# TASK GROUP 2: Investigation of Blade Material Behaviour under Complex Stress States

# DETAILED PLAN OF ACTION WP6: Complex Loading

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# 1 INTRODUCTION

In this report the actions are defined that are needed for work package 6 to reach the objectives. The objectives and work description are given in the technical annex and repeated for convenience in this document.

The Detailed Plan of Action (DPA), Phase 1, for TG2: “Investigation of blade material behaviour under complex stress states” consists in essence of 4 test series, denoted respectively DP1 to DP4. A comprehensive explanation as of the scope, methodology and planning of each test series is presented in the sequel. Additionally, WP6 contains a comprehensive numerical investigation aiming to provide validated composite mechanics and FEM formulation guidelines/recommendations for rotor blade design.

An overview of testing effort:

DP1: Static tests for UD material characterization; 125 straight edge + 50 TEC specimens
DP2: CA fatigue tests for UD material characterization; 105 straight edge
DP3: Verification tests for static strength; 40 straight edge + 15 cruciform + 15 tubes
DP4: Verification tests for fatigue strength; 40 straight edge + 30 cruciform + 45 tubes

Involved partners: UP(TL), TUDT, DLR, VUB, ECN, CRES

# 2 DPA FOR WP 6

## 2.1 Description of work

The objectives of this work package are: (i) to define and validate a multi-axial failure theory in static and fatigue loading, by adapting existing theories (ii) to generate test results of UD plies and MD laminates for the reference material (iii) to implement advanced FEM formulations and (iv) to quantify complex stress state effect on design efficiency.

***Task 6.1: DPA - Definition of specimen and test plans***
Definition of the baseline material combination and test standards to be used by all labs for multi-axial testing, possibly involving FEM calculations and preliminary experiments. Design of experimental set-ups and specimen geometry to achieve the desired state of stress will be performed in a rational manner using numerical simulation. Complex-stress failure criteria will be benchmarked and used for theoretical predictions. Definition of necessary tests (static, fatigue) for advanced FEM analyses.

***Task 6.2: Optimised stress analysis***
A large rotor blade will be modelled using various thick shell FEM formulations. The stresses will be compared with results from "conventional" analysis techniques. Complex stress situations will be identified for experimental simulation.

***Task 6.3: Reliable strength prediction (static loading)***
Within this task all relevant 'static' material properties of the reference material at ambient conditions will be characterised using a statistically significant sample size: elastic constants, strength and thermal expansion coefficients. A number of uni-axial (UD reference material, on- and off-axis) and multi-axial coupon tests (cruciform shape and tubes) will be performed to validate failure criteria and assess reliability methods to accurately predict failure probability.

***Task 6.4: Reliable strength prediction (fatigue loading)***
All S-N lines will be characterised at specific stress ratios, R, and frequency resulting in constant life diagrams of individual material properties, for the UD reference material. In addition, a number of uni-axial and multi-axial different coupon tests will be performed: (a) Uni-axial tests on laminates of UD and MD stacking sequence (on- and off-axis), (b) Multi-axial testing on cruciform specimens and tension/compression-torsion tubes. Strength criteria, suitable for cyclic complex stress states, will be assessed by comparing theoretical predictions with test results. Fatigue reliability methods to predict failure probability will be assessed as well.

***Task 6.5: Impact of complex stress state effect***
For the complex stress states and test data generated in this work package and Task 3.3 the effectiveness of the different stress analysis approaches and failure prediction schemes will be critically assessed, for both static and fatigue conditions, by straightforward comparison of theoretical strength predictions with experimental data.

### 2.1.1 Modifications to the annex

The above description of work complies with Annex I of the contract; no modifications have been made.

## 2.2 Laminate and specimen definition

Three different laminates, made of the reference material, will be tested in TG2, namely UD, $[0_4]$, MD, $[(\pm45/0)_4/\ \pm45]$, and $[\pm45]_n$ in on- and off-axis configurations. In an effort to keep consistency between tests of different TGs, facilitate result comparison and also minimize production logistics, the “optimat standard geometry” (SOB) will be used as in many cases as possible, albeit at various thickness, to account for stiffness anisotropy.

Besides the straight edge coupon geometry, cruciform specimens of MD lay-up and tubes made of $[\pm45]_n$ will be used for biaxial tests. Finally, small cubical specimens, cut at various directions from $[0]_n$ will be used for the determination of Thermal Expansion Coefficients (TEC) of the UD reference material.

Details on specimen geometry, number of coupons and specific comments are given in Table 1

## 2.3 Test Plan

### 2.3.1 Types of test, instrumentation and reporting

The various types of tests foreseen in WP6 are static tests for characterization of mechanical properties, constant amplitude, CA, fatigue and thermo-mechanical experiments for TEC determination. As already mentioned, various specimen geometries, i.e. straight edge coupons, cruciform and tubular specimens as well as small cubes for thermo-elastic analyses will be used.

Depending on the type of test, strain or clip gauges and rosettes, Platinum PT100 sensors for temperature measurements and various NDT sensors along with the necessary data acquisition systems will be used throughout the duration of the test series.

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 testing

The following test series are foreseen:

*DP1. TESTS FOR UD MATERIAL CHARACTERIZATION*

Scope: Measurement of elastic engineering constants $\{E_1, E_2, G_{12}, v_{12}\}$, TEC $\{\alpha_1, \alpha_2\}$, strength {X, X’, Y, Y’, S}, where:

$E_1$: Elastic modulus in fiber direction, 1
$E_2$: Elastic modulus transversely to the fiber direction, 2
$G_{12}$: Shear modulus in plane 1-2
$v_{12}$: Major Poisson ratio
$\alpha_1$: Thermal expansion coefficient in fiber direction
$\alpha_2$: Thermal expansion coefficient transversely to the fiber
X: Tensile strength in fiber direction, 1
X’: Compressive strength in fiber direction, 1
Y: Tensile strength transversely to the fiber direction, 2
Y’: Compressive strength transversely to the fiber direction, 2
S: Shear strength in plane 1-2

Test specification: Static tests will be performed in displacement control mode and at a strain rate equal to that of CA fatigue tests. TEC will be measured using DuPont's TMA system at a temperature range of [-40, 60] $^{o}$C. Test categories as per specimen geometry are given code names as follows:

**DP1_A**: Static tension, compression in fiber direction
**DP1_B**: Static tension, compression transversely to the fiber
**DP1_S**: Static in-plane shear
**DP1_ATEC**: Thermal Expansion coefficient in fiber direction
**DP1_BTEC**: Thermal Expansion coefficient transversely to the fiber

Details on specimen geometry, number of coupons and specific comments are given in Table 1

*DP3. VERIFICATION TESTS FOR STATIC STRENGTH*

Scope: Validation of multi-axial failure theories and assessment of reliability methods to accurately predict failure probability

DP3.1 Axial tests on off-axis UD and MD laminates

Test specification: Static tests will be performed in displacement control mode and at a strain rate equal to that of DP1 test series. Off-axis coupons (5Tension+5Compression), at two different orientations, 10$^{o}$ and 60$^{o}$, from UD and MD laminates will be tested. Test categories as per specimen geometry are given code names as follows:

**DP3.1a**: Static tension, compression in 10$^{o}$ off-axis direction, UD
**DP3.1b**: Static tension, compression in 60$^{o}$ off-axis direction, UD
**DP3.1c**: Static tension, compression in 10$^{o}$ off-axis direction, MD
**DP3.1d**: Static tension, compression in 60$^{o}$ off-axis direction, MD

DP3.2 Multi-axial tests on [±45] and MD laminates

Test specification: Multi-axial static tests will be performed in load control mode and at a strain rate equal to that of DP1 test series. Cruciform specimens, loaded in biaxial tension, will be tested at VUB, while tubular specimens subjected to combined torsion-tension/compression will be tested at DLR:
Fifteen (15) cruciform specimens made of MD layup will be tested at five different biaxiality ratios, i.e. 3 specimens per stress state, spanning the first quadrant of $\sigma_1$-$\sigma_2$ plane
Fifteen (15) tubular specimens made of [±45] layup will be tested at torsion, tension, compression, torsion & tension, torsion & compression, i.e. 3 specimens per stress state
Test categories as per specimen geometry are given code names as follows:

**DP3.2a**: Static biaxial tension, cruciform specimen, MD
**DP3.2b**: Static torsion-tension/compression in $[\pm 45]_n$

Details on specimen geometry, number of coupons and specific comments are given in Table 1

### 2.3.3 Fatigue testing

The following test series are foreseen:

*DP2. CA FATIGUE TESTS FOR UD MATERIAL CHARACTERIZATION*

Scope: Measurement of fatigue strength $\{X_F, Y_F, S_F\}$ at R ratios equal to 0.1, -1 and 10, for a specific test frequency. Definition of constant life diagram per individual material property. The following notation is valid:

N: number of cycles
$\sigma_a$: stress amplitude
$\sigma_m$: mean stress
$R=\sigma_{min}/\sigma_{max}$: Stress ratio
f: cyclic test frequency (in Hz)
$X_F= X_F$ (N, R, f): Fatigue strength in fiber direction
$Y_F= Y_F$ (N, R, f): Fatigue strength transversely to the fiber
$S_F= S_F$ (N, R, f): Shear fatigue strength in plane 1-2

Test specification: CA fatigue tests will be performed in load control mode and at a frequency (from 2 to 10 Hz) such that the specimen surface temperature does not exceed 35$^o$C. Three (3) stress levels will be investigated (5 coupons each) corresponding to expected life of 1E+03, 5E+05 and 1E+06 (some coupons to 1E+07) cycles respectively. Test categories as per coupon geometry and property characterization are given code names as follows:

**DP2_$X_F$**: Determination of fatigue strength in fiber direction, all R
**DP2_$Y_F$**: Determination of fatigue strength transversely to the fiber, all R
**DP2_$S_F$**: Determination of shear fatigue strength in plane 1-2, R=0.1

Details on specimen geometry, number of coupons and specific comments are given in Table 1

## *DP4. VERIFICATION TESTS FOR FATIGUE STRENGTH*

Scope: Validation of fatigue strength criteria (life prediction models) for laminated composites under multi-axial cyclic loading. Assessment of fatigue reliability methods to accurately predict failure probability

### DP4.1 Axial tests on off-axis UD and MD laminates

Test specification: CA fatigue tests will be performed in load control mode and at a frequency (from 2 to 10 Hz) such that the specimen surface temperature does not exceed 35$^o$C. Two (2) stress levels will be investigated corresponding to expected life of 1E+03 and 1E+06 cycles respectively. 5 off-axis coupons, possibly at different stress ratios, at two different orientations, 10$^o$ and 60$^o$, from UD and MD laminates will be tested. Test categories as per specimen geometry are given code names as follows:

**DP4.1a**: CA fatigue, R=0.1, in 10$^o$ off-axis direction, UD
**DP4.1b**: CA fatigue, R=0.1, in 60$^o$ off-axis direction, UD
**DP4.1c**: CA fatigue, R=-1, in 10$^o$ off-axis direction, MD
**DP4.1d**: CA fatigue, R=-1, in 60$^o$ off-axis direction, MD

### DP4.2 Multi-axial tests on [±45] and MD laminates

Test specification: Multi-axial CA fatigue tests will be performed in load control mode and at a frequency (from 2 to 10 Hz) such that the specimen surface temperature does not exceed 35$^o$C. Cruciform specimens, loaded in biaxial tension, will be tested at VUB, at two (2) stress levels, corresponding to expected life of 1E+03 and 1E+06 cycles respectively. Tubular specimens subjected to combined torsion-tension/compression will be tested at DLR and Stuttgart University: Thirty (30) cruciform specimens made of MD lay-up will be tested in total, two stress levels, at three different biaxiality ratios, i.e. 5 specimens per stress state, spanning the first quadrant of $\sigma_1$-$\sigma_2$ plane, under R=0.1. Forty-five (45) tubular specimens made of $[\pm45]_n$ will be tested at torsion, torsion & tension, torsion & compression, i.e. 15 specimens per stress state, under R=-1. Test categories as per specimen geometry have code names as follows:

**DP4.2a**: CA fatigue biaxial tension, cruciform specimen, MD
**DP4.2b**: CA fatigue in torsion, torsion-tension/compression in $[\pm45]_n$

Details on specimen geometry, number of coupons and specific comments are given in Table 1

## *2.4 Numerical analyses plan*

### 2.4.1 Type of analyses and reporting

A 35 m rotor blade will be modelled using alternative FEM shell formulations. The calculated stresses & strains developed in each ply will be compared with results from "conventional " analysis methods, based mainly in beam FEM models, accounting only for some of the existing stress tensor components.

### 2.4.2 Numerical analyses

A number of issues related to composite mechanics and FE modelling will be investigated:

1. Transfer of loading distributions derived from aeroelastic simulations (elastic blade model with beam FE formulation) to structural blade model (3D shell or brick elements)
2. Composite mechanics used in 1D analyses (beam elements) and 2D shell formulations. For example, investigate the effect of using discrete layer formulation or homogenized medium according to Classical Lamination Theory (CLT) in 1D calculations and compare with 2 or 3D results.
3. Modelling and stress calculation in a number of structural details such as shear web-skin adhesive joint, bonding lines of 2 blade halves, bolted joints etc.
4. Definition and benchmarking of static failure criteria. Management of failed layers or elements, First Ply Failure (FPF) vs. Last Ply Failure (LPF) concepts.
5. Calibration of partial conversion factors to account for equivalent "stress intensity" between beam and 3D shell FE formulations.
6. Linear vs. Non-Linear elastic analyses using beam and shell FE formulations.

## *2.5 Evaluation*

Based on the test data generated in this work package, concerning complex stress states, and Task 3.3, the effectiveness of the different stress analysis approaches and failure prediction schemes will be critically assessed, for both static and fatigue conditions, by straightforward comparison of theoretical predictions with experimental data. Quantification of complex stress state effect on blade design will be achieved while validated composite mechanics and FEM formulation guidelines/recommendations will be released.

# 3 TEST SPECIMEN SPECIFICATIONS ACCORDING TO TG2 DPA PHASE 1

Notes
**1.** Length x width x thickness = L x w x t. **2.** Tab in all coupons as supplied by LM, L= 55 mm, t = 2 mm, not tapered
**3.** All coupons are straight edge. **4.** T-T = Tension-Tension. **5.** T-C = Tension – Compression **6.** C-C = Compression - Compression
**7.** A number in {..} indicates same content of the cell as in the respective row.

| | Test code name | Description | Laminate stacking sequence | L x w x t in (mm) | Number of specimens | Comment |
|---|---|---|---|---|---|---|
| 1 | DP1_A | Static tension, compression ( ‖ ) | $[0_4]$, COMBI 1250 | 145 x 25 x 3.52* | 50 | * Thickness of COMBI 1250: 0.88 mm |
| 2 | DP1_B | Static tension, compression ( ⊥ ) | $[90_7]$, COMBI 1250 | 145 x 25 x 6.16* | 50 | |
| 3 | DP1_S | Static In-plane shear | $[45/-45]_S$, COMBI 1250 | 250 x 25 x 3.52* | 25 | |
| 4 | DP1_ATEC | Thermal expansion coefficient ( ‖ ) | $[0_7]$, COMBI 1250 | 15 x 6.16* x 6.16* | 25 | |
| 5 | DP1_BTEC | Thermal expansion coefficient (⊥ ) | $[90_7]$, COMBI 1250 | 15 x 6.16* x 6.16* | 25 | |
| 6 | DP2_$X_F$ | CA fatigue, T-T, T-C or C-C ( ‖ ) | {1} | {1} | 45 | |
| 7 | DP2_$Y_F$ | CA fatigue, T-T, T-C or C-C ( ⊥ ) | {2} | {2} | 45 | |
| 8 | DP2_$S_F$ | CA fatigue, in-plane shear | {3} | {3} | 15 | |
| 9 | DP3.1a | Static tension, compression (10° off-axis) | $[10_7]$, COMBI 1250 | {2} | 10 | |
| 10 | DP3.1b | Static tension, compression (60° off-axis) | $[60_7]$, COMBI 1250 | {2} | 10 | |
| 11 | DP3.1c | Static tension, compression (10° off-axis) | $[(35,-55/-10)_4/35,-55]$ | 150 x 25 x 6.57* | 10 | * Thickness of biaxial fabric: 0.61 mm |
| 12 | DP3.1d | Static tension, compression (60° off-axis) | $[(-15,75/-60)_4/-15,75]$ | {11} | 10 | |
| 13 | DP3.2a | Static biaxial tension of cruciform specimen | $[(\pm45/0)_3/\pm45]$ | N/A | 15 | Specimen specifications by VUB |
| 14 | DP3.2b | Static torsion-tension/compression of tubes | $[\pm45]_n$ | N/A | 15 | Specimen specifications by DLR |
| 15 | DP4.1a | CA fatigue, R=0.1, 10° off-axis | {9} | {2} | 10 | |
| 16 | DP4.1b | CA fatigue, R=0.1, 60° off-axis | {10} | {2} | 10 | |
| 17 | DP4.1c | CA fatigue, R=-1, 10° off-axis | {11} | {11} | 10 | |
| 18 | DP4.1d | CA fatigue, R=-1, 60° off-axis | {12} | {11} | 10 | |
| 19 | DP4.2a | CA biaxial tension of cruciform specimen, R=0.1 | {13} | N/A | 30 | {13} |
| 20 | DP4.2b | CA torsion-tension/compression of tubes, R=-1 | {14} | N/A | 45 | {14} |

# 4 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** | **UD** | | | | | | | | | | **MD** | | | | | | | | | | **±45º (shear/tubes)** | | | | | | | | | | **Remarks** |
| **Axial (//)** | T | | | | | | | | | | 25 | | | | | | | | | | | | | | | | | | | | | | |
| | C | | | | | | | | | | 25 | | | | | | | | | | | | | | | | | | | | | | |
| **Transverse (⊥)** | T | | | | | | | | | | 25 | | | | | | | | | | | | | | | | | | | | | | |
| | C | | | | | | | | | | 25 | | | | | | | | | | | | | | | | | | | | | | |
| **10°** | T | | | | | | | | | | 5 | | | | | | | | | | 5 | | | | | | | | | | | | |
| | C | | | | | | | | | | 5 | | | | | | | | | | 5 | | | | | | | | | | | | |
| **60°** | T | | | | | | | | | | 5 | | | | | | | | | | 5 | | | | | | | | | | | | |
| | C | | | | | | | | | | 5 | | | | | | | | | | 5 | | | | | | | | | | | | |
| **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% | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

NB: Final distribution over the partners not yet implemented. Numbers in grey denote work within other TGs.

## Static Tests on ISO/ASTM specimens at ISO speeds

| 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 | UD | | | | | | | | | | MD | | | | | | | | | | ±45º (shear/tubes) | | | | | | | | | | Remarks |
| Axial (//) | T | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 25 | | |
| | C | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Transverse (⊥) | T | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | C | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Thickness | C | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Shear | IPS | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 13 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 23 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 4 Point Bending | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Shear | IPS | 40°/-60°/100% | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Hygro Thermal | $\alpha_1$ | | | | | | | | | | 25 | | | | | | | | | | | | | | | | | | | | | | |
| | $\alpha_2$ | | | | | | | | | | 25 | | | | | | | | | | | | | | | | | | | | | | |
| | $\beta_1$ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | $\beta_2$ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

## Static Tests on special test 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 | UD | | | | | | | | | | MD | | | | | | | | | | ±45º (shear/tubes) | | | | | | | | | | Remarks |
| 2D test specimens [2] | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2D stress state | | Cruciform | | | | | | | | | | | | | | | | | | 15 | | | | | | | | | | | | | 3 UD layers |
| | | Tubes | | | | | | | | | | | | | | | | | | | | | | | 15 | | | | | | | | |
| Long test specimens as reference for repaired specimens [4] | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Axial (//) | T-T | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Bending | T up | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | C up | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Repaired test specimens [4] | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Axial (//) | T | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| (long spec.) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Bending | T up | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| (long spec.) | C up | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Thick test specimens [4] | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Axial (//) | T | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | C | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Transverse (⊥) | T | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | C | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Thickness | C | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | Shear | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Bending | T up | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | C up | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Hygro Thermal | $\alpha_1$ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | $\alpha_2$ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | $\beta_1$ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | $\beta_2$ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Repaired thick test specimens [4] | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Axial (//) | T | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Bending | T up | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | C up | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

# CA 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 | UD | | | | | | | | | | MD | | | | | | | | | | ±45? (shear/tubes) | | | | | | | | | | Remarks |
| Standard Optimat Specimens | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Axial (//) | 0.1 | shear on long test |  |  |  |  |  |  |  |  | 15 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 15 |  | ISO standard |
| | 0.5 | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| | -0.4 | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| | -1 | |  |  |  |  |  |  |  |  | 15 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| | -2.5 | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| | 10 | |  |  |  |  |  |  |  |  | 15 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| | 2 | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Transverse (⊥) | 0.1 | |  |  |  |  |  |  |  |  | 15 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| | -1 | |  |  |  |  |  |  |  |  | 15 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| | 10 | |  |  |  |  |  |  |  |  | 15 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 10° | 0.1 | |  |  |  |  |  |  |  |  | 10 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 60° | 0.1 | |  |  |  |  |  |  |  |  | 10 |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 10° | -1 | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 10 |  |  |  |  |  |  |  |  |  |  |  |  |
| 60° | -1 | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 10 |  |  |  |  |  |  |  |  |  |  |  |  |
| Axial (//) | 0.1 | 40°/-60°/100% |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| | 0.1 | submersed |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| | -1 | 40°/-60°/100% |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| | 10 | 40°/-60°/100% |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 2D test specimens [2] | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 2D Stress state | 0.1 | Cruciform |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 30 |  |  |  |  |  |  |  |  |  |  |  |  | 3 UD layer |
| | -1 | Tube |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 45 |  |  |  |  |  |  |  |  |
| Long test specimens as reference for repaired specimens [4] | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Axial (//) | 0.1 | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Repaired test specimens [4] | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Axial (//) | 0.1 | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Thick test specimens [4] | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Axial (//) | 0.1 | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| | -1 | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| | 10 | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Repaired thick test specimens [4] | | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Axial (//) | 0.1 | |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |

# VA and Block 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** | **UD** | | | | | | | | | | **MD** | | | | | | | | | | **±45º (shear/tubes)** | | | | | | | | | | **Remarks** |
| **Standard Optimat Specimens** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | W | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | WX | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | RW | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | RWX | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | NW | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | NWX | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | AB | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | AB | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | AB | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 0.1 | HL | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | -1 | HL | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 10 | HL | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | AB | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | AB | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | | AB | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 0.1 | HL | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | -1 | HL | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 10 | HL | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

## Residual Strength 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 | UD | | | | | | | | | | MD | | | | | | | | | | ±45º (shear/tubes) | | | | | | | | | | Remarks |
| Standard Optimat Specimens | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Axial (//) | 0.1 | 20/50/80% | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | -1 | 20/50/80% | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 10 | 20/50/80% | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Transverse (⊥) | 0.1 | 20/50/80% | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | -1 | 20/50/80% | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 10 | 20/50/80% | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

# 5 TIME SCHEDULE

| ID | Task Name | Duration |
|---|---|---|
| 1 | **WP6: COMPLEX LOADING** | 619 days |
| 2 | **Task 6.1: DPA-Definition of specimen and test plans** | 249 days |
| 3 | Specimen manufacturing | 20 days |
| 4 | **Task 6.2: Optimised stress analysis** | 250 days |
| 5 | **Task 6.3: Reliable strength prediction (static loading)** | 199 days |
| 6 | DP1. Static tests for UD material characterization | 135 days |
| 7 | DP3.1 Axial tests on off-axis UD and MD laminates | 50 days |
| 8 | DP3.2 Multi-axial tests on [+/-45] and MD laminates | 50 days |
| 9 | Comparison of theoretical predictions with test results | 15 days |
| 10 | **Task 6.4: Reliable strength prediction (fatigue loading)** | 305 days |
| 11 | DP2. CA fatigue tests for UD material characterization | 267 days |
| 12 | DP4.1 Axial tests on off-axis UD and MD laminates | 120 days |
| 13 | DP4.2 Multi-axial tests on [+/-45] and MD laminates | 247 days |
| 14 | Comparison of theoretical predictions with test results | 16 days |
| 15 | **Task 6.5: Impact of complex stress state effect** | 65 days |