Preliminary tests Part 1
Static and fatigue tests of UD and MD laminates

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Version 1
Confidential

OPTIMAT BLADES

TC

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Note: Appendix A is made available as a separate pdf document
1 INTRODUCTION

Contents of this report
In this document tests reported which form part of the so-called 'Preliminary Tests' of the "Optimat Blades" project. These tests were carried out prior to the manufacturing of the main body of standard OPTIMAT test specimens.

The objectives of this test campaign were:
1. to anticipate problems with the standard geometry and lay-up (e.g. regarding influence of geometry on strength, Euler buckling, capability of test rigs, etc.
2. to choose the best geometry for the standard OPTIMAT specimen.

To this end, specimens with different gauge lengths, lay-up and geometry were tested. Preliminary tests were also conducted at other institutes: UP [5], DLR [6] and RISØ [7].

This report contains the results, graphs and photos from static and fatigue tests carried out at the Knowledge Centre WMC (a co-operation between Delft University of Technology and ECN. It consists of 27 static compression tests, 13 static tensile test and 12 fatigue tests for four series with different geometries. The results will also be included in optiDAT.

Changes made in this revision
-

Acknowledgements
Special thanks to Ed van der Harst for his help in carrying out the tests.
2 TEST SET-UP AND PROCEDURE

Overview
Three kinds of tests were performed on the thin, flat laminate specimens: static tension and compressive tests and fatigue tests with R=-1. Most of the tests have been carried out in the 100 kN Schenck test machine, the other tests in the 250 kN in-house developed test machine.

Materials tested and notation
The tested coupons are made of the reference E-glass/epoxy materials for the Optimat Blades project [1]. These are:

- ‘UD’ or ‘unidirectional material’: 1150 g/m² in 0° direction and 50 g/m² in 90° direction with a 50 g/m² Chopped Strand Mat
- ‘±45°’ or ‘biaxial material’: non-woven stitch-bonded glass roving in 2 layers, 400 g/m² in +45° and 400 g/m² in –45° with a two thin additional layers of 2 g/m² in 0° and 90°

For the matrix material, SP systems Prime 20 epoxy is used with slow hardener. The tabs for the tests are made out of GRP.
The thickness per layer was specified by LM to be about 0.88 mm for the unidirectional material and 0.61 mm for the biaxial material.
Test specimens were provided by LM Glasfiber A/S Denmark, cut from different plates.

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Table 1: Laminate lay-up and nominal thickness of the test plates

The tests are denoted by $PV(W)xxYz(z)z$ in which:
- $V$ = D or R, test specimen shape (Dog bone or Rectangular).
- $W$ = A, B, or C, (for plate 5) free length between the tabs of 35, 40 and 45 mm respectively.
- $xx$ = number LM used for the plate, in this series 04 (= GEV ).
- $Y$ = T, C or F, type of test (static Tension, static Compression, or Fatigue).
- $zz(z)$ = number of the individual test specimens; for plate 5 three digits are used.

These plate numbers are included in optiDAT in the column ‘delivered under name’.

Strain gauges
Where strain gauges have been used, strain gauge 001S000 denotes the front side of the test specimen and strain gauge 002S000 denotes the back side. The strain gauges used were 10 mm gauge length TML FLA-10-11 strain gauges, from Tokyo Sokki Kenkyujo Co.
3 STATIC TESTS

Test specimen geometry
The test specimens have been cut from the plates, described in Table 1. The plan form of the specimens is either rectangular or dog bone-shaped, see Figure 1. The actual thickness $t$, width and free length $L$ (between the grips) of the tested specimens is given in Table 2.

![Figure 1: Dimensions of specimens D01 (dog bone shaped, left) and R01](image)

Overview of measurement results
The mounting procedure of the specimens is as follows:

a. the specimen is mounted in the lower grips of the test machine
b. the strain gauge channel values are set to zero
c. the upper grips are closed.

The tests have been executed in displacement control with a speed of approx. 2 mm/min.

In Table 2 the actual geometry and measured data are presented for the static tests. The stress and strain given in the table are the values at failure. For the stress the applied force is divided by the initial cross sectional area in the middle of the specimen. In case of the strain, the mean value is taken of the two strain gauge readings, unless one of the gauges clearly produced erroneous data. The strain gauge measurement system normally reaches up to $18500 \, \mu \text{strain}$, although the strain gauge accuracy is not guaranteed for those strain levels. The Young's modulus ($E$) has been determined based on linear regression of the stress-strain curve for strains between 500 and 2500 $\mu \text{strain}$.

In the appendix, per static test one graph is presented containing the force versus the displacement of the actuator and the force against the strain gauge readings (if strain gauges
were present). Furthermore, 2 photos of each failed test specimen are presented, taken from each side.

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Table 2: Static test results
Discussion

For plates 1, 2 and 5 specimens equipped with strain gauges have been tested. In Figure 2 an overview is given of the Young's moduli. As expected, the pure UD material results in the highest stiffness, the larger the fraction of 45° oriented layers, the lower the stiffness becomes. Based on the results for plate 1 specimens, the loading direction (tension or compression) does not have a significant effect. There is a significant effect, though, of the specimen shape. For both plate 1 and plate 2, the dog bone specimen has a significantly higher value for the Young's modulus than the rectangular specimens. Since the material and lay-up are the same, this can only be attributed to the shape. As a result of this shape, the strain in the middle of the dog bone specimen is approx. 10% lower at the same applied stress than for the rectangular specimen.

![Figure 2: Young's moduli in compression for 3 plates and tensile modulus for plate 1](image)

The strength results of the compressive tests are given in Figure 3. In this graph the failure load (in kN) is given as well as the failure strength (in MPa) for all compression tests. From this figure it can be seen that for plates 1 and 2 the dog bone shaped specimen all fail at a lower load (either force or stress) than the rectangular specimens. For plate 3, on the other hand, the difference is small (due the relatively large scatter no 'hard' conclusions can be drawn here).

For the 'ud' specimens (plate 1), a clear difference can be observed between the dog bone and the rectangular specimens. From the test figures (e.g. figure A 1, figure A 3 and figure A 5 for the dogbone and figure A 5 etc for the rectangular specimens) it is clear that all dogbone shaped specimens encountered buckling. The strain-force curves show a strong divergent behaviour near failure. For the rectangular specimens 2 specimens fail before buckling occurs, one specimen experiences vast bending at a strain as low as 75% of the failure strain. Due to the buckling phenomena, the average dog bone specimens strength comes out 20% lower for the specimens of plates 1.
For prismatic specimens, the ASTM standard [3] states a minimum required specimen thickness, to prevent Euler buckling. This formula, which is also given in ISO 14126 [4], is as follows:

\[ h > \frac{L}{0.9096 \sqrt{(1 - 1.2\frac{F_{cu}}{G_{xz}}) \frac{E_c}{F_{cu}}}} \]  

(eq. 1)

For plate 1, the following values are applied:
- nominal thickness of \( h = 4.5 \) mm,
- \( E_c = 40 \) GPa (see above)
- out-of-plane shear modulus of \( G_{xz} = 5.8 \) GPa (assumed value)

For a free length of \( L = 50 \) mm, Euler buckling is predicted at approx. 250 MPa, which is only half of the strength found for the rectangular specimens. In view of this limited accuracy, results of this equation will not be used any further in this report.

![Figure 3: Compressive strength for 4 different plates](image)

For plate 2 buckling can be observed for all specimens, either rectangular or dogbone shaped. This is a surprising outcome, since plate 2 is merely plate 1 with 2 additional layers of 45-degree oriented materials. The failure loads are higher, compared to plate 1.

For plate 3 no specimens have been equipped with strain gauges, therefore no objective data are available to decide on buckling. In view of the increased thickness, it can however be argued that Euler buckling is not expected to happen at the measured strength of 475 MPa.

For the test results of plate 5, the main difference is the free length. As can be expected, the specimens with the shortest length (35 mm) do not show any buckling, whereas the longest specimens will probably have experienced buckling. This can be judged from the two
specimens equipped with strain gauges: both show the typical divergence of the strain curves.

The tensile strength results are given in graphical form in Figure 4. The number of tests is more limited than the compressive tests. Two specimens (pr01t01 and pd03t01) shown here should be regarded as run-outs, since the specimens could not be failed in the 100 kN test machine. Specimen pr01t01 was later mounted in the 250 kN test machine and failed at 87.4 kN.

![Figure 4: Tensile strength for different plates](image)

There are no firm indications for strength differences due to the specimen shape. Although the rectangular specimens are slightly weaker, this is only a few percent and therefore not significant. The addition of ±45° layers (plate 2 and plate 3) increases the failure load, but not in proportion to the thickness. This can be expected, since the material added is less strong than the 'ud' material.

When comparing the tensile strength to the compressive strength, for rectangular specimens, the following can be observed. For the specimens of plate 1, the 'ud' laminate, the compressive strength is approximately 65% of the tensile strength. When 45° oriented layers are added at the outside (plate 2), this ratio increases to 72%. For the test plates with an (almost) equal number of 'ud' and ±45° layers, the ratio increases to approx. 75%, due to a decreased tensile strength at almost constant compressive strength.
4 FATIGUE TESTS

Test specimen geometry

The test specimens have been cut from the plates, described in Table 1. The plan form of the specimens is either rectangular or dogbone-shaped, see [2]. The actual thickness, width and free length (between the grips) of the tested specimens is given in Table 2.

Overview of measurement results

The specimens were mounted in the test machine following the same procedure as used for the static loaded specimens. For every specimen a slow cycle is executed (and measured) first, at a frequency of 0.02 Hz. This slow cycle can be used as part of the stiffness degradation monitoring.

Following that, the fatigue tests is started in load control with a frequency of 2 Hz, except for pr01f31 which was loaded at 1 Hz.

In Table 3 the actual geometry and measured data are presented for the fatigue tests. The stress and strain given in the table are the maximum value in the fatigue cycle. For the stress the applied force is divided by the initial cross sectional area in the middle of the specimen. In case of the strain, the mean value is taken of the two strain gauge readings, unless one of the gauges clearly produced erroneous data. The Young’s modulus (E) has been determined as the mean value of the linear regression slopes of the stress-strain curve for strains between 500 and 2500 μstrain and –500 and –2500 μstrain.

For the fatigue tests, two pages with graphs are given per specimen and two photographs. The first page with graphs gives the result for the slow cycle that precedes the fatigue test. The lay-out is similar as the graph for the static test. The second page gives ranges of the applied force and bench displacement and the strains (for plate 1) over the fatigue life. Furthermore, 2 photos of each failed test specimen are presented, taken from each side.

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Table 3: Fatigue test results

From the specimens that have been equipped with strain gauges (plate 1), relative large bending can be observed for he dogbone specimens and some bending for the rectangular
ones. During the last phase of test pr01f31 and the first of pr01f36, wrong values of the force range were recorded, due to erroneous time averaging settings. The ranges should be 70 and 60 kN respectively, as was recorded for the rest of those specimens. For most specimens some hysteresis has been recorded in the force – bench displacement diagram during the first (slow) cycle. In general, the hysteresis (expressed as ratio of the enclosed area to the elastic energy) increases from plate 1 to plate 3 and is higher for the dogbone shaped specimens. This hysteresis can be a result from heat build-up or damage in the specimen, it can also be caused by slip between e.g. tab and grip. Since it is not possible, at present, to pinpoint the exact cause, no conclusions can be drawn.

Discussion

The values for the Young's modulus, as given in Table 3 for the slow cycles before the fatigue tests, agree with the data found during the static tests. The fatigue results are graphically given as S-N curve in Figure 5. Since only 2 specimens have been tested per configurations, no firm conclusions will be drawn.

![Fatigue results of three plates](image)

For most configurations the two data points are relatively close together, taking into account that the dogbone specimens of plate 2 are tested at different levels. The exceptions for this are the dogbone shaped specimens from plate 3: one specimen failed in a buckling mode, at a mere 172 cycles, whereas the other one failed in an 'ordinary' manner at 36165 cycles. When taking a closer look at the photographs, it can be seen that most of the rectangular specimens failed at the tab, although this position can be expected, it is not favoured. None of the dog bones failed near the narrowest section, most of them failed halfway the narrowest section and the tab.
5 CONCLUSIONS

- The measured Young's modulus of the dogbone specimens is typically 10% higher than for the rectangular specimens. This is a result from the non-uniform strain distribution in the measured section.
- The loading direction (tension or compression) does not have a significant effect on the measured Young's modulus.
- For the compression loaded dogbone specimens of plate 1 and 2, an Euler buckling type of failure occurred, resulting in relatively low compressive strength. For the MD1 laminate (plate 3) the dogbone and rectangular specimens resulted at similar compressive strength values.
- For the MD2 laminate (plate 5), compression tests have been accomplished with different free lengths: 35, 40 and 45 mm. Although buckling was observed for the specimens with 45 mm free length, there is no significant difference between the compression strengths.
- For the specimens that were loaded in tension, no influence of the specimen shape on the strength could be established.
- The compression strength of the MD1 and MD2 specimens (plates 3 and 5) is approx. 85% of the tensile strength. For the specimens with higher percentage of 0° fibres this ratio decreases: 72% for plate 2 and 64% for plate 1.
6 REFERENCES


APPENDIX A   TEST RESULT FIGURES AND PHOTOGRAPHS

In this annex figures are given for the static and fatigue tests and photographs of the specimens after testing.

For the static tests, the applied bench displacement and resulting force are given, e.g. in the upper figure of figure A-1. In the lower figure of figure A-1, when measured, the strains are given against the force. Following this figure with graphs, two photographs are given for each specimen, from the front side and backside of the specimen.

For the fatigue tests, two pages with graphs are given per specimen and two photographs. The first page with graphs gives the result for the slow cycle that precedes the fatigue test (see e.g. figure A 81). The lay-out is similar as the graph for the static test. The second page gives ranges of the applied force and bench displacement and the strains (when strain gauges have been mounted) over the fatigue life.
figure A 1: Axial compressive force vs. bench displacement and strains for pd01c01
figure A 2: Photographs of failed specimen pd01c01 (top: back-side)
figure A 3: Axial compressive force vs. bench displacement and strains for pd01c06
figure A 4: Photographs of failed specimen pd01c06
figure A 5: Axial compressive force vs. bench displacement and strains for pd01c11
figure A 6: Photographs of failed specimen pd01c11
figure A 7: Axial compressive force vs. bench displacement and strains for pr01c06
figure A 8: Photographs of failed specimen pr01c06
figure A 9: Axial compressive force vs. bench displacement and strains for pr01c16
figure A 10: Photographs of failed specimen pr01c16
figure A 11: Axial compressive force vs. bench displacement and strains for pr01c21
figure A 12: Photographs of failed specimen pr01c21
figure A 13: Axial compressive force vs. bench displacement and strains for pd02c21
figure A 14: Photographs of failed specimen pd02c21
figure A 15: Axial compressive force vs. bench displacement and strains for pd02c26
figure A 16: Photographs of failed specimen pd02c26
figure A 17: Axial compressive force vs. bench displacement and strains for pd02c31
figure A 18: Photographs of failed specimen pd02c31
figure A 19: Axial compressive force vs. bench displacement and strains for pr02c26
figure A 20: Photographs of failed specimen pr02c26
figure A 21: Axial compressive force vs. bench displacement and strains for pr02c31
figure A 22: Photographs of failed specimen pr02c31
figure A 23: Axial compressive force vs. bench displacement and strains for pr02c36
figure A 24: Photographs of failed specimen pr02c36
figure A 25: Axial compressive force vs. bench displacement and strains for pd03c21
figure A 26: Photographs of failed specimen pd03c21
figure A 27: Axial compressive force vs. bench displacement and strains for pd03c26
figure A 28: Photographs of failed specimen pd03c26
figure A 29: Axial compressive force vs. bench displacement and strains for pd03c31
figure A 30: Photographs of failed specimen pd03c31
figure A 31: Axial compressive force vs. bench displacement and strains for pr03c26
figure A 32: Photographs of failed specimen pr03c26
figure A 33: Axial compressive force vs. bench displacement and strains for pr03c31
figure A 34: Photographs of failed specimen pr03c31 (resp. back, front and side)
figure A 35: Axial compressive force vs. bench displacement and strains for pr03c36.
figure A 36: Photographs of failed specimen pr03c36
figure A 37: Axial compressive force vs. bench displacement and strains for pra05c06
figure A 38: Photographs of failed specimen pra05c06
figure A 39: Axial compressive force vs. bench displacement and strains for pra05c11
figure A 40: Photographs of failed specimen pra05c11
figure A 41: Axial compressive force vs. bench displacement and strains for pra05c16
figure A 42: Photographs of failed specimen pra05c16
figure A 43: Axial compressive force vs. bench displacement and strains for prb05c55
figure A 44: Photographs of failed specimen prb05c55
figure A 45: Axial compressive force vs. bench displacement and strains for prb05c60
figure A 46: Photographs of failed specimen prb05c60
figure A 47: Axial compressive force vs. bench displacement and strains for prb05c65
figure A 48: Photographs of failed specimen prb05c65
figure A 49: Axial compressive force vs. bench displacement and strains for prc05c111
figure A 50: Photographs of failed specimen prc05c111
figure A 51: Axial compressive force vs. bench displacement and strains for prc05c116
figure A 52: Photographs of failed specimen prc05c116
figure A 53: Axial compressive force vs. bench displacement and strains for prc05c121
figure A 54: Photographs of failed specimen prc05c121
Exercise A 55: Axial tensile force vs. bench displacement and strains for pd01t16
figure A 56: Photographs of failed specimen pd01t16 (top photograph: back side)
figure A 57: Axial tensile force vs. bench displacement and strains for pd01t31
figure A 58: Photographs of failed specimen pd01t31
figure A 59: Axial tensile force vs. bench displacement and strains for pr01t01
figure A 60: Photographs of failed specimen pr01t01
figure A 61: Axial tensile force vs. bench displacement and strains for pr01t11
figure A 62: Photographs of failed specimen pr01t11
figure A 63: Axial tensile force vs. bench displacement and strains for pr01t26
figure A 64: Photographs of failed specimen pr01t26
figure A 65: Axial tensile force vs. bench displacement and strains for pd02t01
figure A 66: Photographs of failed specimen pd02t01
figure A 67: Axial tensile force vs. bench displacement and strains for pd02t06
figure A 68: Photographs of failed specimen pd02t06
figure A 69: Axial tensile force vs. bench displacement and strains for pr02t06
figure A 70: Photographs of failed specimen pr02t06 (resp. back, front, side)
figure A 71: Axial tensile force vs. bench displacement and strains for pr02t11
figure A 72: Photographs of failed specimen pr02t11 (resp. back, front, side)
figure A 73: Axial tensile force vs. bench displacement and strains for pd03t01
figure A 74: Photographs of failed specimen pd03t01 (top photograph: back side)
figure A 75: Axial tensile force vs. bench displacement and strains for pra05t01
figure A 76: Photographs of failed specimen pra05t01
figure A 77: Axial tensile force vs. bench displacement and strains for prb05t70
figure A 78: Photographs of failed specimen prb05t70
figure A 79: Axial tensile force vs. bench displacement and strains for pc05t131
figure A 80: Photographs of failed specimen pc05t131
figure A 81: Force vs. bench displacement and strains during preceding slow cycle for pd01f21
figure A 82: Ranges of force, bench displacement and strains during fatigue life for pd01f21
figure A 83: Photographs of failed specimen pd01f21
figure A 84: Axial force vs. bench displacement and strains during preceding slow cycle for pd01f26
figure A 85: Ranges of force, bench displacement and strains during fatigue life for pd01f26
figure A 86: Photographs of failed specimen pd01f26
figure A 87: Axial force vs. bench displacement and strains during preceding slow cycle for pr01f31
figure A 88: Ranges of force, bench displacement and strains during fatigue life for pr01f31
figure A 89: Photographs of failed specimen pr01f31
figure A 90: Axial force vs. bench displacement and strains during preceding slow cycle for pr01f36
figure A 91: Ranges of force, bench displacement and strains during fatigue life for pr01f36
figure A 92: Photographs of failed specimen pr01f36
figure A 93: Axial force vs. bench displacement and strains during preceding slow cycle for pd02f11
figure A 94: Ranges of force, bench displacement and strains during fatigue life for pd02f11
figure A 95: Photographs of failed specimen pd02f11
figure A 96: Axial force vs. bench displacement and strains during preceding slow cycle for pd02f16
figure A 97: Ranges of force, bench displacement and strains during fatigue life for pd02f16
figure A 98: Photographs of failed specimen pd02f16
figure A 99: Axial force vs. bench displacement and strains during preceding slow cycle for pr02f16
figure A 100: Ranges of force, bench displacement and strains during fatigue life for pr02f16
figure A 101: Photographs of failed specimen pr02f16
figure A 102: Axial force vs. bench displacement and strains during preceding slow cycle for pr02f21

OPTIMAT BLADES prelim. fatigue

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time: 80 to 140 sec.

avg_F01

no strain gauges
figure A 103: Ranges of force, bench displacement and strains during fatigue life for pr02f21
figure A 104: Photographs of failed specimen pr02f21
figure A 105: Axial force vs. bench displacement and strains during preceding slow cycle for pd03f11
figure A 106: Ranges of force, bench displacement and strains during fatigue life for pd03f11
figure A 107: Photographs of failed specimen pd03f11
figure A 108: Axial force vs. bench displacement and strains during preceding slow cycle for pd03f16
figure A 109: Ranges of force, bench displacement and strains during fatigue life for pd03f16
figure A 110: Photographs of failed specimen pd03f16
figure A 111: Axial force vs. bench displacement and strains during preceding slow cycle for pr03f16
figure A 112: Ranges of force, bench displacement and strains during fatigue life for pr03f16
figure A 113: Photographs of failed specimen pr03f16
figure A 114: Axial force vs. bench displacement and strains during preceding slow cycle for pr03f21
figure A 115: Ranges of force, bench displacement and strains during fatigue life for pr03f21
figure A 116: Photographs of failed specimen pr03f21