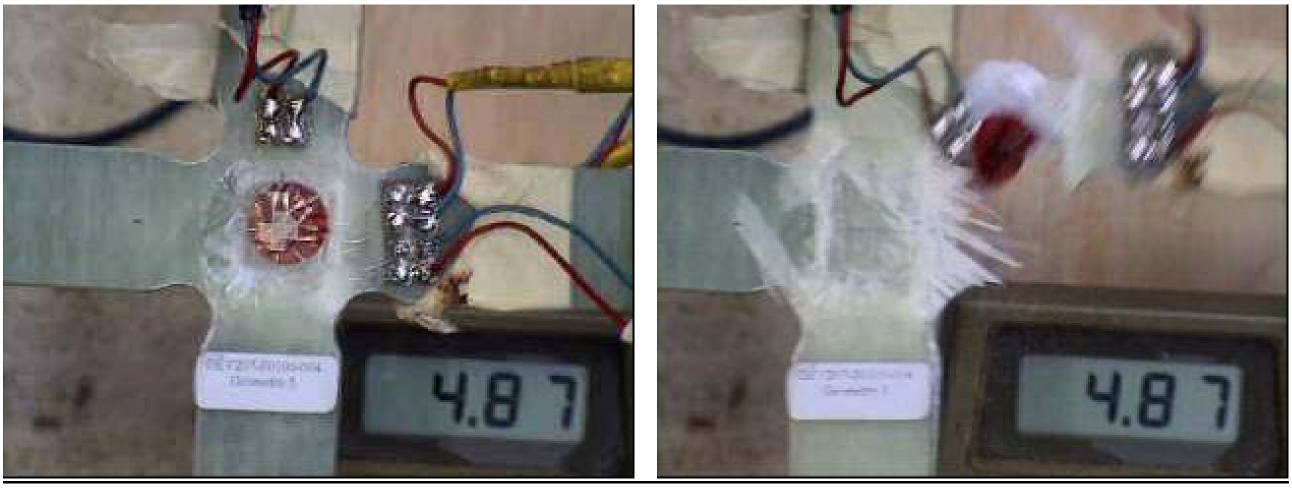

Fig.4 Cruciform specimen GEV 207 S0100-004 (geometry 5) at failure

Review and validation of failure theories

A comprehensive investigation and comparison of multi-axial failure theories for composites, both under static and dynamic loading conditions, especially with regard to their implementation into commercial FE codes, is underway at UP. Progressive damage analyses and non-linear material response towards reliable Last Ply Failure predictions are also into consideration. Theoretical calculation of failure loads for simulated tests with UD and MD coupons loaded off-axis, but also multi-axial tests will be compared to corresponding test results, when available. An example of First Ply Failure predictions using Tsai-Hahn and Puck criteria (implemented as external user subroutines into ANSYS) is presented in Fig.5. Results for failure index (inverse strength ratio) are for the outermost UD layer of an OB MD coupon loaded in compression with an equivalent stress resultant of 40 kNm^{-1}. Due to symmetry, the upper right quarter of the coupon was only modeled.

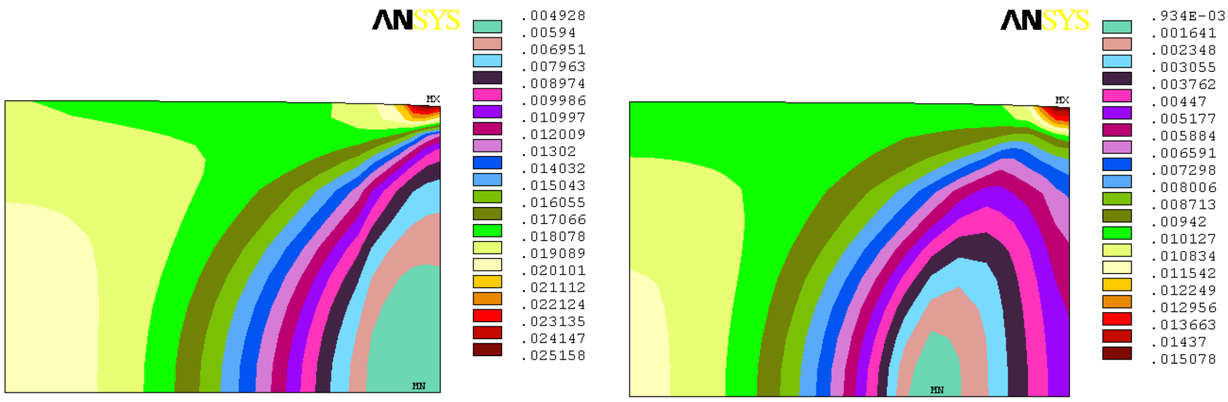

Fig.5 Tsai-Hahn (left) and Puck (right) criteria FPF predictions for MD coupon under compression

Comparison of planned activities versus progress achieved

Bi-axial tests, either in specimens of tubular shape or cruciform geometry, both under static and fatigue loading, will be used to validate failure theories and life prediction schemes and will prove, or not, the importance of considering complex stress states in the design of large rotor blades. However, due to various reasons, production of specimens needed for this kind of tests has not yet started. For the cruciform specimen geometry, a consensus has been probably reached on the optimal coupon geometry and production of the specimens for the main phase I is expected to start at LM. On the other hand, although DLR & Stuttgart Univ., but also VUB, have considerable experience and proved technology in testing tubular composite specimens, no such type of specimens has been produced so far.

To implement plane stress (complex stress states) formulations, either in FEM calculations or failure prediction schemes, the complete set of in-plane material properties is needed, meaning that for the UD material, specimens in the transverse to the fiber direction as well as appropriate for measuring shear properties must be tested. For a number of reasons, [±45] ISO coupons have not been produced so far and as a result, a considerable number of special tests concerning basic UD material characterization, e.g. in shear, are not yet performed. This highly affects other TG's as well, e.g. TG5, where input from CA cyclic test in shear are a prerequisite to define appropriate stress levels for the residual strength tests.

On the other hand, standard OB UD coupon was proved inadequate for compression in the fiber direction and additional preliminary investigations are under way to determine the appropriate number of layers to avoid buckling. Even if an agreement is reached on the optimal geometry, it is not easy to estimate the expected delay on the modified time schedule.

In summary, according to the DPA of TG2:

- 465 specimens were scheduled for phase I
- 275 specimens are not yet delivered
- 169 specimens have been tested successfully, i.e. circa 89% of specimens delivered were tested

<u>Planned activities for the next half-year period</u>

In the first semester of 2004, the effort will be towards performing as many as possible bi-axial tests in order to reduce delays observed in the modified time schedule. Testing of standard OB coupons will run in parallel in several test rigs, while numerical analyses with FE blade models will be concluded.

References

1. T. P. Philippidis, T. T. Assimakopoulou, V. A. Passipoularidis, A. E. Antoniou, OB_TG2_O002.pdf
2. A. Smits, D. van Hemelrijck, OB_TG2_R016.pdf, rev 000