DETAILED PLAN OF ACTION WP10 AND WP11

FORMAT FOR THE TL's

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1 INTRODUCTION

In this report the actions are defined that are needed for work packages 10 and 11 to reach the objectives. The objectives and work description are given in the technical annex and repeated for convenience in this document.

Warning: this report has not been fully updated yet for TG4. It is just intended to serve as an example for the other TL's.

2 DPA FOR WP 10

2.1 Description of work

The typical thick laminate will be defined in terms of material build-up, production cycle and geometric properties (thickness, curvatures). The test plan for this WP will be defined, including specimen dimensions for thin and thick samples. Only flat specimens will be produced and tested in this WP, the analysis however will also involve the effect of curvature.

Flat thin and thick laminates will be produced (under industrial quality) on basis of the laminate definition of Task 10.1 Both types of specimens will be tested in static and fatigue loading in such a way that the thickness effect can be deduced. The specimens will be loaded in 4-point bending and ordinary uni-axial tension and compression and will be monitored by ordinary (surface mounted) strain gauges and embedded optical fibres. The latter will be used for monitoring strains inside the laminate. In contrast to the usual practise in this project, LM will produce the thin test plates, because the delicate optical sensors will be embedded during production. During testing NDT will be performed which results from Task 13.3.

Ordinary thin laminate theory (e.g. the classical laminated plate theory) will be compared to FEM analyses (e.g. 3D elements) for the flat specimens as tested in Task 10.2. For this information will be used from Task 6.3. For both types of analyses the effect of residual stresses will be estimated, based on results from Task 8.3. For the FEM analyses different elements will be used, amongst them brick elements. Surface strain patterns will be compared as well as strains at the inside.

Based on the results of Tasks 10.2 and 10.3 and Tasks 3.3 and 6.3 the accuracy of thin laminate theory will be defined, compared to the more elaborate FEM analyses and the test results.

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

In view of specifications given in aerospace literature, e.g. MIL Handbook 17 which mentions 1/4 inch as limit, most primary structures in wind turbine blades can be regarded as 'thick'.
For large blades, the thickness of <u>blade girder laminates</u> usually exceeds 25 mm UD (plus some ±45°), therefore thick UD should be evaluated. For the 'thin' version the laminate that will be tested in Tasks 1 and 2 is acceptable. The thick laminate would be a scaled version of the thin laminate, with a thickness of approx. 20 mm 0°.
The <u>blade root laminate</u> typically consists of equal fractions UD and ±45° layers. The industrial partners advised against including layers with 90° fibre orientation, since these are either not used or used in minor quantities only. The MD laminate that is typical for the blade root section therefore will be a 25 mm thick $(0/\pm45)_s$ laminate. The 'thin' version could be the 8.06 mm thick $((\pm45,0)_5, \pm45)$ laminate, as mentioned in (*specimen proposal IIb*). It is proposed to have the same basic lay-up for the thick MD laminate: $((\pm45,0)_{25}, \pm45_5)$, although it can be argued that a more alternated lay-up will lead to higher strength (more interface planes between UD and ±45). The reasons for selecting the above lay-up are:

1. it resembles the state-of-the-art of blade production

2. it remains as close as possible to the 'thin' lay-up

The specimen shapes will be kept constant, when going from the thin to the thick specimen. All dimensions will be scaled with the thickness.
For the thick specimen this will result in an approx. net area of 100*25=2500 mm^2; for an expected tensile strength of 800-900 MPa the maximum applied force will be in the order of 2000-2250 kN. This barely allows testing in the largest test machine now available at TU Delft, Uni of Patras or CRES: the 2500 kN test machine of TU Delft.

The cure cycle proposed by T. Jacobsen (LM Glasfiber, SC) consists of a 4 hours post-cure at 80°C. This differs from information given by the other industrial partners, one using lower post-cure temperatures, the other higher. For phase 1 the post-cure cycle will be used of the laminate production (4 hours at 80°C).

During the first phase, a typical component will be characterised (thickness, curvature, lay-up) that will be evaluated using FEM analyses regarding aspects like residual stress. This will be needed as input for phase 2.

2.3 Test Plan

2.3.1 Types of test, instrumentation and reporting

Flat thin and thick laminates will be produced (under industrial quality) on basis of the laminate definition above.
In order to measure the strains, either during the full test (static test) or during the first cycles (fatigue test, to establish the initial strain), all specimens will have either strain gauges or clip gauges, mounted back to back. Half of the thick plates will have embedded fibre optic sensors to monitor the stress state during production. At least two sensors will be embedded per specimen.
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 material needs to be characterised in detail, to allow adequate FEM analysis later. This means static properties of the UD layer, the UD and the MD material.
For the pure UD all results will be achieved following ISO or ASTM standards, compression in a combined loading rig (like the one of Wyoming), see Table 1. The specified laminates (UD and MD) will be tested using the 'standard test specimen' of Optimat Blades, see Table 2 and Table 3. Out-of-plane shear properties will be established by the Iosipescu test method.
Properties will be established based on at least 5, preferably 10, reliable specimens results.

For all UD and MD specimen shapes, strain distributions will be recorded for at least 3 specimens each, to be able to compare to the FEM analyses. The method that will be used for the strain measurement still has to be decided on (e.g. thermoelastic or photoelastic)

In the above mentioned tables, tests that are expected to be done by other TG's are given between brackets. The out-of-plane properties of the pure UD and thin laminates are expected to be established by TG2 also.
It is proposed to the TC that the hygro-thermal properties (thermal and moisture expansion coefficients) of the thick laminates will be established by partners of TG3 also.

2.3.3 Fatigue testing

Fatigue testing will be carried out in order to compare the thin to the thick specimens. This will be limited to the R-values: 10, -1 and 0.1 at life cycle levels of log(N)=3, 4.65 and 6. For each combination of R-value and stress level 5 reliable results are needed.
The tests are given in Table 4; it is assumed that the thin versions of the specimens will be tested in TG1 or TG2.

2.4 Numerical analyses plan

2.4.1 Type of analyses and reporting

Numerical analyses will be performed, using simple computer codes (classical laminated plate theory) and FEM programs. The results of the calculations will be based on measured UD material data and will be compared to experimental results.
The analyses plan describes 4 steps, each partner will report on its activities after completing each step.

2.4.2 Numerical analyses

Material test data will be delivered to the FEM specialists, comprising of in-plane and out-of-plane mechanical data and hygro-thermal data (thermal and moisture expansion coefficients) of the UD layer.

The first step in the analytical assessment will be the prediction of the axial mechanical properties of the thin test coupons (stiffness and strength for the UD and MD laminates). The classical laminated plate theory (CLT, to be done by Uni of Patras) can only predict stiffness and strength of the prismatic cross section (if any); the plate element FEM approach (Patras, ECN) and brick element approach (LM) should give a better prediction of the strain distribution and strength due to coupon shape and clamping force. Higher order shear theories may be needed to cope with the complex stress state at the specimen free edge. These predictions will be compared to in-plane and out-of-plane mechanical properties. Different failure criteria will be used to predict the strength of the specimen, including post-first-ply behaviour.
Secondly, the bending test specimen will be modelled and predictions of stiffness, strain distribution and strength will be compared to the measurement data.

In the next steps, a similar assessment of the thick specimen will be accomplished.
Because of the large thickness, residual stresses can be expected to result from the cure cycle. For this reason the residual stresses will be monitored using embedded fibre optic strain sensors in some of the specimens during the plate production and cutting to shape. Based on the cure cycle environment (especially temperature) residual stresses should be predicted with the FEM packages (and CLT).
In step 4, the thick laminate specimen properties will be predicted and will be compared to the 'thick laminate" testing of UD and MD.

2.5 Evaluation

Based on the results of Tasks 10.2 and 10.3 and Tasks 3.3 and 6.3 the accuracy of thin laminate theory will be defined, compared to the more elaborate FEM analyses and the test results.

3 DPA FOR WP11

3.1 Description of work

The location, type and importance of damaged zones will be defined by the industrial partners. Defects encountered during production like dry spots and web to skin delaminations will need different repair techniques than those caused by lightning strikes or impact. Repair techniques will be surveyed and evaluated on aspects like costs, complexity, and suitability to large thickness and to application on site. The most-promising techniques will be selected. The minimum target value for the repair efficiency will be stated (e.g. 90% of the baseline strength). The industrial partners, LM, Polymarin and Gamesa will provide input on location and extend of defects and possible repair techniques based on their practical experience, which will be aided by the research background from CRES.

The typical repair procedure can be characterised as:
1. (inspection and decision that part will be repaired instead of replaced)
2. removal of damaged zone (slope may range from 1:50 to 1:100)
3. prepare the area for bonding
4. laminate the repair patch, or laminate layers to the desired thickness (cure cycle !)
5. inspection of repair
(For dry spots, resin injection may be an alternative.)

Small specimens will be produced with and without typical flaws and inspected using the techniques given in Task 13.3. The flawed specimens will be repaired inspected before and after repair. Different repair techniques (typically 3) will be applied. As a baseline, the flaw-less specimens will be tested either by bending or uni-axial tension or compression loading. The repaired specimens will be tested by the same method. The industrial partners will produce the test specimens, to be tested by CRES and TUDT, with CCLRC assisting in NDT.

The results of the repair techniques on the small specimens will be compared to the baseline on the aspects mentioned in Task 11.1 and measured strength and stiffness. The most-promising repair method(s) will be selected. In view of the present uncertainties on repair efficiency, it is not clear whether repair of a large-scale component is useful.
Based on the results achieved in this WP, a go/no-go decision will be made on the continuation for a large component (Task 12.5) by all partners.

3.1.1 Modifications to the annex

There are no modifications to the description as given in Annex I of the contract.

3.2 Laminate and specimen definition

Repair in the workshop of 'flaws' found during/after production is regarded as the most probable situation, according to the industrial partners. Repair at the site is regarded to be less probable, although it will offer more room for improvement.

The following types of defects to be repaired are: delaminations, severe fibre misalignment (wrinkle, fold) and dry spots, and cracks in the third place. Damage due to lightning, although this may become more important for offshore wind turbine blades, can be characterised as large-scale delamination and is therefore less suited to be tested by relatively small specimens. The locations of the defects are limited to parts of the primary structure, e.g. the girder part of the blade, not the foam sandwich.

Since the major concern is the strength bearing part, the laminate choice is the MD laminate (8.06 mm thick $((\pm 45,0)_5, \pm 45)$). The specimen has straight edges, to rule out evaluation complications when using dogbone shapes. Different repair configurations will be investigated, among the parameters varied are: depth of damage (halfway or full thickness), slope of cut-away material (1:50 or 1:100).
For practical reasons most tests on repaired specimens will be on 'thin' (typically 5 mm) specimens, at the end of phase 1 a limited number of thick MD specimens will be prepared and tested. Due to the area needed for repair, the specimen free length will be much larger than is used for the standard specimen: 500 to 1000 mm.

3.3 Test Plan

3.3.1 Types of test, instrumentation and reporting

Before and after repair, NDI will be applied to establish the damage (zone, depth) and the quality of the repair. This NDI can be simple (visual, coin tapping), but can also be more complicated (A- or C-scan, thermography).

3.3.2 Static Tests

In view of the different specimen shape, the baseline tests on flawless specimens, have to be repeated here, even though the results may be comparable to those of WP10. In view of the large length, compression tests are not expected to be feasible due to buckling. The application of anti-buckling devices is questionable for the repaired specimens.
For every repair configuration, five specimens will be tested per property. Repaired specimens will be tested in axial static tension loading and in 4 point bending (repaired part in tension or in compression loading).
For the most-promising repair configurations, similar repair will be accomplished the thick MD specimens (part-thickness flaw), which will be tested in axial and 4 point bending. For the same configurations, a fatigue test program will be accomplished in axial loading for both the thin and thick specimen.
The tests are given in Table 5 and Table 6.

The distribution of tests over the partners is shown tentatively in Table 5 as an example for the other TLs.

3.3.3 Fatigue tests

Text to follow

3.4 Evaluation

The results of the repair techniques on the small specimens will be compared to the baseline on the aspects mentioned in Task 11.1 and measured strength and stiffness. The most-promising repair method(s) will be selected. In view of the present uncertainties on repair efficiency, it is not clear whether repair of a large-scale component is useful.
Based on the results achieved in this WP, a go/no-go decision will be made on the continuation for a large component (Task 12.5) by all partners.

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										±45° (shear/tubes)										Remarks
Axial (//)	T																																
	C																																
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%																															

NB: distribution over the partners tentatively as an example for the other TLs. Numbers in gray 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																																5 at 10%/s and 5 at ISO speed
	C																																
Transverse (⊥)	T																																
	C																																
Thickness	C			5																													
Shear	IPS																																
	13			5																													
	23			5																													
4 Point Bending											5										5												
Shear	IPS	40°/-60°/100%																															
Hygro Thermal	α_1							3										3															
	α_2							3										3															
	β_1							3										3															
	β_2							3										3															

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										±45° (shear/tubes)										Remarks
2D test specimens [2]																																	
2D stress state		Cruciform																															3 layer
		Tubes																															
Long test specimens as reference for repaired specimens [4]																																	
Axial (//)	T-T																		5														
Bending	T up																		5														
	C up																		5														
Repaired test specimens [4]																																	
Axial (//)	T																																
(long spec.)														30					60														
Bending	T up													30					60														
(long spec.)	C up													30					60														
Thick test specimens [4]																																	
Axial (//)	T			5										5										5									
	C			5										5																			
Transverse (⊥)	T			5										5																			
	C			5										5																			
Thickness	C			5										5																			
	Shear			10										10																			
Bending	T up			5																													
	C up			5																													
Hygro Thermal	α_1			5										5																			
	α_2			5										5																			
	β_1			5										5																			
	β_2			5										5																			
Repaired thick test specimens [4]																																	
Axial (//)	T			5																													
Bending	T up			5																													
	C up			5																													

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												Riso standard
	0.5																																
	-0.4																																
	-1										15										15												add tests at low freq.???
	-2.5																																
	10										15										15												
	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%																															
2D test specimens [2]																																	
2D Stress state	0.1	Cruciform																															3 layer
	-1	Tube																															
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													15										15									
	-1													15										15									
	10													15										15									
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	**MANAGEMENT AND STEERING**	**328 days**
2	**PROJECT KICK-OFF**	0 days
3	Task 2.3: Proposal for reference material	5 mons
4	Task 1.2: Approval of reference material	2 wks
5	Task 2.4: Reporting detailed Plan of Action for phase 1	2 wks
6	Task 1.3: Approval of Detailed Plan of Action for phase 1	2 wks
7	**FIRST ASSESSMENT**	0 days
8	**WP10: COMPARISON OF THIN AND THICK PLATE PROPERTIES**	**563.4 days**
9	Task 10.1: DPA - Laminate definition and test plan	5 mons
10	**Task 10.2: Production and test of thin and thick laminates**	**367.4 days**
11	production of thick specimens	3 mons
12	static testing thin and thick	3 mons
13	fatigue testing thick	10.7 mons
14	**Task 10.3: Theoretical assessment**	**367.4 days**
15	generation of UD properties	3 mons
16	prediction thin axial secimen properties	2 mons
17	prediction thin bending secimen properties	4 mons
18	prediction of residual stresses thick spec.	2 mons
19	prediction thick specimen properties	5.7 mons
20	Task 10.4: Intermediate evaluation	3 mons
21	**WP11: REPAIR OF HIGH-LOADED FLAT BLADE PARTS**	**563.4 days**
22	Task 11.1: DPA - Identification of repair zones and techniques	5 mons
23	**Task 11.2: Production and test of flawed small specimens**	**367.4 days**
24	production of specimens	2 mons
25	static test of flawless specimens	2 mons
26	fatigue test of flawless specimens	10 mons
27	NDI defect specimens	1 mon
28	repair of defect specimens	4 mons
29	NDI of repaired specimens	1 mon
30	static test of repaired specimens	2 mons
31	selection of most-promising repair techniques	1 mon
32	production of repaired specimens	2 mons
33	fatigue test of repaired specimens	3.7 mons
34	Task 11.3: Evaluation of the repair techniques	3 mons