Adjusted Detailed Plan of Action for Task Group 4 after MTA
WP10, 11 and 12

OB_TG4_R009
Rev. 004

Confidential

OPTIMAT BLADES

TG 4

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CHANGE RECORD

Issue/revision	date	pages	Summary of changes
0	1-3-05	all	new document
1	1-5-05	all	Small error corrections
2	31-6-05	11,12 27	Clearer definitions of test set-up and thick specimens Updated thin repair geometries by LM
3	4-7-05	11,12	Test specimens S07 and S09 reduced to 1980 mm length
4	8-7-05	11,12	Text slightly adjusted
5	19-9-05	11 22	Text adjusted for bearing strength plates. Test

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1. INTRODUCTION

In this report the actions are defined that are needed for Work Packages 10, 11 and 12 to reach the objectives. The objectives and work description are given in the technical annex and repeated for convenience in this document.

This report replaces OB_TG4_R001.

A number of major changes in the work of TG4 (WP 10,11,12) have occurred, as will be outlined in this report.
The most important changes to the original DPA as outlined in OB_TG4_R001 are:

- The original work of WP10 is based on the establishment of material properties in thickness direction and comparison between FE work and tests. However, the material properties in thickness direction are not used by most industry partners. Furthermore, solid elements for laminates are poorly supported in FE packages. Therefore, the original aim of WP 10 of establishing properties in thickness direction and verification between FE analyses and tests had to be deserted.
- Due to major delays, the extra work to be done in WP12 on thick, curved and repaired parts will be skipped.

1.1. Estimated number of specimens

Based on the test plans given in this document, the claimed number of specimens can be summarised from the test tables at the end of this DPA.

2. DESCRIPTIONS IN DoW

As stated in the introduction, the work to be done in TG4 is changed quite significantly. This can be seen in the allocated PMs per partner in 2.1. For the completeness of this DPA the work package descriptions, as well as deliverables and milestones for the relevant WPs are given in 0 to 2.3.

2.1. PM overview original and current DoW

Original DoW	WP10	WP11	WP12	Total
ECN	7		2	9
WMC	8	4	8	20
CCLRC	1	1	1	3
CRES		5	4	9
UP	8			8
LMG	2	3	3	7
Polymarin		3	3	6
Gamesa		3	3	6
Total	26	19	24	69

New DoW	WP10	WP11	WP12	Total
ECN	7			7
WMC	7	5	3	15
CCLRC	1			1
CRES		8	2	9
UP	3			3
LM	2	3	2	7
Polymarin		3		3
Gamesa		5		5
Total	19	24	7	50

NB: rounded of to full PMs, summations calculated from slightly more accurate PMs.

- Due to a reduction in the programme, the number of PMs for WP10 and WP12 has been reduced by almost 50%.
- The larger number of repair variations investigated plus the extra work done on specimens from Polymarin for WP11 has meant an increase in the PMs for WP11.

Description of WP10

Work package No : **WP 10**		Start month: **1**		End month: **26**				
Work package title:	**COMPARISON OF THIN AND THICK PLATE PROPERTIES**							
	Work package leader:	WMC						
Participant:	ECN	WMC	CCLRC	UP	LM			
Person-months per participant:	7.4	7.0	0.5	3.0	1.5			

Objectives:

To establish the accuracy of thin-walled theory by comparison to finite element calculations and test results for thin and thick flat plates.

Description of work:

Task 10.1: DPA - Laminate definition and test plan
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. WMC, with input from industrial partners. *Finished*

Task 10.2: Production and test of thin and thick laminates
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 uni-axial tension 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. LM will produce the thin test plates, because the delicate optical sensors will be embedded during production. LM produces the laminates, whereas tests are carried out by WMC and UP

Task 10.3: Theoretical assessment
Ordinary thin laminate theory (e.g. the classical laminated plate theory) will be compared to FEM analyses for the flat specimens as tested in Task 10.2. Surface strain patterns will be compared as well as strains at the inside. ECN and UP carry out FEM analyses. *Finished*

Task 10.4: Intermediate 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.

By all partners.

Deliverables:

4 Definition report of typical thick laminate
23 Evaluation on the effect of thick laminate

Milestones and expected results:

M6 DPA on thick laminates and laminate definition
M14 Evaluated thickness influence

2.2. Description of WP11

Work package No : **WP 11**		Start month: **1**		End month: **26**			
Work package title:	**REPAIR OF HIGH-LOADED FLAT BLADE PARTS**						
	Work package leader:	WMC					
Participant:	WMC	CRES	LM	Polymarin	Gamesa		
Person-months per participant:	5.0	7.5	3.2	3.0	5.0		

Objectives:
To implement suitable repair methods that will bring back functionality and strength to the blades by benchmarking and verification on small components.

Description of work:

Task 11.1: DPA - Identification of repair zones and techniques
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, 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. *Finished*

Task 11.2: Production and test of flawed small specimens
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 by uni-axial tension. The repaired specimens will be tested by the same method. The industrial partners will produce the test specimens, to be tested by CRES and WMC.

Task 11.3: Evaluation of the repair techniques
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.

Deliverables:
5 Suitable repair techniques for small specimens
13 Evaluation of repair techniques as used for small specimens (report)

Milestones and expected results:
M7 DPA on repair locations and techniques
M15 Go/no-go decision repair of curved components

2.3. Description of WP12

Work package No : **WP 12**	Start month: **27**		End month: **43**					
Work package title:	**PROPERTIES OF REPAIRED THICK LAMINATES**							
	Work package leader:	WMC						
Participant:	WMC	CRES	LM					
Person-months per participant:	3.0	1.5	2.0					

Objectives:
To validate the repair properties for thick laminates as used in large blade components.

Description of work:

Task 12.1: DPA - Sub component definition
The results achieved for relatively small, flat specimens cannot be translated directly to large, curved components. A thick walled test specimen will be defined in terms of geometry, material choice and lay-up and production cycle.

Task 12.2: Sub component design and production
During production optical fibres may be embedded in the components in order to monitor the strains during production and afterwards (residual stresses). These sensors will also be used in Task 12.3 for the internal strains. LM will fabricate the test specimen, to be tested at WMC.

Task 12.3: Static test of components
The components will be tested in static tensile loading. Global (e.g. actuator displacements) and local (using e.g. surface mounted strain gauges and embedded optical fibres) properties will be measured. The tests are carried out by WMC.

Task 12.4: Evaluation
The results of Task 12.3 (stresses, strains, deflections, strength) will be compared to the measured values of WP10 and WP11. From this the influence of residual stresses on thick laminates and multi-axial loading will be highlighted. By all partners, but larger role for CRES

Deliverables:

38 Interaction effects between thick and repairs

Milestones and expected results:

M19 DPA on repaired thick components
M28 Finalisation of activities on thickness influence
M29 Finalisation of activities on repair

3. GENERAL DESCRIPTION OF WORK

3.1. Description of work

The typical thick laminate has been defined in terms of material build-up, production cycle and geometric properties (thickness, curvatures).

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 uni-axial tension and compression where possible and will be monitored by ordinary (surface mounted) strain gauges and both bonded 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.

The experimental comparison between thin and thick laminates, will tell whether any significant difference in static and fatigue strength exists. The results will be complemented by residual strain measurements from the embedded fibres, which, if measurements of the experimental system are successful, may shed light on the induced strains during the hardening process.

Modifications to the original DoW

Fairly elaborate changes has been made, due to time constraints as well as changes of insight gained during the project as to the relevance of various tasks:

- The FE predictions of residual stresses due to fabrication will be skipped due to lack of material properties.
- The tests in 3-direction are no longer functional, as they would mainly be used as input for the FE analyses. Should they have been necessary, LM was both willing and capable of producing a brick of 150 mm thickness, from which the standard OPTIMAT and Iosipescu test specimens could be cut.
- The use of optical fibres is dependent on technical possibilities at WMC.

Modifications to the new DoW

The updated DPA is fully in agreement with the new DoW as outlined in the MTA report and chapter 2.1 to 2.3.

3.2. 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 blade girder laminates 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: a 4 mm nominal thick UD laminate. The thick laminate would be a scaled version of the thin laminate, with a thickness of approx. 20 mm 0°.
The blade root laminate 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 32 mm thick $(0/\pm45)_s$ laminate. The 'thin' version could be the 6.4 mm thick $((\pm45,0)_4, \pm45)$ laminate, as mentioned in earlier documents. It is proposed to

have the same basic lay-up for the thick MD laminate and same UD thickness as for the UD specimen: $((\pm45_5,0_5)_4, \pm45_5)$.

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 UD specimen this will result in an approx. net area of 100*20=2000 mm^2; for an expected tensile strength of 800-900 MPa the maximum applied force will be in the order of 1600-1800 kN. This only allows testing in the largest test machine available to the OPTIMAT partners: the 2500 kN test machine of WMC.

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).

3.3. Test set-up for thick specimens

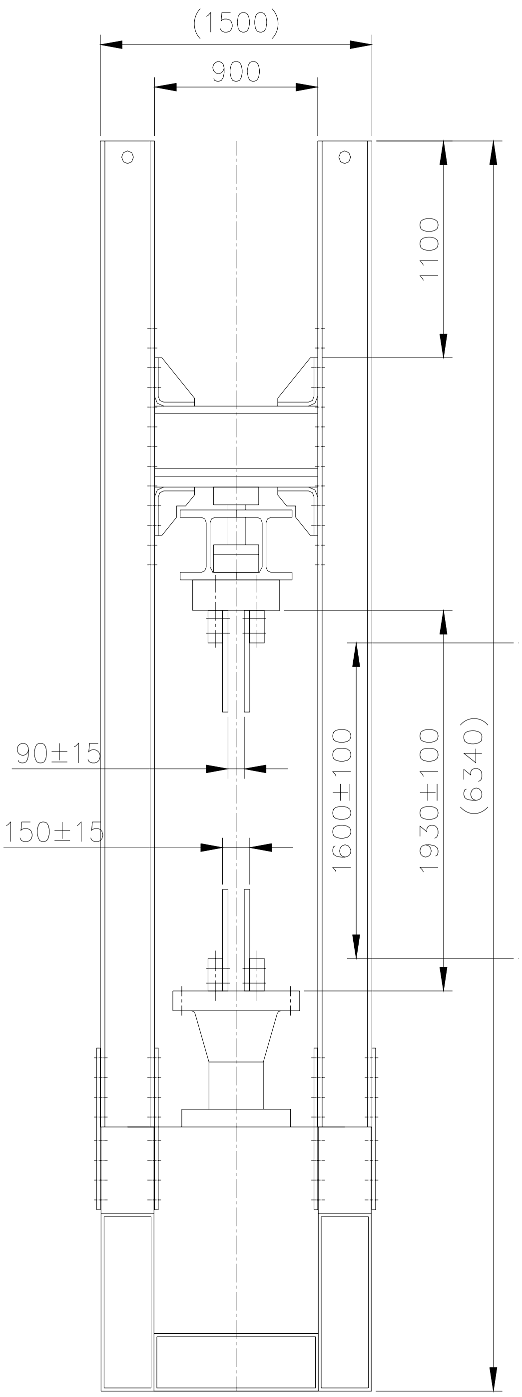


Figure 1 Test set-up for the thick laminate specimens

For the thick specimens of WP10 and WP12, the only available test machine within the OPTIMAT consortium is the 2500 kN test machine (actually 3300 kN static and 2500 kN fatigue, both in tension and compression).
Due to the necessity of force introduction by bolts through the specimen, a free length of 900 mm remains from the middle position of the actuator (+ or – 100 mm actuator movement).

For 32 mm total thickness, we need a scarf length of 550 for a repair depth of 1/3 of the thickness and even 1100 mm for a repair depth of 2/3 of the thickness and even + extra length for a proper load introduction.

M30: $A_{b;s}$=561 mm^2. $F_p=k_p \cdot f_{t;b;rep} \cdot A_{b;s}$ = 0.7·1000·561=393 kN. For 12.9 bolts: 471 kN.

Assuming (!) a friction coefficient of 0.3 between steel and the glass-fibre epoxy at each side of the specimen yields a shear force of 283 kN, requiring about 9 12.9 M30 bolts for a proper load introduction. Using a shear load, an M30 10.9 bolt can take about 2*339=678 kN, so just 4 bolts could transfer the whole load. The two connecting 25 mm plates of ordinary S235 steel can take a bearing force of 540 kN per per M30 bolt, enough for 6 M30 bolts.

The specimen itself, though 90 mm thick, may fail earlier on. Since the steel plates have a lot of reserve, we can use a smaller bolts spacing perpendicular to the force, namely 2.4 d_g between the bolts and 1.2 d_g at the sides, for a total width of 4.8 d_g.

For M30, the hole size d_g is about 33 mm, resulting in a width of 158 mm (still more than the available 140 mm). The plate bearing strength is than reduced to 2·0.67·360·30·25=362 kN for 25 mm thick plate per M30 bolt, not quite enough for 6 M30 bolts, requiring slightly thicker plates. It looks possible to squeeze two rows of bolts into 140 mm, without the bearing force of the plate dipping too much below the shear strength of the bolts. The length of the plates is determined by the 4 bolt rows and end distance, $1.2 \cdot d_g + 3 \cdot 2.2 \cdot d_g + 1.2 \cdot d_g = 9.0 \cdot d_g$=297 mm. The tab length could then be 300 mm as well.

Allowing a square area between load introduction and scarf yields a total specimen length of 2·300+2·140+ 1100 =1980 mm, say 2 m. Obviously, for 1/3 repair depth, the repair length with be 550 mm, rather than 1100, resulting in shorter, more convenient, test specimens. On the other hand, the thin specimens tested so far, showed about 25% reduction in strength compared to the reference specimens, so repairing 1/3 of the thickness is almost pointless as the gained strength would probably be below 10%. Therefore, WMC and LM have decided to opt for 2/3 repair thickness and thus the test specimens are 1980 mm long, shown below, even though this required an extension of 600 mm to the WMC test machine, to accommodate the longer 2/3 depth repair test specimens.

The standard OPTIMAT MD coupons have a width of 25 mm and a thickness of 6.57 mm. The static tensile strength was about 90 kN, resulting in about 140·32.85/25·6.57=2520 kN, very close to the capacity of the test machine. The space between the plates is about 90 mm, so the tabs would be about 30 mm thick, so they could simply be produced from the same material as the main part of the test specimen.

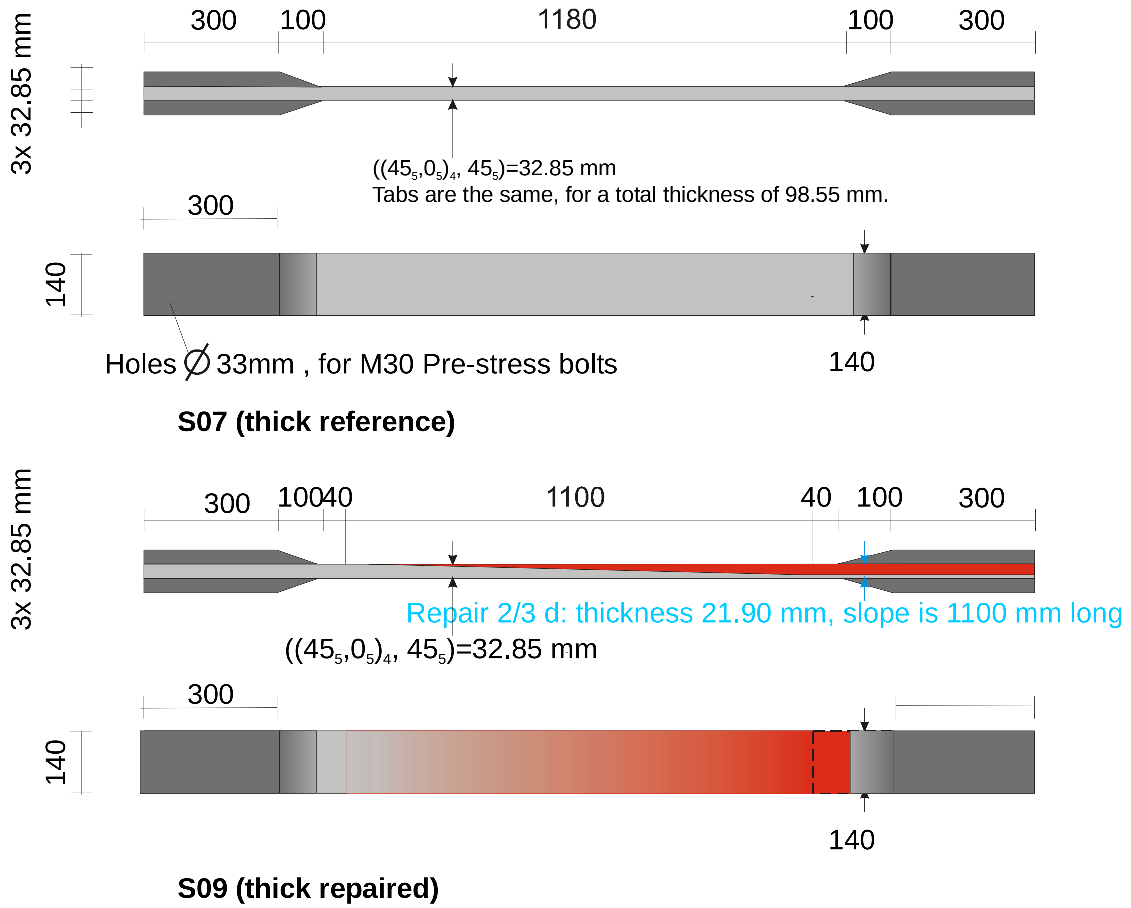
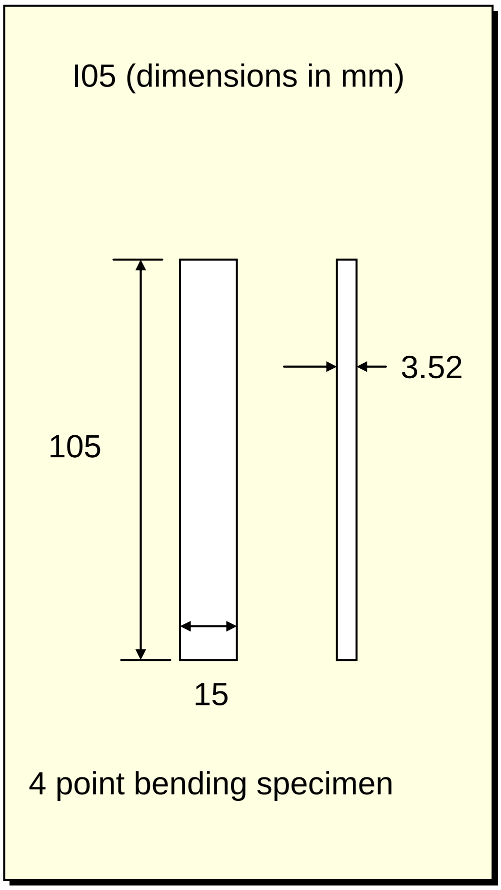
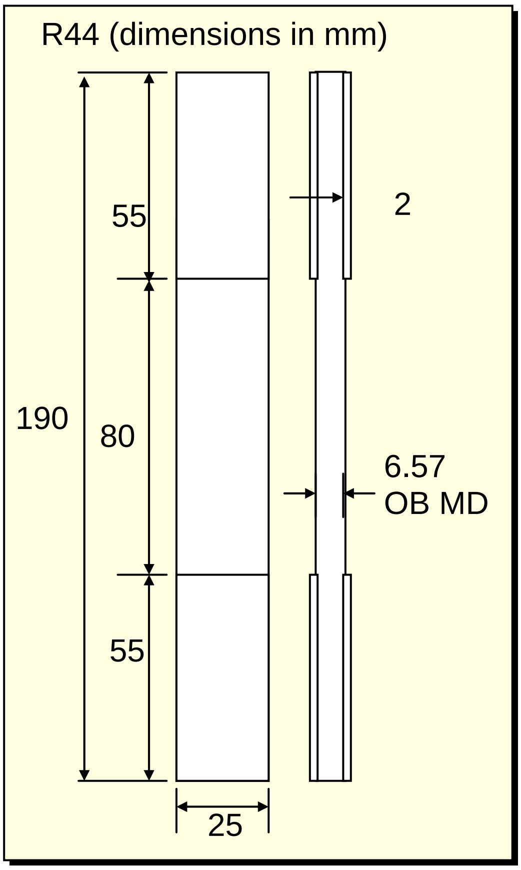


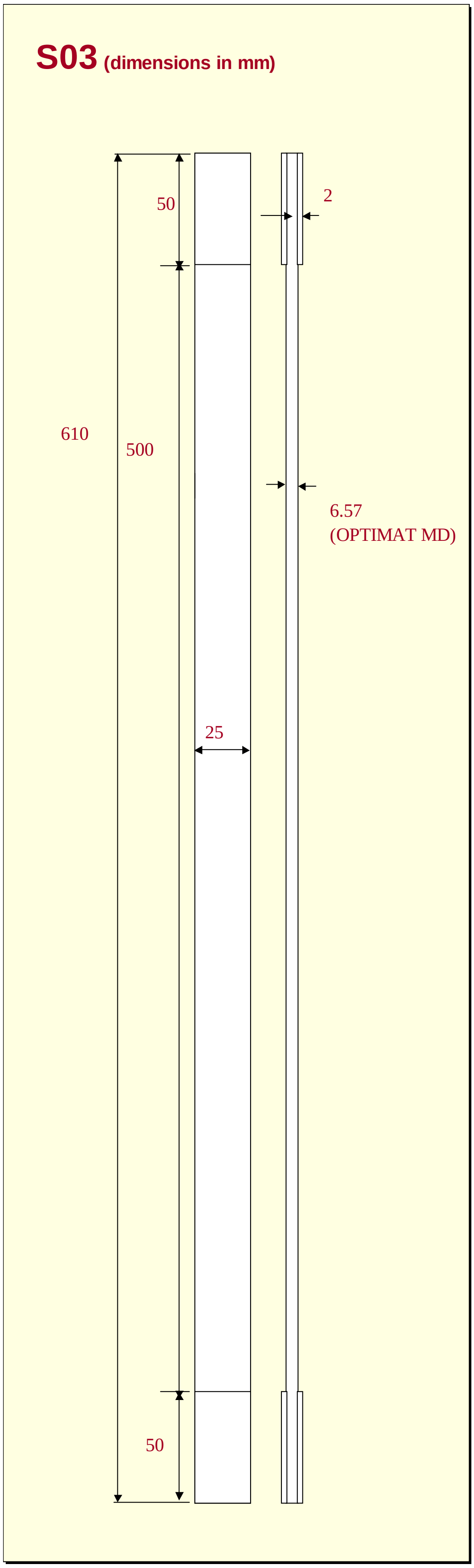
Figure 2 Thick test specimens S07 (reference) and S09 (repaired) for a 1980 mm specimens

The repaired specimens type S09 for 2/3 d as shown above have a repair depth of 21.90 mm and a slope length of 1100 mm. The total length of the test specimen is 1980 mm.
The bolt pattern with 6 M 30 bolts is based on the old test specimen definition, which had a length of 2180 mm (as shown for the S09 specimen).
Should 6 bolts prove insufficient than an reduced bolt distance 8 bolt configuration could be tried, as shown for the S07 specimen. The latter option requires new steel plates for the WMC test machine.

3.4. Other test specimens used within TG4







4. TEST PLAN FOR WP10

4.1. 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. Depending on the technical possibilities WMC will use optical fibre measurements. In that case, a number of the thick plates, intended for in-plane static testing, will have embedded fibre optic sensors to monitor the stress state during production. At least two sensors will be embedded per specimen. In this way half of the thick specimens, intended for in-plane static testing will have optical fibre sensors.

All thick laminate tests can only be executed in the WMC laboratory, due to test machine capacity. Mounting of specimens in the 2500 kN test rig, however, is more labour intensive compared to smaller machines. The fatigue test frequency will be low (around 1 Hz). For this reason the amount of tests was kept limited and some re-shuffling of MM between UP and WMC has taken place, where WMC concentrates more on TG4 and UP concentrates on TG2.

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.

Tests with optical fibres

In case WMC has a good functioning OF measurement system, It is expected that up to 20 specimens (in WP10 and WP12) will be monitored with optical sensors. In that case, 20 embedded sensors will be needed, as well as 20 temperature sensors (necessary for compensating the measurements for temperature effects) and 20 bonded sensors. Typically, a test specimen would have one temperature sensor and 2 bonded or laminated sensors. A few tests may be carried out at elevated temperatures and/or higher humidity.

4.2. Static testing

Since no interest is apparent in testing the properties in thickness direction, the originally planned tests in thickness direction will not be performed. Test are carried out in tension and compression, in 0° and 90°, MD and UD.

Number of thin specimens for static tests

The reference tests on thin specimens have already been carried out:

- The determination of strength properties in 11T and 11C directions has been established in TG3, just like the Iosipescu shear tests.
- The determination of transverse fibre and shear properties for thin laminates has been established within TG2.
- Flexural tests in 4-point bending (ISO 14125) to be established by WMC (*partly done*).
- Thermal expansion coefficients for UD material and thin MD laminate (e.g. using ISO 11359) is established in TG2.

Therefore: no static tests on thin laminates are currently foreseen, unless the optical fibre measurement system is employed (see Chapter 0).

Number of thin specimens for use of optical fibres in static tests

NB: the tests mentioned here are only carried out if a good optical fibre measurement system is available.

In case the optical fibres are used, 8 additional static tests will be performed on standard OPTIMAT specimens like type R0400.
Depending on the optical fibre system selected, it is possible that these specimens will have to be twice as long in order to accommodate the optical fibres.
The specimen geometry is tentatively called R4400. It may be that this ends up being standard R0400 specimens in case the optical fibre length is small enough.

In this case:

- 2 extra static test on MD 0° tension are foreseen under ambient conditions.
- 2 extra static test on MD 0° tension are foreseen under hot/wet conditions.
- 2 extra static test on MD 0° compression are foreseen under ambient conditions*.
- 2 extra static test on MD 0° compression are foreseen under hot/wet conditions*.

*NB: The compression tests will not be carried out if the gauge length requires longer specimens, since buckling will then impede static compression tests. However, even in that case tests to a lower level of compression are still possible.

Number of thick specimens for static tests

- Properties will be established based on preferably 5, reliable specimen results.
- Tests will be carried out <u>only</u> for MD <u>not</u> for UD.
- Tests will be carried out <u>only</u> for 0° (11-direction) but <u>not</u> at 90° (22-direction)
- Only in tension <u>not</u> in compression

Altogether 5·1·1·1= 5 total thick MD 0° specimens to be tested.

In case the optical fibre system is used: 2 of the specimens (MD 0° in tension) will be outfitted with optical fibres, but no additional tests will be carried out.

4.3. Fatigue testing

Fatigue testing will be carried out in order to compare the thin to the thick specimens. Tests will only be carried out for 0° UD and MD material for R=-1 and R=0.1, for a nominal fatigue life of 50.000 and 1.000.000 cycles.
In case the optical fibres are employed, a limited number of additional tests at 10^7 cycles may also be carried out.

Number of thin specimens for fatigue tests

No thin specimens will be tested, since this work has already been carried out in other WPs, unless optical fibres are used(see Chapter 0).

Number of thin specimens for use of optical fibres in fatigue tests

In case the optical fibres are used, additional static tests will be performed on standard OPTIMAT specimens R4400. Depending on the optical fibre system selected, it is possible that these specimens will have to be twice as long in order to accommodate the optical fibres.

In this case, up to 10 R4400 specimens will be tested in fatigue:

- 3 extra fatigue tests at R=0.1 are foreseen at N=50.000, N=10^6 and N=10^7 cycles respectively under ambient conditions.
- 3 extra fatigue tests at R=0.1 are foreseen at N=50.000, N=10^6 and N=10^7 cycles respectively under hot/wet conditions.
- 2 extra fatigue tests at R=-1 are foreseen at N=50.000 and N=10^7 under ambient conditions*
- 2 extra fatigue tests at R=-1 are foreseen at N=50.000 and N=10^7 under hot/wet conditions*

*NB: The fatigue tests at R=-1 will not be carried out if the gauge length requires longer specimens, since buckling will then impede the compression part of the load cycle.
However, even in that case, a few initial cycles at a lower level are still possible.

Number of thick specimens for fatigue tests

For the thick specimens, only 1 R-value will be evaluated (R = 0.1) at the level aimed at 50.000 and 1.000.000 cycles, conform OB_TC_R014 rev.3:

- F_{max}=5·2.23 kN/mm width (for 5 times the thickness and width of standard OPTIMAT R04 specimens: F ranges from 139.4 kN to 1394 kN) for a nominal life of 5000 cycles.
- F_{max}=5·1.31 kN/mm width (for 5 times the thickness and width of standard OPTIMAT R04 specimens: F ranges from 81.9 kN to 819 kN) for a nominal life of 1000000 cycles.

For each combination of R-value and stress level 5 reliable results are needed.
Thus, a total of 5·1·2= 10 0° thick MD specimens are required.

For the thick laminates, fatigue testing of 5 specimens at (average) 1 million cycles, 1 Hz 58 days running time, or about 2.5 months through-put time.

In case the optical fibre system is used: 4 of the specimens will be outfitted with optical fibres and tested at 50.000 and 1.000.000 cycles.

4.4. Numerical analyses plan

Numerical analyses have been performed, using simple computer codes (classical laminated plate theory) and FEM programs.

The first step in the analytical assessment is 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) can incorporate stress distributions across the surface as well. The brick elements to be used by LM have been discarded due to the pressure on LM to produce the much larger than anticipated amount of test specimens. *Done.*

4.5. Evaluation

Based on the comparison between mechanical behaviour of thin and thick test specimens, the effect of laminate thickness can be assessed.

5. DPA FOR WP11

5.1. 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. *Done.*

Small specimens will be produced both complete and with scarf and plug and patch repair zones. 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 LM and GAMESA will produce the test specimens, to be tested by WMC and CRES respectively.

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 for fatigue testing.

5.2. Background to repair techniques

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 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 1:25 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.)

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.

5.3. Laminate and specimen definition

Since the major concern is the strength bearing part, the laminate choice is the MD laminate (6.57 mm thick $((\pm 45,0)_4, \pm 45)$). 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 (1/3 or 2/3 of thickness), slope of cut-away material (1:25 to 1:100).

Gamesa will also manufacture specimens with prepregs repairs, plug and patch and extra tape over the repair.

The present configuration of the specimen lay-out is given in the following sketch.

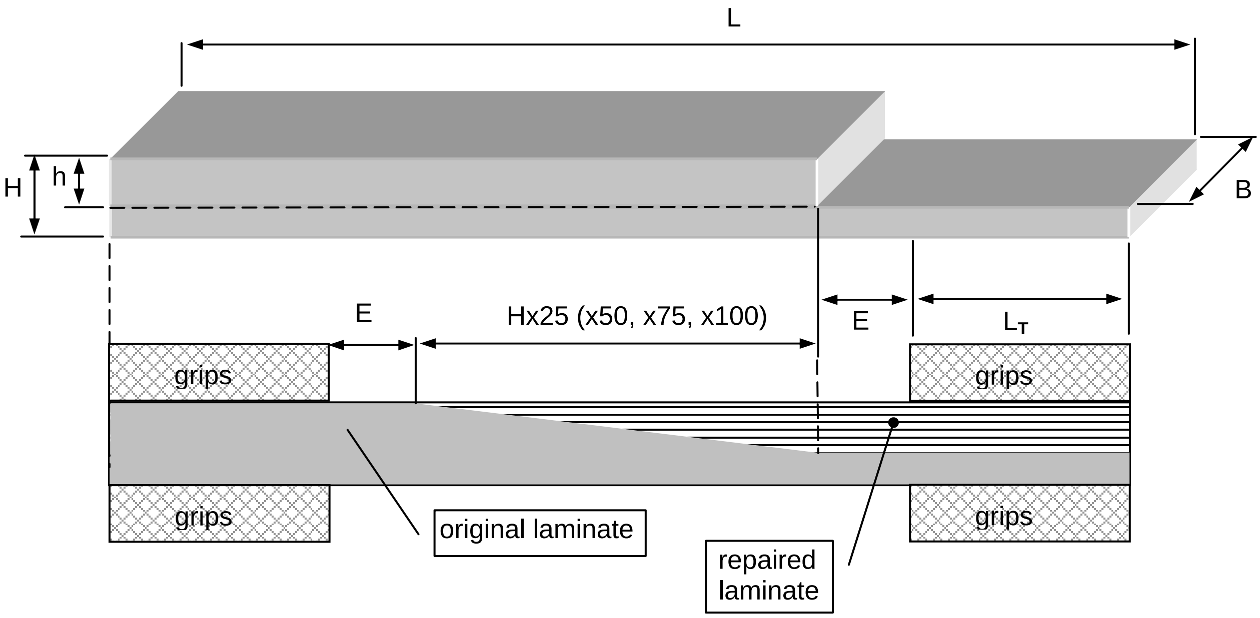


Figure 3 Repaired specimen

The initial defect is modelled as a channel, machined away from the specimen. Nominal dimensions are: thickness H=6.57 mm, width B=25 mm. Two channel depth to thickness ratios will be investigated: h/H=1/3 and 2/3.

5.4. Test Plan

Types of test, instrumentation and reporting

Specimens will be tested in axial tension only.

Static Tests

In view of the different specimen shape, baseline tests on specimens with the correct length, have to be repeated. In view of the large length, compression tests are not feasible due to buckling.
For every repair configuration, 5 specimens will be tested per repair variant. All repaired specimens will be tested in axial static tension loading.

For the static tests schedule, each industrial partner will apply a number of repair variants (slope or method) for both depth/thickness ratios. For each variant 5 specimens are to be tested. For instance in case of four repair variants, each with two depth/thickness ratios, this means (5 specimens * 4 * 2 =) 40 repaired axial specimens.

As a reference, 5 un-defected specimens will be tested per partner and per test type. CRES will test specimens manufactured by GAMESA and WMC will test specimens manufactured by LM.

Fatigue tests

The fatigue tests will only be accomplished on thin specimens with the most-promising repair method. The test plan is limited to axial tension-tension fatigue only, due to the slenderness of the long specimens, which are prone to buckling. This test program is carried by both CRES for the specimens from GAMESA and by WMC for the specimens from LM, since WMC will also carry out the thick specimen tests from LM for WP10, as well as thick repaired specimens for WP12.

15 specimens are foreseen: R=0.1 at 3 levels, conform OB_TC_R014 rev.3 for repair depth of 1/3 and 2/3 of the plate thickness:

- F_{max}=2.23 kN/mm width (for 25 mm width: F ranges from 5.58 kN to 55.75 kN) for a nominal life of 5000 cycles.
- F_{max}=1.77 kN/mm width (for 25 mm width: F ranges from 4.43 kN to 44.25 kN) for a nominal life of 50000 cycles.
- F_{max}=1.31 kN/mm width (for 25 mm width: F ranges from 3.28 kN to 32.75 kN) for a nominal life of 1000000 cycles.

5.5. 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 per manufacturer will be selected.

6. DPA FOR WP 12

6.1. Description of work

WP12 complements the work of WP10 (influence of laminate thickness) and WP11 (influence of repairs) by testing a number of repaired thick specimens.

For practical reasons the tests in WP11 on repaired specimens will be on 'thin' specimens. For the best repair method, repair will be accomplished on thick MD specimens, to be tested in axial loading. The test machine of WMC will be modified to accommodate the long test specimens, see 3.3, enabling the selected slope for WP11(1:50), in combination with the repair of 2/3 thickness will be tested.

Number of repaired thick specimens for static tests

- Properties will be established based on preferably 5 reliable specimen results.
- Tests will be carried out only for MD, repaired with the best repair method found in WP11.
- Tests will be carried out only for 0° (11-direction)
- Only in tension. Not in compression

Altogether 5·1·1·1= 5 total thick MD 0° specimens to be tested.

Number of thick specimens for fatigue tests

For the thick specimens, only 1 R-value will be evaluated (R = 0.1) at the level aimed at 50.000 and 1.000.000 cycles, conform OB_TC_R014 rev.3:

- F_{max}=5·2.23 kN/mm width (for 5 times the thickness and width of standard OPTIMAT R04 specimens: F ranges from 139.4 kN to 1394 kN) for a nominal life of 5000 cycles.
- F_{max}=5·1.31 kN/mm width (for 5 times the thickness and width of standard OPTIMAT R04 specimens: F ranges from 81.9 kN to 819 kN) for a nominal life of 1000000 cycles.

:

For each combination of R-value and stress level 5 reliable results are needed.
Thus, a total of 5·1·2= 10 0° repaired MD specimens are required.

For the thick laminates, fatigue testing of 5 specimens at (average) 1 million cycles, 1 Hz 58 days running time, or about 2.5 months through-put time.

7. OVERVIEW OF TEST SPECIMENS FOR WP10, 11 AND 12

7.1. Overview of TG4 tests

No of tests	Specimen type	Test type	Producer	Produced	Test Lab	Finished	Remarks
WP10							
5	I05	Static 4-P bending	LM	Yes	WMC	Yes	
0/5/10	*R44*	*Static test w. optical fibres*	*LM*	*Wait for WMC*	*WMC*	*No*	*Depends on OF measurement system WMC*
5	S07	Static tests 2500 kN	LM	Start ASAP	WMC	No	No optical fibres
0/5/10	*R44*	*Fatigue test w. OF*	*LM*	*Wait for WMC*	*WMC*	*No*	*Depends on OF measurement system WMC*
10	S07	Fatigue tests 2500 kN	LM	Start ASAP	WMC	No	No optical fibres:
WP11	(see also 7.3)						
5	S03	Static	GAMESA	Yes	CRES	Yes	
70	S31…S48	Static	GAMESA	Partly	CRES	No	See separate table for repaired specimens
5	S03	Static	LM	Yes	WMC	Yes	
30	S31…S36	Static	LM	Yes	WMC	Yes	
0/10/20	*S37/S38/S??*	*Static*	*LM*	Can start	*WMC*	*No*	*Extra slopes, say 1:25 and 1:40 if LM wants*
15	S03	Fatigue	GAMESA	Yes	CRES	No	
30	S??/S??	Fatigue	GAMESA	Wait for static test results	CRES	No	Best slope at 1/3 and 2/3 repair thickness
15	S03	Fatigue	LM	Yes	WMC	No	
30	S31/S32	Fatigue	LM	Yes	WMC	No	1:50 at 1/3 and 2/3 repair thickness
WP12							
5	S09	Static tests 2500 kN	LM	Start ASAP	WMC	No	
10	S09	Fatigue tests 2500 kN	LM	Start ASAP	WMC	No	
Total number of tests: 275, of which 40 tests are optional. In the original version of the DPA, 386 tests were planned for WP10, WP11, WP12 together 10 static tests and 20 fatigue tests on the 2500 kN test machine are foreseen.							

7.2. TG4 tests in OPTIMAT tables

NB: cells in pink denote a decrease of tests compared to the old DoW, cells in Green denote an increase in tests.

Static Tests on Optimat Blades specimens

Partner			WMC	DLR	CCLRC	RISOE	CRES	VUB	UP	VTT	WMC	DLR	CCLRC	RISOE	CRES	VUB	UP	VTT	WMC	DLR	CCLRC	RISOE	CRES	VUB	UP	VTT		WP
lay-up	Test	Type of test			UD								MD						±45º (shear/tubes)								Remarks	
Axial (//)	T																										TG4: for strain patterns: DELETED	
	C																										TG4: for strain patterns: DELETED	
Transverse (^)	T																										TG4: for strain patterns: DELETED	
	C																										TG4: for strain patterns: DELETED	
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%																										

Static Tests on ISO/ASTM specimens

Partner			WMC	DLR	CCLRC	RISOE	CRES	VUB	UP	VTT	WMC	DLR	CCLRC	RISOE	CRES	VUB	UP	VTT	WMC	DLR	CCLRC	RISOE	CRES	VUB	UP	VTT		
lay-up	Test	Type of test			UD								MD						±45º (shear/tubes)								Remarks	
Axial (//)	T																											
	C																											
Transverse (^)	T																											
	C																											
Thickness	C																										33-direction R03/R04 Possible but DELETED TG4	
Shear	IPS																										moved to TG3	
	13																										Iosipescu specimens 13 Possible but DELETED	
	23																										Iosipescu specimens 23 Possible but DELETED	
4 Point Bending			5																								I05 (4p bending UD) done, I06 (4p bending MD) DELETED.	10
Shear	IPS	-40°/+60°/100%																										
Hygro Thermal	α1																											
	α2																											
30°	T																											

Static Tests on special test specimens

Partner			WMC	DLR	CCLRC	RISOE	CRES	VUB	UP	VTT	WMC	DLR	CCLRC	RISOE	CRES	VUB	UP	VTT	WMC	DLR	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																										
		Tubes																										
Long test specimens as reference for repaired specimens 4																												
Axial (//)	T										5				5												S03:Done	11
Axial (//)	T										10																R44 2x length for optical fibres instead of line 4 (with stress	10 optical
Bending	C up																										S05: DELETED	
Repaired test specimens 4																												
Axial (//)	T										50				70												S31-S48 CRES/GAMESA 7 repairs WMC/LM 3 (….5) repairs 5 tests	11
(long spec.)	C																											
Bending	T up																											
(long spec.)	C up	rep. compr.																									DELETED: S05 800x30x50 top is S06	
Thick test specimens 4																												
Axial (//)	T										5																S07	10
	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										5																S09	12
Bending	T up																											
	C up	rep. compr.																									DELETED	

Constante Amplitude Fatigue Tests

Partner			WMC	DLR	CCLRC	RISOE	CRES	VUB	UP	VTT	WMC	DLR	CCLRC	RISOE	CRES	VUB	UP	VTT	WMC	DLR	CCLRC	RISOE	CRES	VUB	UP	VTT		
lay-up	R	Type of test			UD								MD						±45º (shear/tubes)								Remarks	
Standard Optimat Specimens																												
Axial (//)	0.1	shear on long test									10																R44= R04 2x length for optical fibres	10 optical
	0.5																											
	-0.4																											
	-1																											
	-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%																										
2D test specimens 2																												
2D Stress state	0.1	Cruciform																										
	-1	Tube																										
Long test specimens as reference for repaired specimens 4																												
Axial (//)	0.1										15				15												S03	11
Repaired test specimens 4																												
Axial (//)	0.1										30				30												S31-S48: Best of row 48 GAMESA/CRES and 1:50 LM/WMC 1/3	11
Thick test specimens 4																												
Axial (//)	0.1										10																S07	10
	-1																										DELETED	
	10																											
Repaired thick test specimens 4																												
Axial (//)	0.1										10																	12

7.3. TG4 repaired specimens overview

WP11: overview of repair techniques, produced by GAMESA

NB: the tests in the blue lines still need to be produced by GAMESA and delivered to CRES.
All repair variations must be produced and tested for two repair depths: 1/3 and 2/3 of the thickness respectively.

WP11: overview of repair techniques, produced by LM

STATIC TEST: Tensile strength

PLATE	TEST	REP. PROCEDURE	BASE MATERIAL	REPAIR MATERIAL	MANUNFACTURER	SLOPE	h	New Name	TEST	Sent to WMC	Tested
128	TENSILE STRENGH	REFERENCE SPECIMENT	RIM	N/A	LM	N/A	N/A	GEV207_S0300_0001...0018	NA	2003	7
126	TENSILE STRENGH	REFERENCE SPECIMENT	RIM	N/A	LM	N/A	N/A	GEV207_S0300_0019...0020	NA	2003	
133	TENSILE STRENGH	SCARF	RIM	LIQUID RESIN	LM	1:50	1/3	GEV207_S3100_0007...0014	NA	2004	5
131	TENSILE STRENGH	SCARF	RIM	LIQUID RESIN	LM	1:50	2/3	GEV207_S3200_0007...0014	NA	2004	5
134	TENSILE STRENGH	SCARF	RIM	LIQUID RESIN	LM	1:75	1/3	GEV207_S3300_0007...0014	NA	2004	5 (+1)
130	TENSILE STRENGH	SCARF	RIM	LIQUID RESIN	LM	1:75	2/3	GEV207_S3400_0007...0014	NA	2004	5
132	TENSILE STRENGH	SCARF	RIM	LIQUID RESIN	LM	1:100	1/3	GEV207_S3500_0007...0014	NA	2004	5 (+1)
129	TENSILE STRENGH	SCARF	RIM	LIQUID RESIN	LM	1:100	2/3	GEV207_S3600_0007...0014	NA	2004	5
	TENSILE STRENGH	SCARF	RIM	LIQUID RESIN	LM	1:25	1/3	Not Used	NA	2005	
	TENSILE STRENGH	SCARF	RIM	LIQUID RESIN	LM	1:25	2/3	GEV207_S3800_0001...0007	NA	2005	
	TENSILE STRENGH	SCARF	RIM	LIQUID RESIN	LM	1:40	1/3	Not Used	NA	2005	
	TENSILE STRENGH	SCARF	RIM	LIQUID RESIN	LM	1:40	2/3	GEV207_S4800_0001...0007	NA	2005	

PLATE	TEST	REP. PROCEDURE	BASE MATERIAL	REPAIR MATERIAL	MANUNFACTURER	SLOPE	h	New Name	TEST	Sent to CRES	Tested
126	TENSILE STRENGH	REFERENCE SPECIMENT	RIM	N/A	LM	N/A	N/A	GEV207_S0300_0021...0035	NA	2003	
127	TENSILE STRENGH	REFERENCE SPECIMENT	RIM	N/A	LM	N/A	N/A	GEV207_S0300_0036...0054	NA	2003	
133	TENSILE STRENGH	SCARF	RIM	LIQUID RESIN	LM	1:50	1/3	GEV207_S3100_0001...006	NA	2004	
131	TENSILE STRENGH	SCARF	RIM	LIQUID RESIN	LM	1:50	2/3	GEV207_S3200_0001...006	NA	2004	
134	TENSILE STRENGH	SCARF	RIM	LIQUID RESIN	LM	1:75	1/3	GEV207_S3300_0001...006	NA	2004	
130	TENSILE STRENGH	SCARF	RIM	LIQUID RESIN	LM	1:75	2/3	GEV207_S3400_0001...006	NA	2004	
132	TENSILE STRENGH	SCARF	RIM	LIQUID RESIN	LM	1:100	1/3	GEV207_S3500_0001...006	NA	2004	
129	TENSILE STRENGH	SCARF	RIM	LIQUID RESIN	LM	1:100	2/3	GEV207_S3600_0001...006	NA	2004	

Constante Amplitude Fatigue Tests

PLATE	TEST	REP. PROCEDURE	BASE MATERIAL	REPAIR MATERIAL	MANUNFACTURER	SLOPE	h		TEST	for WMC	
126	TENSILE STRENGH	REFERENCE SPECIMENT	RIM	N/A	LM	N/A	N/A	Enough made: CRES sends to WMC			
	FATIGUE	SCARF	RIM	LIQUID RESIN	LM	1:50	1/3	GEV207_S3100_0207...0226	R 0.1	2005	
	FATIGUE	SCARF	RIM	LIQUID RESIN	LM	1:50	2/3	GEV207_S3200_0207...0226	R 0.1	2005	

NB: the tests in the blue lines must still be produced by LM for testing at WMC.
The tests in the white lines are optional: depending on the interest of LM in tests with steeper repair slopes.