Evaluation on the effect of thick laminates
WP10

OB_TG4_R013
Rev. 000

Confidential

OPTIMAT BLADES

TG 4

Arno van Wingerde
## CHANGE RECORD

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1. INTRODUCTION

In this report the results of WP10 are reported. The objectives and work description are given in the technical annex and repeated for convenience in this document.

The main change made at the MTA to the original as outlined in [2] is that 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 was deserted, to be replaced by a more direct comparison between experimental results on thin and thick laminates.
1.1. Description in DoW

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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.

**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.

**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. GENERAL DESCRIPTION OF WORK

2.1. 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/±45)s laminate. The 'thin' version could be the 6.4 mm thick ((±45,0)₄, ±45) 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: ((±45₅,0₅)₄, ±45₅).

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

In principle, the aim is to keep the specimens shape consistent when going from thin to thick laminates. In practise this was not always possible.

For the thick UD specimen this will result in an approx. net area of 100*20=2000 mm²; 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)

2.2. Types of test, instrumentation and reporting

Flat thin and thick laminates will be produced (under industrial quality) on basis of the laminate definition of 2.1.

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. 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 (0.5 or 1.0 Hz). For this reason the amount of tests was kept limited and some re-shuffling of PM 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.
2.3. 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. Tests are carried out in tension in 0° on MD material.

**Number of thin specimens for static tests**

The reference tests on thin specimens have already been carried out in WP11:
- The determination of strength properties in 11T and 11C directions has been established in TG1 and TG3, just like the losipescu 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) were established in TG4.
- Thermal expansion coefficients for UD material and thin MD laminate (e.g. using ISO 11359) have been established in TG2.

Therefore: no static tests on thin laminates are necessary within WP10.

**Number of thick specimens for static tests**

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

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

2.4. 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 = 0.1, for a nominal fatigue life of 5,000 and 1,000,000 cycles.

**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 between 5,000 and 1,000,000 cycles, conform OB_TC_R014:
- \( F_{\text{max}} = 5 \cdot 2.23 \text{ kN/mm width} \) (for 5 times the thickness of standard OPTIMAT R04 specimens: F ranges from 139.4 kN to 1394 kN) for a nominal life of 5000 cycles.
- \( F_{\text{max}} = 5 \cdot 1.31 \text{ kN/mm width} \) (for 5 times the thickness of standard OPTIMAT R04 specimens: F ranges from 81.9 kN to 819 kN) for a nominal life of 1000000 cycles.

However, in practice, in order to check the problems with the gripping system, the tests were conduction at various load levels.

For the thick laminates, the frequency is maximal 1 Hz, because of the limitations of the test machine. Therefore, fatigue testing of 5 specimens at (average) 1 million cycles at 1 Hz requires 58 days running time, or about 2.5 months through-put time.

2.5. 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.

2.6. Evaluation

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

2.7. Modifications to the original DoW

Fairly elaborate changes have 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. However, extra FE analyses were carried out to analyze the gripping problems [4].
- 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 was stated to be dependent on technical possibilities at WMC. As the optical measurement system did not meet the required technical standards, measurements with optical fibres were in the end not carried out.
- 2 PMs were shifted between TG2 and TG4 and WMC and University of Patras:
  - WMC got two more PMs in TG4
  - The University of Patras got 2 PMs in TG2. from TG4.

2.8. Modifications to the new DoW

The updated DPA [3] is fully in agreement with the new DoW as outlined in the MTA report [1] and chapter 1.1.
2.9. Dimensioning of the thick specimens

For the thick specimens of WP10, 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).

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 $140 \times 32.85/25 \times 6.57 = 2520$ 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.

\[ ((45,0), 45) = 32.85 \text{ mm} \]

Tabs are the same, for a total thickness of 98.55 mm.

Holes ø 33mm, for M30 Pre-stress bolts

**S07 (thick reference)**

**S09 (thick repaired)**

*Figure 2* Thick test specimens S07 (reference) and S09 (repaired)

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 determination of the geometry is outlined in more detail in [5].
2.10. Other test specimens used within WP10

![Figure 3 Dimensions of thin specimen used as reference for WP10](image)

Figure 3 Dimensions of thin specimen used as reference for WP10
3. TEST SET-UP

Because of the large forces required, only WMC had the capacity to carry out the tests in their 2500 kN test machine, shown in Figure 4. See also Figure 1 for the major dimensions.

Figure 4 test set-up for the thick test specimens
3.1. Gripping problems

Due to manufacturing limitations at LM and the necessity for economical production of the test specimen, as well as a test specimen which would mimic the dimensions of the small test specimens to which the results of the thick specimens are compared, a rectangular specimen was selected with a straight tabbing area.

The forces at the start of the gripping area are the same as those in the main test specimen, however a number of factors make the situation in the gripping area less favourable:

♦ There is a more uneven stress distribution across the cross section.
♦ There exists a perpendicular clamping force.
♦ There are holes where bolts are connecting the gripping area to the steel plates of the test machine.

Although failure at the standard OPTIMAT specimens also occurs typically at the start of the grip, it is deemed acceptable in that case, because of expectance that the failure will not be significantly lower than is the case for ideal specimens, which has been shown by comparison with other test geometries.

However, in case of the thick specimens, the holes make the situation in the gripping area considerably worse than for the thin specimen and it is obvious that failure would occur in the gripping area at possibly considerably lower forces than the actual strength of the cross section. Therefore, the tabs need to do more than just alleviate the effect of the clamping force and slightly uneven stress distribution.

For this reason the tabs are made from the same material as the main part, so that the tabbed area is three times as thick.

The problem with this approach is that the redistribution of strains from the centre area to the tabs is rather abrupt, causing the tabs to shear off easily from the centre part. No space is available for a more gradual transition from the centre part to the tabbed part and on top of that, the quality of the glue used between tabs and test specimen was also rather poor.

As outlined in Chapter 2.9, the allowable space for load introduction is also rather small. Therefore a number of bolt configurations were analysed and tested [4]. The resultant geometry is one, where the first row of two bolts is kept small (M20, so as to have more net area left), the second row contains two M30 and the third row two M39 bolts.

The development of the grips used for testing is further outlined in chapter 4.1.
4. TEST RESULTS

4.1. Selection in OPTIDAT

The easiest way to select the thick laminates in OPTIDAT, is to select by laminate “TMD” (thick Multi Directional).

4.2. Static tests

Table 1 Overview of static test results

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<th>σ&lt;sub&gt;max&lt;/sub&gt;</th>
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<td>GEV214_S0700_0012</td>
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<td>633.58</td>
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</table>

NB: GEV214_S0700_012 was carried out outside of the OPTIMAT programme, and is therefore not listed in OPTIDAT.

The static tests carried out, show an unusually large scatter in the results. This is due to the gripping problems, which can be seen in Figure 5, which shows the failure of the tabbed area of the first test. The figure also shows the three different bolt diameters used, per end: 2xM20, 2xM30 and 2xM39.

![Figure 5 Damage in grip of specimen GEV214_S0007_0001](image)

In spite of the clamping force, the tabs broke off from the specimen itself at a rather low force level (around 500 kN). This meant that the centre part, the test specimen itself, had to carry the full load, whereas it was severely weakened by the presence of the holes, the concentrated load introduction at the holes and the perpendicular clamping force itself. Perhaps even more revealing is the drawing of the failed tab area in Figure 6.
It turned out that in the first test, where the specimen was connected with bolts to the steel plates, a major loss of pre-stress due to shear contraction (Poison-effect) occurs. The first two bolts M20/M30 are about 160 mm long, steel quality 10.9: yield stress = 900 MPa, $\varepsilon_{\text{yield}} = 900/210000= 0.4\%$, $\Delta l = 0.4\% \times 160 = 0.69$ mm. As can be seen in Figure 7, where an FE model half the thickness shows a Poison contraction of 0.3 mm in thickness direction (over half thickness: thus yielding a total Poison contraction of 0.6 mm thickness) reduction lowers prestress force by 80%. The M39 bolts were about 240 mm long, but are quality 8.8: yield stress about 2/3, length about 3/2, relative to the M20/M30 bolts: also 80% loss of the prestress force. As a first upgrade the bolts were replaced by long bolts and busses for the next test:GEV214-S0007_0002, as can be seen in Figure 4.
Still, the poor adhesion between tabs and the continuous part of the test specimen resulted in an only marginally higher static strength for the next static test.

The third test was carried out with slightly tapered tabs and extra laminate glued over the tab ends, resulting in a higher static strength. Moreover, the first holes for the M20 bolts were dropped, instead two M39 bolts were placed outside of the test specimen. The bolt arrangement and glued layers can be seen in Figure 8 for the failed test specimen.

Finally, the fourth test was carried out (actually outside of the official OPTIMAT BLADES test programme) by replacing the second row bolts by larger diameter bolts outside the test specimen as well as the first (avoiding the holes for the M20 and M30 bolts in the tabs) and here the results were significantly better, see the overview of test results in Table 1.
4.3. Fatigue tests

The fatigue tests were carried out at R=0.1, with the minimum load in a cycle being 10% of the maximum load.

<table>
<thead>
<tr>
<th>Optimat/FACT name</th>
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A graphical overview of the fatigue tests is given in Figure 9.

4.4. Conclusions

The main posed in the description of WP10 is: can the properties of thick laminates be derived from the test results of thin laminates?

The results are most easily summarised in a graph. The thin specimens are given with blue symbols. The static results on thick laminates are given are yellow (first two static tests) and red (third static test) symbols. It is obvious that the high cycle fatigue results of thin and thick laminates are comparable. For two low-cycle fatigue tests and especially for the static tests, the thick specimens are about 30% lower (yellow symbols) or at the lower bound of the thin results (red symbol).

However, it is known that the clamping system used for the thick specimen is flawed and that the glue between tabs and specimen is of particularly low quality. This means that the tabs effectively carry no load, so that the holes at the end of the specimen weaken the cross section, so that failure occurs under the tabs.

In fact, as mentioned in 4.1 after the official OPTIMAT BLADES testing was finished, another test was carried out to test an approved clamping system, which reached about 2500 kN, or 630 MPa (open red symbol), lending further support to the overall impression that thick laminates behave about the same in both static and fatigue testing as the thin laminates. Therefore concluding from the work of WP10, the results of material tests on thin coupons, can indeed be used to predict the performance of the much thicker laminates which occur in blades of wind turbines.

![Static and Fatigue results](image-url)

Figure 9 Overview of test results of thin and thick laminates
5. LITERATURE

5.1. Reports from the OPTIMAT website

1. Mid Term Assessment Report, OB_PC_R013, 10242.
2. DPA TG4 - WP 10, 11, OB_TG4_R001, doc. no. 10025.
3. DPA TG4 Phase II - WP 10, 11 and 12, OB_TG4_R009, doc. no. 10243.
4. FE analysis of thick test specimens, OB_TG4_R011, doc. no. 10292.
5. 2500 kN test set-up for thick laminates, OB_TG4_R015, doc. no. 10368.