

IRPWind

INTEGRATED RESEARCH PROGRAMME ON WIND ENERGY

Project acronym: **IRPWIND**

Grant agreement n° 609795

Collaborative project

Start date: 01st December 2013

Duration: 9 months

TITLE: MULTI-AXIAL FATIGUE MODEL VERIFICATION

IRPWIND PROJECT – 2ND CALL FOR JOINT EXPERIMENTS

DELIVERABLE NUMBER FINAL REPORT

Lead Beneficiary: The Knowledge Centre Wind Turbine Materials and Constructions (WMC)

Delivery date: 31/01/2018

Dissemination level: PU



The research leading to these results has received funding from the European Union Seventh Framework Programme under the agreement 609795.

Author(s) information (alphabetical):

| Name | Organisation | Email |
|---------------|-----------------|--|
| A. Antoniou | Fraunhofer-IWES | alexandros.antoniou@iwes.fraunhofer.de |
| J. Estarriaga | CENER | jestarriaga@cener.com |
| F. Lahuerta | WMC | f.lahuerta@wmc.eu |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |

Acknowledgements/Contributions:**Document Information**

| Version | Date | Description | Prepared by | Reviewed by | Approved by |
|---------|----------|-------------|-------------|-------------|-------------|
| 0 | 08/02/18 | | All | | |
| | | | | | |

Definitions/Acronyms

| DoW | Description of Work | | |
|-----|---------------------|--|--|
| UD | unidirectional | | |
| | | | |
| | | | |
| | | | |

doi: 10.5281/zenodo.1169791



Table of Contents

| | |
|--|----|
| Table of Contents | 3 |
| Executive Summary | 5 |
| Introduction | 6 |
| 1. Multiaxial methodology..... | 7 |
| 1.1 Description | 7 |
| 2. CENER test description..... | 10 |
| 2.1 Work Package 1 (WP1)..... | 10 |
| 2.2 Work Package 2 (WP2)..... | 14 |
| 2.2.1 Multiaxial Fatigue Tests..... | 14 |
| 2.2.1.1 DVal1_0_R-1 | 14 |
| 2.2.1.2 DVal1_10_R-1..... | 16 |
| 2.2.1.3 DVal1_60_R-2..... | 17 |
| 2.2.2 Benchmarking tests..... | 19 |
| 2.2.2.1 Coupons manufactured by IWES | 20 |
| 2.2.2.2 Coupons manufactured by CENER | 24 |
| 3. IWES test description..... | 27 |
| 3.1 Work Package 1 (WP1)..... | 27 |
| 3.2 Work Package 2 (WP2)..... | 29 |
| 4. WMC test description..... | 31 |
| 4.1 UD-45-STT tension test..... | 31 |
| 4.2 UD ±45 layup test CA R=0.1 | 36 |
| 4.3 UD 90 layup test CA R=0.1..... | 40 |
| 4.4 UD 90 layup test CA R=0.1..... | 45 |
| 4.5 MU-045-STT tension test..... | 49 |
| 4.6 UD Multiaxial layup test CA R=-1 | 54 |
| 4.7 UD-0-STT tension test. Benchmark test. | 58 |
| 4.8 UD-0-I-STT tension test. Benchmark test. Manufactured at IWES..... | 63 |
| 5. UD static tension test benchmark | 68 |
| 5.1 Introduction | 68 |
| 5.2 Material..... | 68 |
| 5.3 Manufacturing process and lay-up | 68 |
| 5.4 Coupon geometry and tabs | 69 |
| 5.5 Instrumentation, coupon tests and reporting | 69 |
| 6. Conclusions | 73 |
| 7. References | 74 |
| 8. Appendix | 75 |
| 8.1 CENER tests..... | 75 |
| 8.1.1 WP1- Fatigue. UD_0°_R=0.1 | 75 |
| 8.1.2 WP2- Fatigue. DVal1_0°_R=-1 | 76 |
| 8.1.3 WP2- Fatigue. DVal1_10°_R=-1..... | 77 |
| 8.1.4 WP2- Fatigue. DVal1_60°_R=-2..... | 77 |
| 8.1.5 WP2- Static. Benchmarking tests. Coupons manufactured by IWES | 78 |
| 8.1.6 WP2- Static. Benchmarking tests. Coupons manufactured by CENER | 78 |
| 8.2 IWES tests..... | 79 |
| 8.3 WMC tests | 93 |
| 8.3.1 UD-45-STT tension test..... | 93 |

| | | |
|-------|---|-----|
| 8.3.2 | UD ± 45 layup test CA R=0.1 | 95 |
| 8.3.3 | UD-90-STT tension test..... | 99 |
| 8.3.4 | UD 90 layup test CA R=0.1..... | 102 |
| 8.3.5 | MU-045-STT tension test..... | 108 |
| 8.3.6 | UD Multiaxial layup test CA R=-1 | 111 |
| 8.3.7 | UD-0-STT tension test. Benchmark test. | 120 |
| 8.3.8 | UD-0-I-STT tension test. Benchmark test. Manufactured at IWES. | 122 |

Executive Summary

This report shows the results of the tests performed in the project “Multi-axial fatigue model verification”, which was awarded in the 2nd call for Joint Experiments within the IRPWind project.

Technicians from WMC, IWES and CENER have been working on it from April 2017 until February 2018.

The report is divided into four parts: Three parts focused on the work done by each of the partners, and the last one comparing the results of the UD static tension test benchmarking.

Descriptions of the testing set-ups, results tables and graphs are shown in the body of the report, while photographs of the tested specimens are shown in the Appendix.

This report has been share openly in Research Gate (www.researchgate.net) and Zenodo (zenodo.org).

Introduction

Regarding the development of precise calculation methodologies, in the frame of IRPWIND WP7.1 project, CENER has worked in a methodology that analyses the fatigue damage in each layer of composite laminate structures, especially blades.

Inputs to the methodology are CLDs (Constant Life Diagrams) of a pure UD- laminate built up on three R-Ratios for the three main loading directions (longitudinal, transverse and shear), which sum eight S-N curves.

Under WP7.3 of IRPWIND project, four S-N curves have been tested. For a preliminary and partial validation of the methodology, a small testing campaign of multiaxial laminates made out of the same UD material, loaded on-axis and off-axis, is scheduled within WP7.1.

In this context, an extensive experimental validation of the methodology is required, with valid and solid experimental results. The joint experiments between WMC, IWES and CENER have the following main objectives:

- Perform the necessary missing tests utilized as inputs to the methodology developed in IRPWIND WP7.1. (4 S-N curves to achieve the total of 8 S-N curves that are inputs to the methodology).
- Do a benchmark between test laboratories by performing static tests longitudinal to the fibre.
- Expand the current European composite material Open Access database
- Validate the robust fatigue design methodology developed in IRPWIND WP7.1 under multiaxial stress states, which will be achieved by:
 - Testing plane pure UD coupons loaded in a 5-10° off-axis direction (with respect to the fibre axis).
 - Testing plane multiaxial laminate coupons (UD laminated at various orientations) loaded on-axis and 10° off-axis.

1. Multiaxial methodology

1.1 Description

Over the last decades, a great deal of work has been done to develop more reliable fatigue calculation methodologies in composite materials. Due to the complicated failure mechanisms, this is not a simple issue. Nowadays, several different approaches exist.

CENER has been working in the development of a Semi-empirical approach, according to the following points:

- The life predictions are based on the observance of cyclic test results for the fabrics that define the lay-ups:
 - o Biaxial or triaxial fabrics can be considered as a combination of 2 or 3 uniaxial fabrics.
 - o Longitudinal, transversal and shear loading are separately tested.
 - o Different R-ratios ($R=-1$, 0.1 and 10) are taken into account to build the CLDs (Constant Life Diagrams).

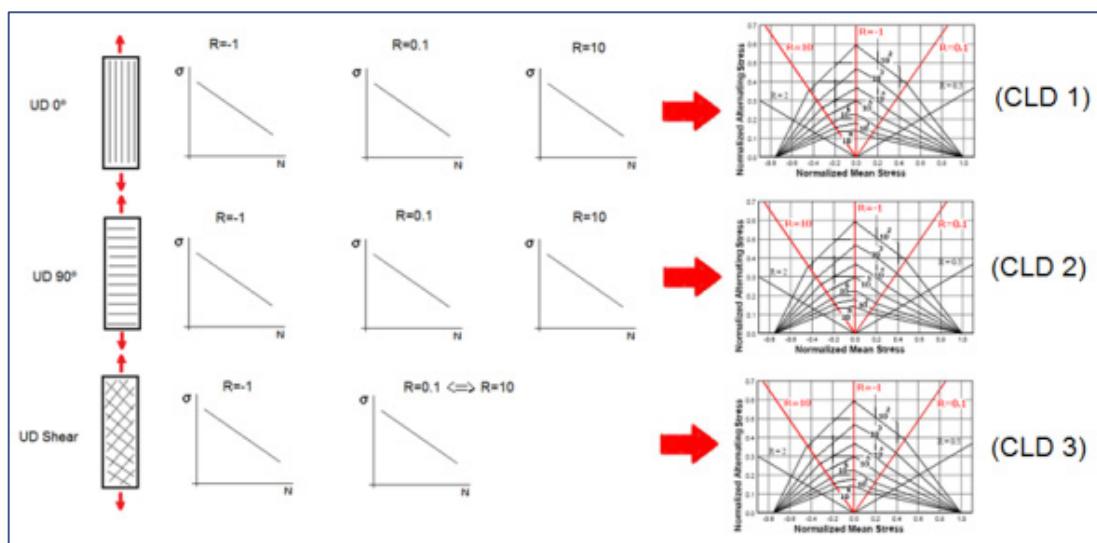


Figure 1 Material characterization

- By means of a FE-software, the stress tensor components σ_1 , σ_2 , ζ_{12} are obtained -for unitary load cases- in every element and layer. Then, these results are scaled by the real loads to extract the stress-time histories.

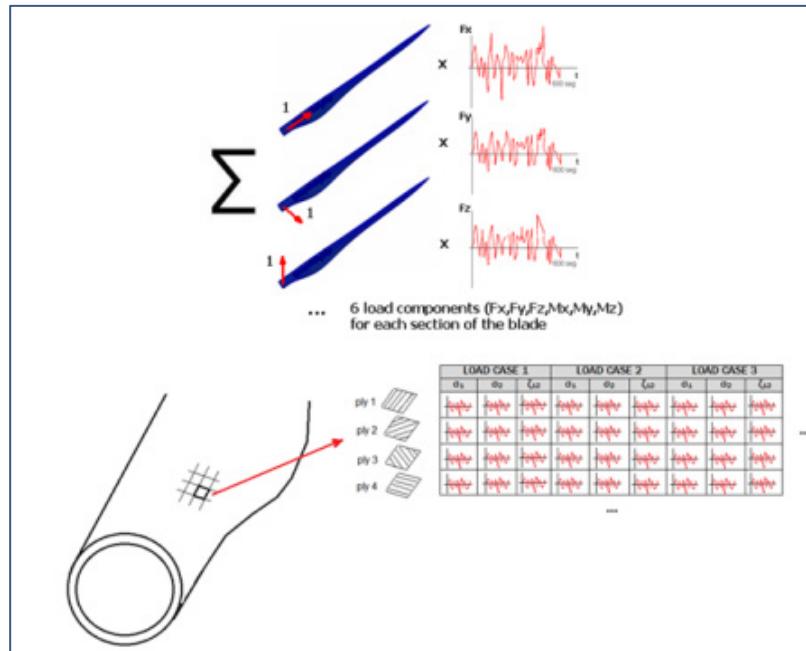


Figure 2 Stress time histories

- $\sigma_{eq} = f(\sigma_1, \sigma_2, \zeta_{12})$ are calculated according to different theories: Tsai-Hill, Stassi D'alia and Hoffman.

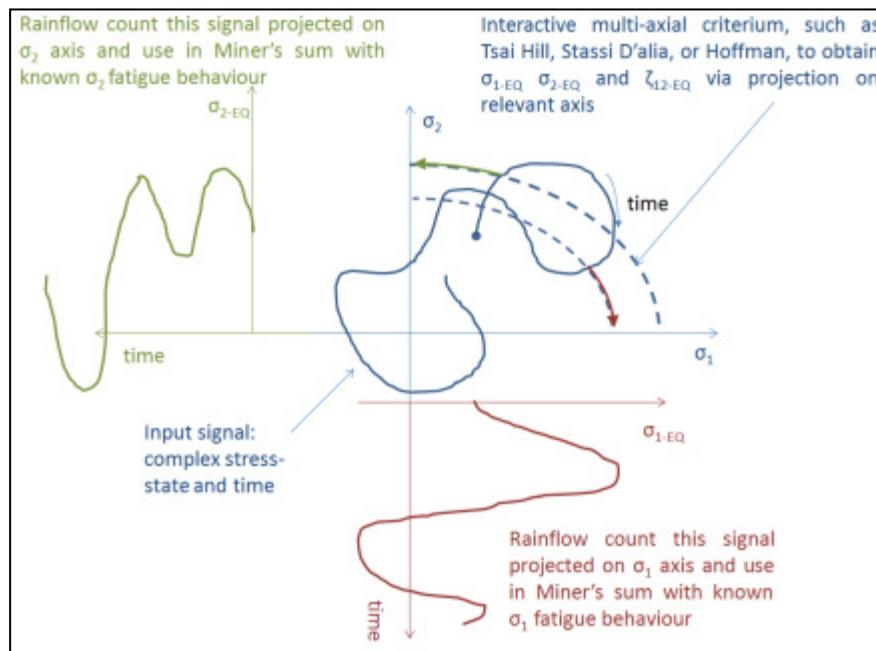


Figure 3 Metric of damage

- Rainflow Counting Algorithm and Miner rule are applied to calculate the damage.

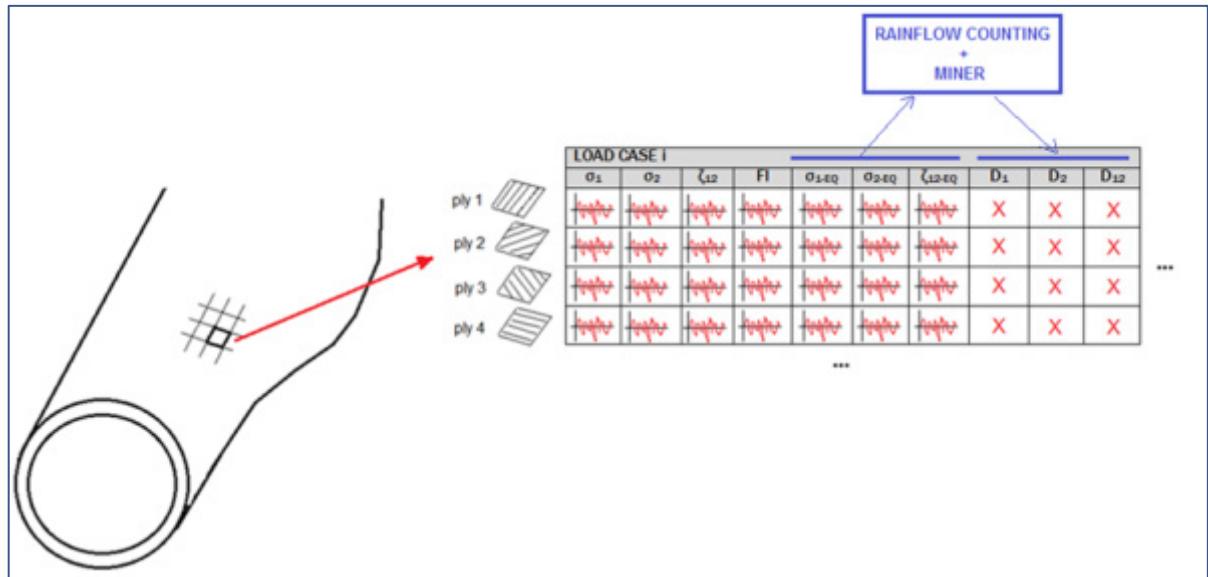


Figure 4 Damage Calculation

An in-house tool called FATCOMP has been developed to implement this calculation methodology. Once the cycles are counted, FATCOMP interpolates between the constant life curves to calculate the damage. As indicated in the following figure, an intermediate value between N1 and N2 will be the predicted life corresponding to the cycle (σ_m , σ_a).

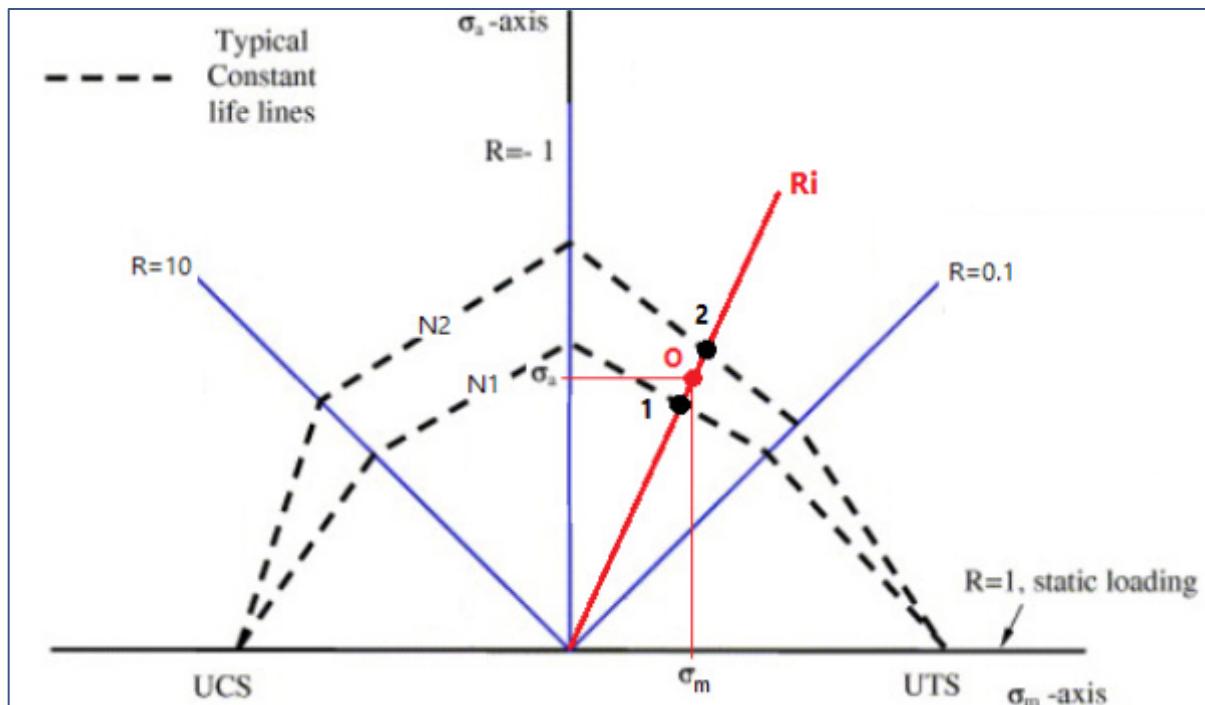


Figure 5 Interpolation done by FATCOMP to calculate the life (damage)

At the time, a simplistic methodology has been chosen. Some important issues as load sequence effects and stiffness degradation have not been taken into account yet. Once the basic methodology is validated it will have sense to move forward.

2. CENER test description

2.1 Work Package 1 (WP1)

Within WP1, CENER was responsible for the manufacturing and testing of several coupons under fatigue loading.

With regard to the materials, a high modulus glass fibre infused with epoxy resin –both currently used by several blade manufacturers- was selected to manufacture the composite panels.

| | |
|---------------------|-------------------------------------|
| UD Fabric | UD 1800 gsm, FV HM 3B W2020 |
| Resin | MOMENTIVE EPIKOTE MGS RIMR 135/035c |
| Curing Agent | MOMENTIVE EPIKURE MGS RIMH 137 |

Table 1. Material specification

The manufacturing process parameters are summarized in the following table:

| Curing cycle | | |
|---------------------|---|----------|
| Step | Temperature / time | Pressure |
| Infusion | 40 °C | -0,9 Bar |
| Maintenance | 5 min 40 °C | -0,9 Bar |
| Heating Maintenance | 0,5 °C/min until 50 °C 300 min 50 °C | -0,9 Bar |
| Heating Maintenance | 0,5 °C/min hasta 60 °C 300 min a 60 °C | -0,9 Bar |
| Heating Maintenance | 0,5 °C/min hasta 70 °C 300 min a 70 °C | -0,9 Bar |
| Cooling | 1 °C/min until room temperature | -0,9 Bar |

Table 2. Test panels manufacturing process specification

The coupons were extracted from a panel made of three layers according to the following lay-up: [0,0,0]. (UD)

The coupons were cut out aligned with the fibre direction.

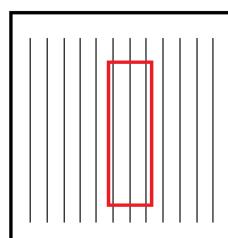


Figure 6 Coupons nesting

The coupons were manufactured according to the geometry shown in Figure 7.
 2 mm thickness tabs composed of biaxial glass fibre fabrics were bonded to the coupons.

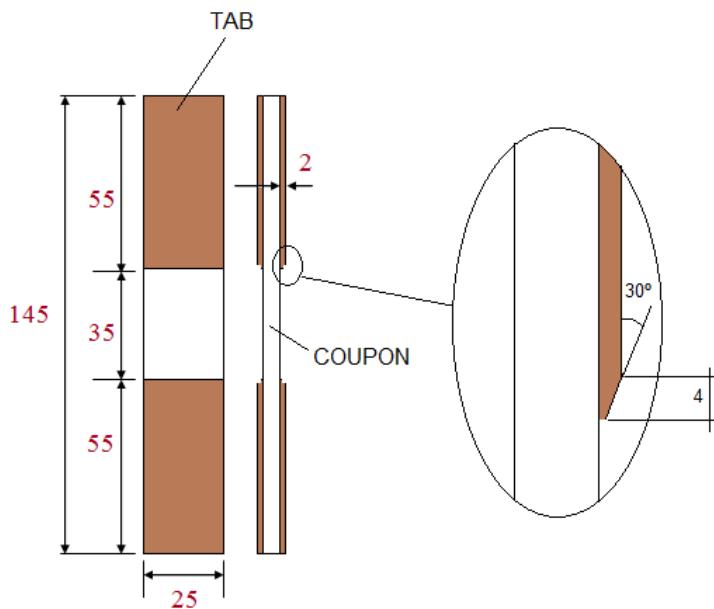


Figure 7 Coupon dimensions (mm)

With regard to the loading, the R-ratio was 0.1 (tension-tension).
 The tests were carried out in a servo hydraulic testing machine INSTRON 8802, with a load capacity and a load cell of 250 kN (class 0.5).

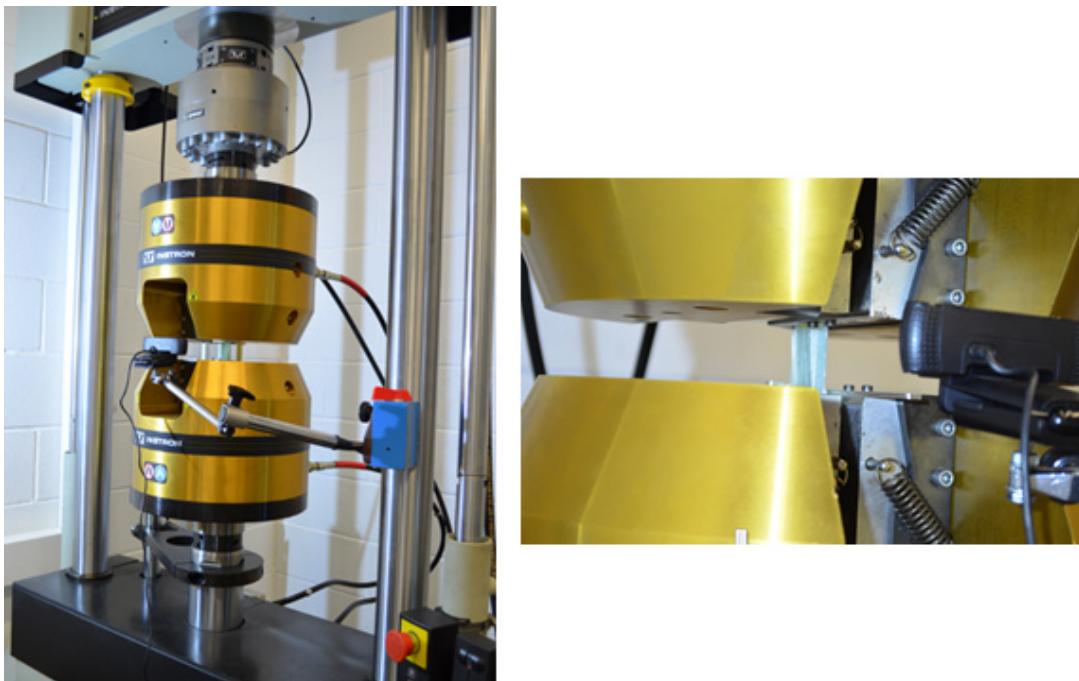


Figure 8 Test set-up

The test results are shown in Table 3 and Table 4.

| | Thickness | Width | Area |
|-----------------------|-----------|-------|--------------------|
| ID | (mm) | (mm) | (mm ²) |
| 47.0064.3.K1.FL0,1.01 | 3.54 | 25.50 | 90.27 |
| 47.0064.3.K1.FL0,1.02 | 3.57 | 25.42 | 90.75 |
| 47.0064.3.K1.FL0,1.03 | 3.61 | 25.24 | 91.12 |
| 47.0064.3.K1.FL0,1.04 | 3.65 | 25.41 | 92.75 |
| 47.0064.3.K1.FL0,1.05 | 3.60 | 25.40 | 91.44 |
| 47.0064.3.K1.FL0,1.06 | 3.50 | 25.12 | 87.92 |
| 47.0064.3.K1.FL0,1.07 | 3.50 | 24.94 | 87.29 |
| 47.0064.3.K1.FL0,1.08 | 3.60 | 25.46 | 91.66 |
| 47.0064.3.K1.FL0,1.09 | 3.65 | 25.34 | 92.49 |
| 47.0064.3.K1.FL0,1.10 | 3.60 | 25.55 | 91.98 |

Table 3. Coupon real dimensions

| ID | F _{max} | F _a | Area | σ _a | Freq. | Cycles to Failure |
|-----------------------|------------------|----------------|--------------------|----------------|-------|-------------------|
| | (kN) | (kN) | (mm ²) | (MPa) | (Hz) | |
| 47.0064.3.K1.FL0,1.01 | 42.79 | 19.25 | 90.27 | 213 | 3 | 15018 |
| 47.0064.3.K1.FL0,1.02 | 34.41 | 15.49 | 90.75 | 171 | 4 | 319891 |
| 47.0064.3.K1.FL0,1.03 | 32.39 | 14.58 | 91.12 | 160 | 4 | 113455 |
| 47.0064.3.K1.FL0,1.04 | 30.77 | 13.85 | 92.75 | 149 | 5 | 2067221 |
| 47.0064.3.K1.FL0,1.05 | 36.84 | 16.58 | 91.44 | 181 | 4 | 161758 |
| 47.0064.3.K1.FL0,1.06 | 37.51 | 16.88 | 87.92 | 192 | 3 | 9827 |
| 47.0064.3.K1.FL0,1.07 | 31.03 | 13.96 | 87.29 | 160 | 4 | 53140 |
| 47.0064.3.K1.FL0,1.08 | 33.71 | 15.17 | 91.66 | 166 | 3 | 255339 |
| 47.0064.3.K1.FL0,1.09 | 32.88 | 14.80 | 92.49 | 160 | 3 | 854002 |
| 47.0064.3.K1.FL0,1.10 | 38.15 | 17.17 | 91.98 | 187 | 2 | 9558 |

Table 4. Test summary

The S-N curve in log-log scale is shown in Figure 9.

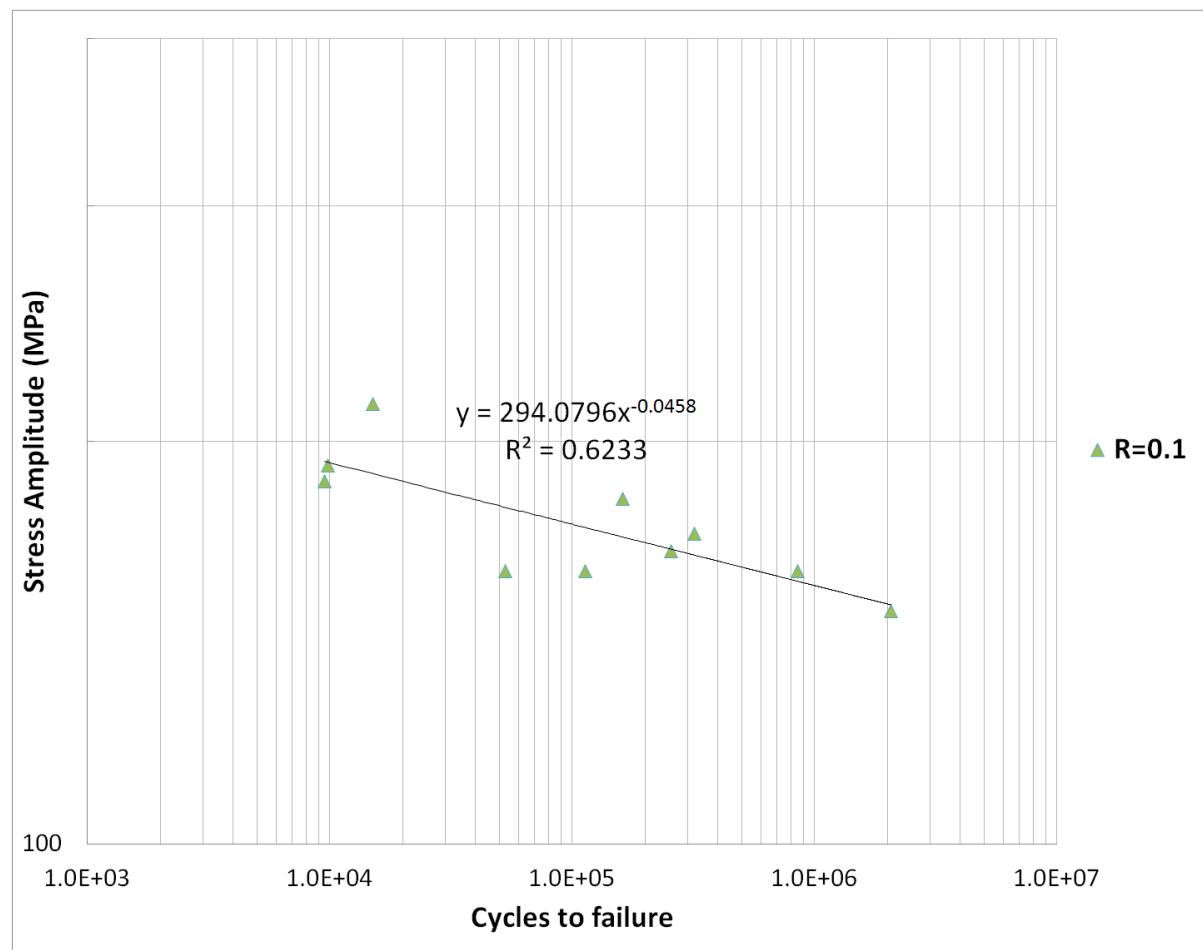


Figure 9 S-N curve. UD laminate 0°. R=0.1

With regard to the Fibre mass fraction, the average measured value is 76.25%

Pictures of the damaged coupons are shown in Appendix 8.1.1.

2.2 Work Package 2 (WP2)

CENER has contributed to WP2 with two kinds of test.

On the one hand, several fatigue tests have been carried out on coupons made of a multiaxial laminate manufactured by CENER. Besides, in the framework of the UD static tension test benchmarking described in section 5 , static tests have been carried out on specimens provided by IWES as well as directly manufactured by CENER.

2.2.1 Multiaxial Fatigue Tests

According to the procedure explained in section 2.1 and using the same material, some multiaxial panels were manufactured.

The lay-up configuration was: [45°, -45°, 0°, 0°, 45°, -45°]

3 different fatigue tests were carried out in a servo hydraulic testing machine INSTRON 8802, with a load cell of 250 kN (class 0.5).

2.2.1.1 DVal1_0_R-1

The coupons were tested under fatigue loads, with the load aligned with the fibres at 0°, and for an R-ratio of -1.

The test results are shown in Table 5 and Table 6.

| | Thickness (mm) | Width (mm) | Area (mm ²) |
|------------------------|-------------------|---------------|----------------------------|
| ID | | | |
| 47.0064.3.R5.F0°.01 | 7.47 | 24.88 | 185.85 |
| 47.0064.3.R5.F0°.02 | 7.52 | 24.99 | 187.92 |
| 47.0064.3.R5.F0°.05 | 7.33 | 24.68 | 180.90 |
| 47.0064.3.R5.F0°.06 | 7.45 | 24.90 | 185.51 |
| 47.0089.0.U.F0°.Ri1.03 | 6.99 | 23.34 | 163.15 |
| 47.0089.0.X.F0°.Ri1.06 | 7.01 | 25.20 | 176.65 |

Table 5. Coupon real dimensions

| ID | F_{max} | F_a | Area | σ_a | Freq. | Cycles to Failure |
|------------------------|-----------|-------|--------------------|------------|-------|-------------------|
| | (kN) | (kN) | (mm ²) | (MPa) | (Hz) | |
| 47.0064.3.R5.F0°.01 | 27.88 | 27.88 | 185.85 | 150.00 | 2 | 490 |
| 47.0064.3.R5.F0°.02 | 21.14 | 21.14 | 187.92 | 112.50 | 2 | 1981 |
| 47.0064.3.R5.F0°.05 | 13.57 | 13.57 | 180.90 | 75.00 | 2 | 1114565 |
| 47.0064.3.R5.F0°.06 | 16.70 | 16.70 | 185.51 | 90.00 | 5 | 5822 |
| 47.0089.0.U.F0°.Ri1.03 | 16.00 | 16.00 | 163.15 | 98.07 | 3 | 190199 |
| 47.0089.0.X.F0°.Ri1.06 | 15.50 | 15.50 | 176.65 | 87.74 | 3 | 1841587 |

Table 6. Test summary

The S-N curve in log-log scale is shown in Figure 10.

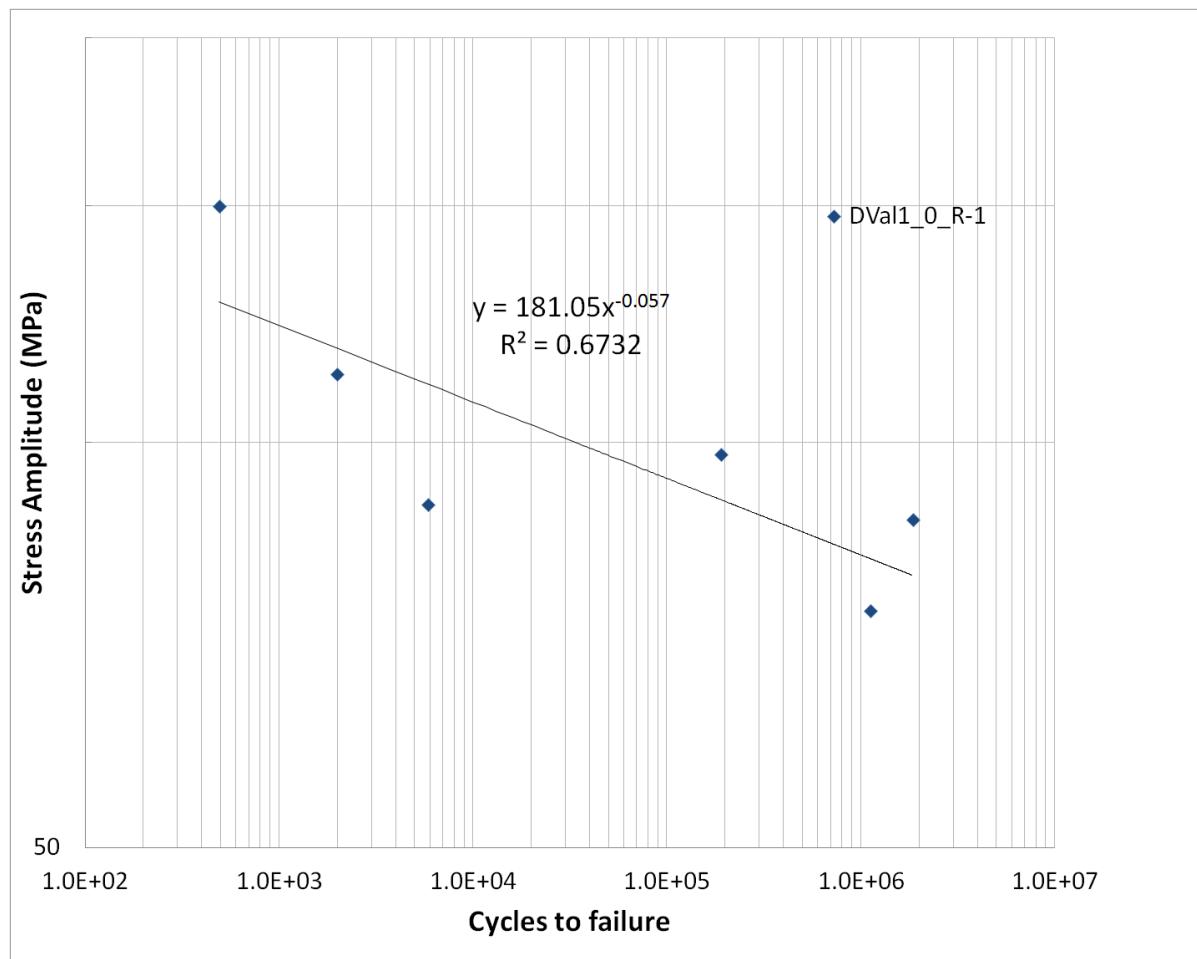


Figure 10 S-N curve. UD laminate 0°. R=0.1

With regard to the Fibre mass fraction, the average measured value is 73.35%. Pictures of the damaged coupons are shown in Appendix 8.1.2 .

2.2.1.2 DVal1_10_R-1

The coupons were tested under fatigue loads, with the load forming an angle of 10° with the fibres at 0°, and for an R-ratio of -1.

The test results are shown in Table 7 and Table 8.

| ID | Thickness (mm) | Width (mm) | Area (mm ²) |
|--------------------------|-------------------|---------------|----------------------------|
| 47.0089.0.X.F10°.Ri2.01 | 7.06 | 24.85 | 175.44 |
| 47.0089.0.X.F10°.Ri2.02 | 7.17 | 24.75 | 177.46 |
| 47.0089.0.X.F10°.Ri2.03 | 7.15 | 24.69 | 176.53 |
| 47.0089.0.T.F10°.Ri2.04 | 7.18 | 24.52 | 176.05 |
| 47.0089.0.T.F10°.Ri2.05 | 7.02 | 24.40 | 171.29 |
| 47.0089.0.Q3.F10°.Ri2.06 | 7.64 | 23.86 | 182.29 |
| 47.0064.3.Q3.F10°.01 | 7.49 | 23.64 | 177.06 |
| 47.0064.3.Q3.F10°.02 | 7.42 | 24.48 | 181.64 |

Table 7. Coupon real dimensions

| ID | F _{max} (kN) | F _a (kN) | Area (mm ²) | σ _a (MPa) | Freq. (Hz) | Cycles to Failure |
|--------------------------|--------------------------|------------------------|----------------------------|-------------------------|---------------|----------------------|
| 47.0089.0.X.F10°.Ri2.01 | 22.74 | 22.74 | 175.44 | 129.60 | 3 | 703 |
| 47.0089.0.X.F10°.Ri2.02 | 21.72 | 21.72 | 177.46 | 122.40 | 3 | 800 |
| 47.0089.0.X.F10°.Ri2.03 | 20.34 | 20.34 | 176.53 | 115.20 | 3 | 1159 |
| 47.0089.0.T.F10°.Ri2.04 | 17.75 | 17.75 | 176.05 | 100.80 | 3 | 2666 |
| 47.0089.0.T.F10°.Ri2.05 | 13.57 | 13.57 | 171.29 | 79.20 | 3 | 636330 |
| 47.0089.0.Q3.F10°.Ri2.06 | 15.75 | 15.75 | 182.29 | 86.40 | 3 | 5486 |
| 47.0064.3.Q3.F10°.01 | 14.66 | 14.66 | 177.06 | 82.78 | 3 | 8584 |
| 47.0064.3.Q3.F10°.02 | 14.11 | 14.11 | 181.64 | 77.69 | 3 | 58368 |

Table 8. Test summary

The S-N curve in log-log scale is shown in Figure 11.

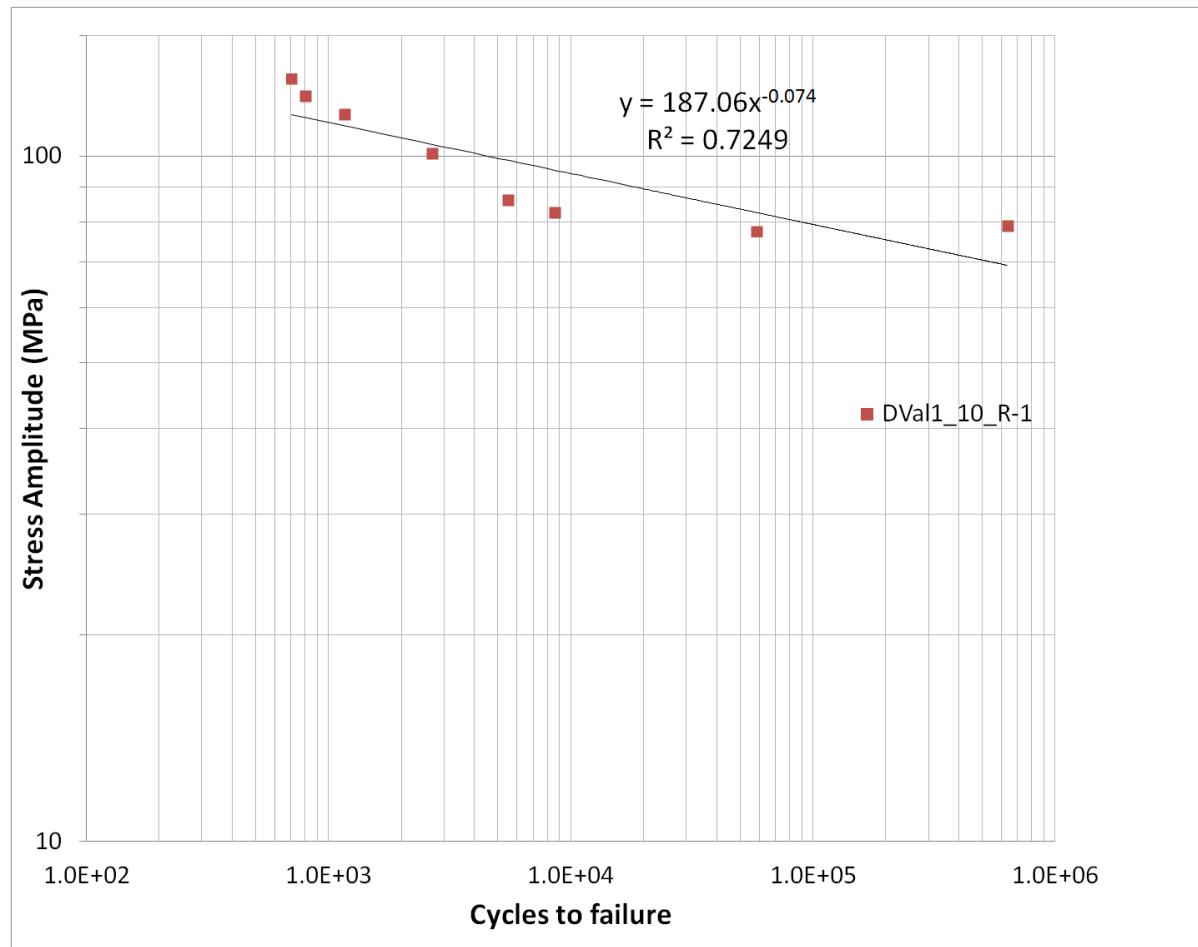


Figure 11 S-N curve. UD laminate 0°. R=0.1

Pictures of the damaged coupons are shown in Appendix 8.1.3.

2.2.1.3 DVal1_60_R-2

The coupons were tested under fatigue loads, with the load forming an angle of 60° with the fibres at 0°, and for an R-ratio of -2.

The test results are shown in Table 9 and Table 10.

| ID | Thickness (mm) | Width (mm) | Area (mm ²) |
|----------------------|-------------------|---------------|----------------------------|
| 47.0064.3.Q2.F60°.01 | 7.70 | 25.11 | 193.35 |
| 47.0064.3.Q2.F60°.02 | 6.97 | 25.57 | 178.22 |
| 47.0064.3.Q2.F60°.03 | 7.68 | 25.01 | 192.08 |
| 47.0064.3.Q2.F60°.04 | 7.65 | 24.53 | 187.65 |

Table 9. Coupon real dimensions

| ID | F_{max} | F_a | Area | σ_a | Freq. | Cycles to Failure |
|----------------------|-----------|-------|--------------------|------------|-------|-------------------|
| | (kN) | (kN) | (mm ²) | (MPa) | (Hz) | |
| 47.0064.3.Q2.F60°.01 | 8.33 | 12.50 | 193.35 | 64.65 | 3 | 11622 |
| 47.0064.3.Q2.F60°.02 | 7.33 | 11.00 | 178.22 | 61.72 | 3 | 1508385 |
| 47.0064.3.Q2.F60°.03 | 8.13 | 12.20 | 192.08 | 63.52 | 3 | 25140 |
| 47.0064.3.Q2.F60°.04 | 7.93 | 11.90 | 187.65 | 63.42 | 3 | 19113 |

Table 10. Test summary

The S-N curve in log-log scale is shown in Figure 12.

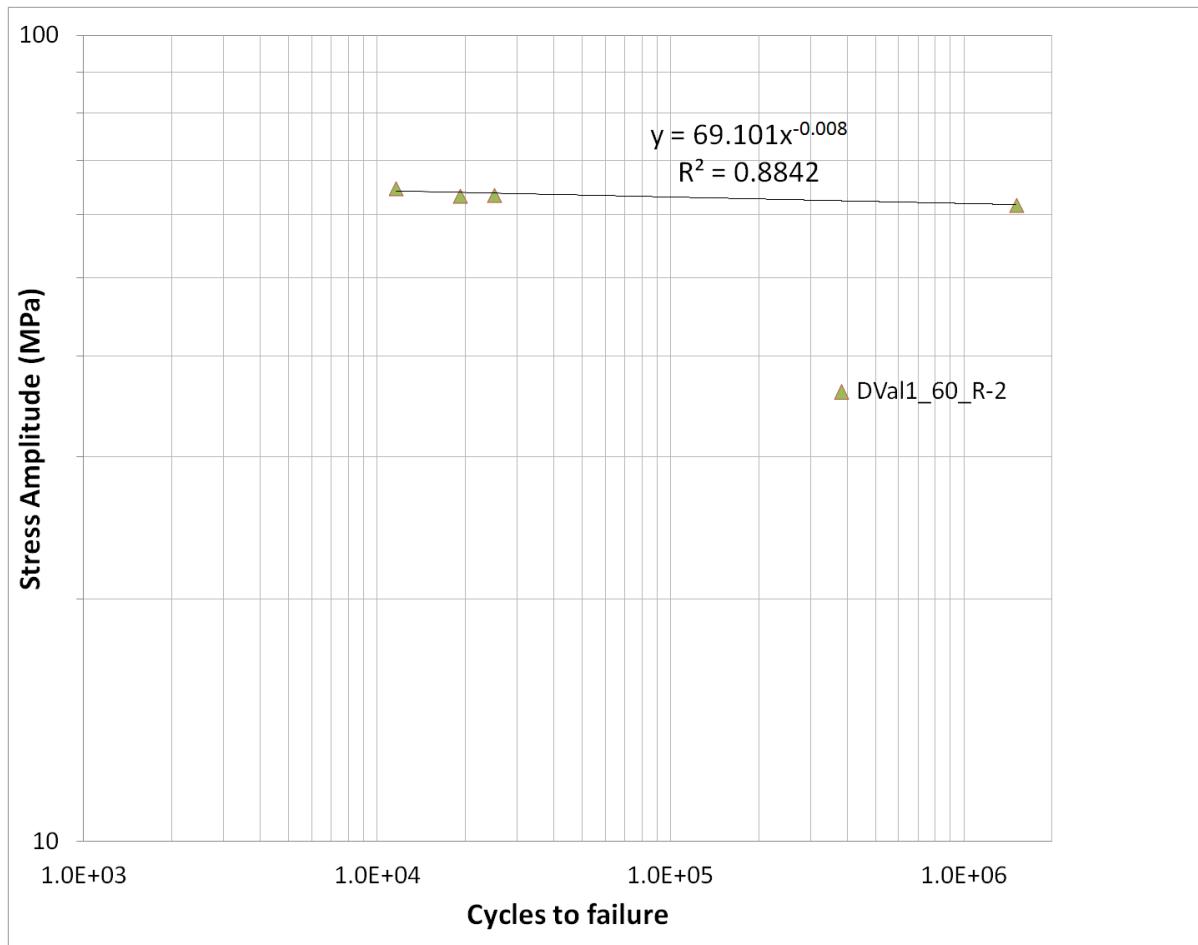


Figure 12 S-N curve. UD laminate 0°. R=0.1

With regard to the Fibre mass fraction, the average measured value is 72.44%. Pictures of the damaged coupons are shown in Appendix 8.1.4.

2.2.2 Benchmarking tests

According to the indications given by IWES (as described in Section 5) two sets of coupons were tested at CENER.

The tests were performed in an electro-mechanic testing machine INSTRON 5589, with a load capacity and a load cell of 600 kN (class 0.5).



Figure 13 Testing machine

2.2.2.1 Coupons manufactured by IWES

These coupons were delivered by IWES and tested at CENER.
The test results are shown in Table 11.

| | width | Thickness | F_{max} | δ_{max} | σ_{max} | E_{side1} | E_{side2} | U_{side1} | U_{side2} |
|------|-------|-----------|-----------|----------------|----------------|-------------|-------------|-------------|-------------|
| | (mm) | (mm) | (N) | (mm) | (MPa) | (MPa) | (MPa) | | |
| 1 | 14,9 | 2,45 | 44300 | 4,84 | 1220 | 45600 | 47200 | 0,285 | 0,29 |
| 2 | 15,8 | 2,4 | 44400 | 4,92 | 1170 | - | 45600 | - | 0,256 |
| 3 | 15,8 | 2,34 | 39900 | 4,55 | 1080 | 44700 | - | 0,256 | - |
| 4 | 14,8 | 2,38 | 41200 | 4,46 | 1160 | 47400 | 47300 | 0,212 | 0,265 |
| 5 | 14,9 | 2,39 | 44600 | 4,91 | 1260 | 47800 | 46400 | 0,257 | 0,271 |
| 6 | 14,9 | 2,36 | 40800 | 4,4 | 1160 | 47600 | 47800 | 0,235 | 0,322 |
| Mean | 15,2 | 2,39 | 42533 | 4,68 | 1175 | 46620 | 46860 | 0,249 | 0,281 |
| Std | 0,5 | 0,04 | 2126 | 0,24 | 61,2 | 1386 | 865 | 0,027 | 0,026 |
| COV | 3,2 | 1,58 | 5,0 | 5,1 | 5,2 | 3,0 | 1,8 | 11,0 | 9,3 |

Table 11. Test summary

(- strain gauges invalid measurements)

The following figures show the strain gauges measurements (in longitudinal ϵ_1 and transversal ϵ_2 direction) vs. load, for both sides of the coupons.

COUPON 1

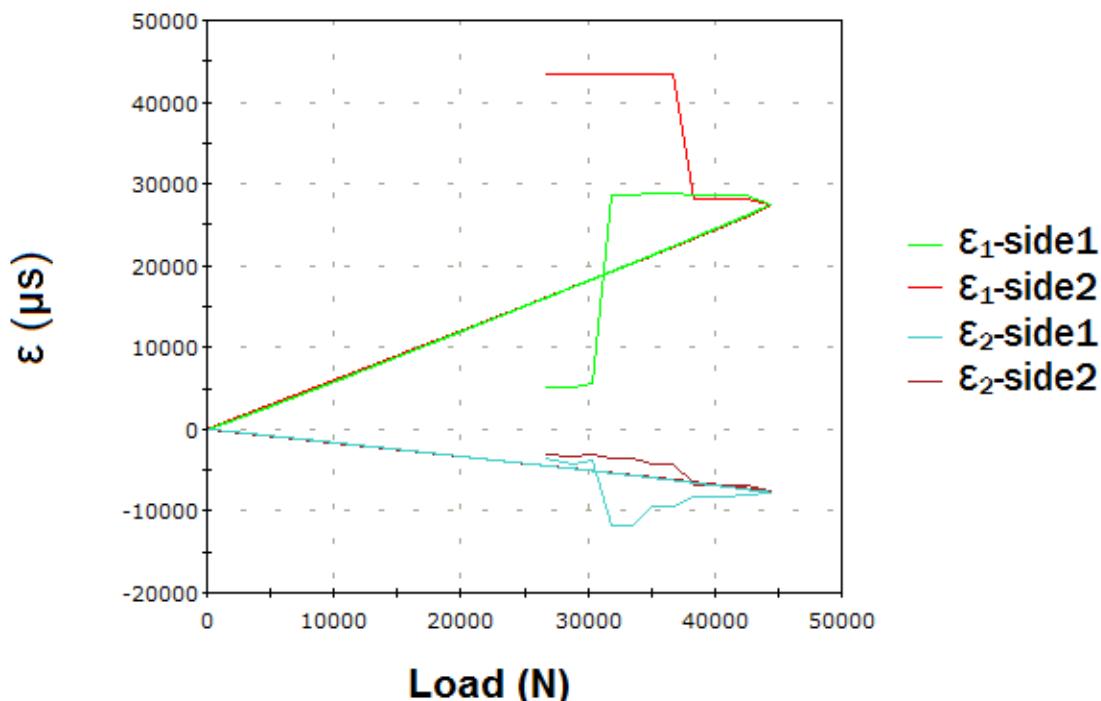


Figure 14 IWES coupons. Strain Measurements. Coupon 1

COUPON 2

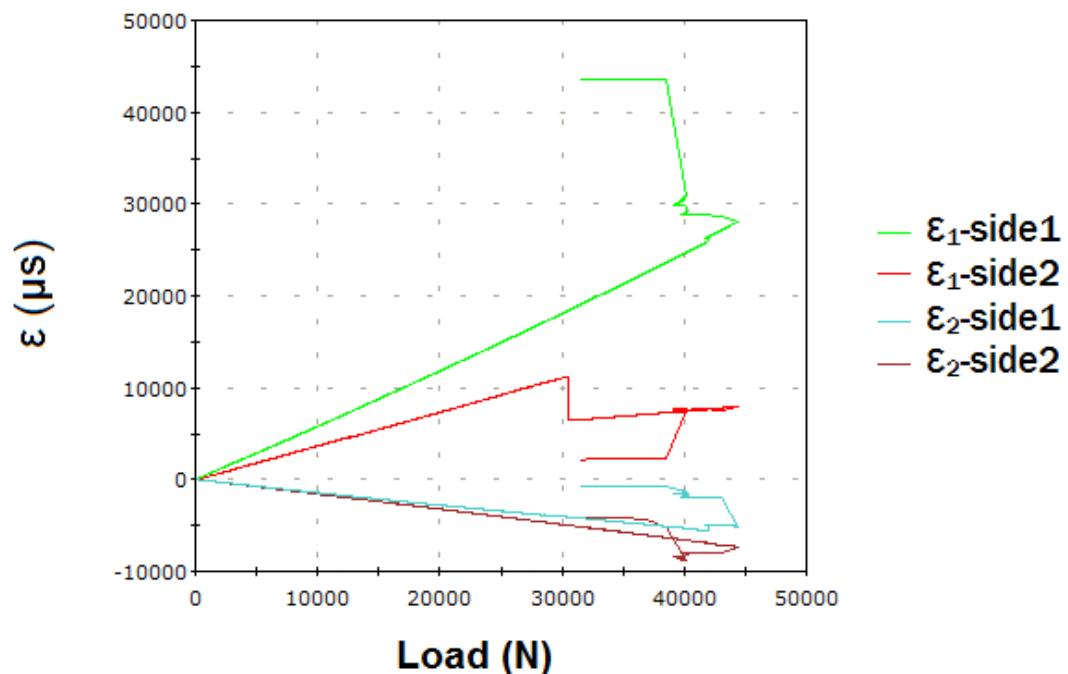


Figure 15 IWES coupons. Strain Measurements. Coupon 2

COUPON 3

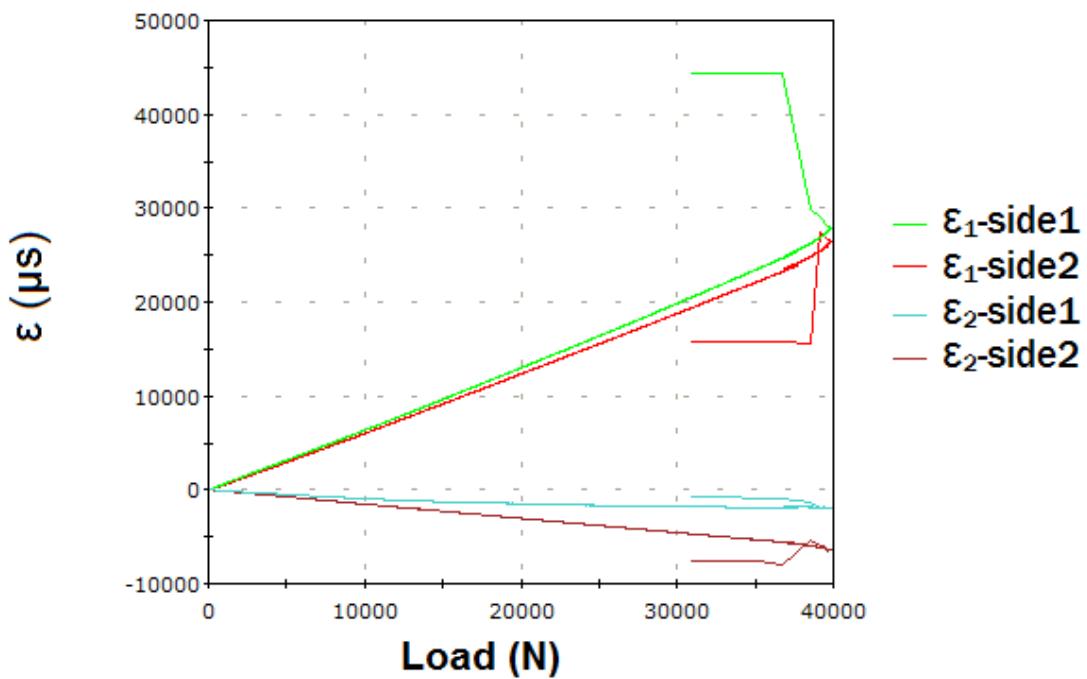


Figure 16 IWES coupons. Strain Measurements. Coupon 3

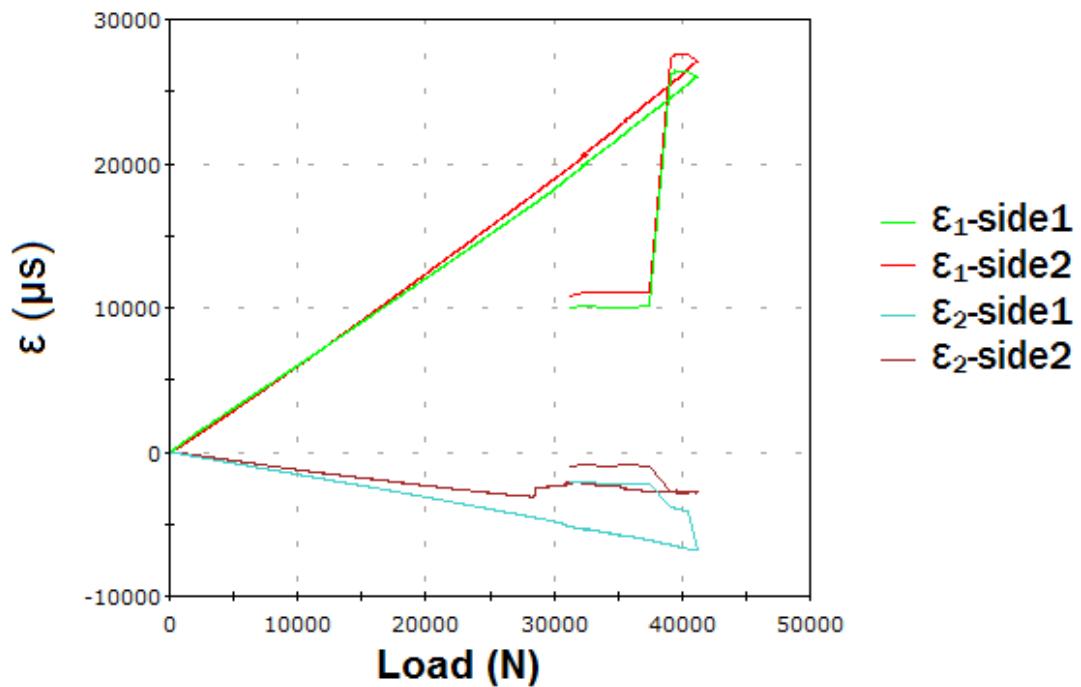
COUPON 4


Figure 17 IWES coupons. Strain Measurements. Coupon 4

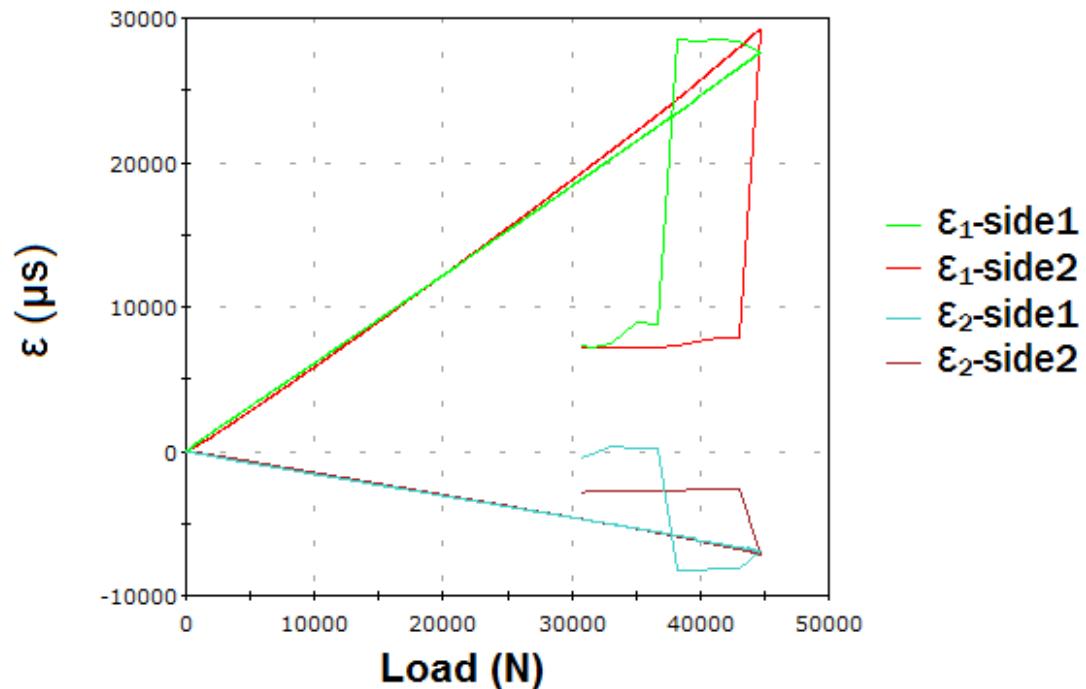
COUPON 5


Figure 18 IWES coupons. Strain Measurements. Coupon 5

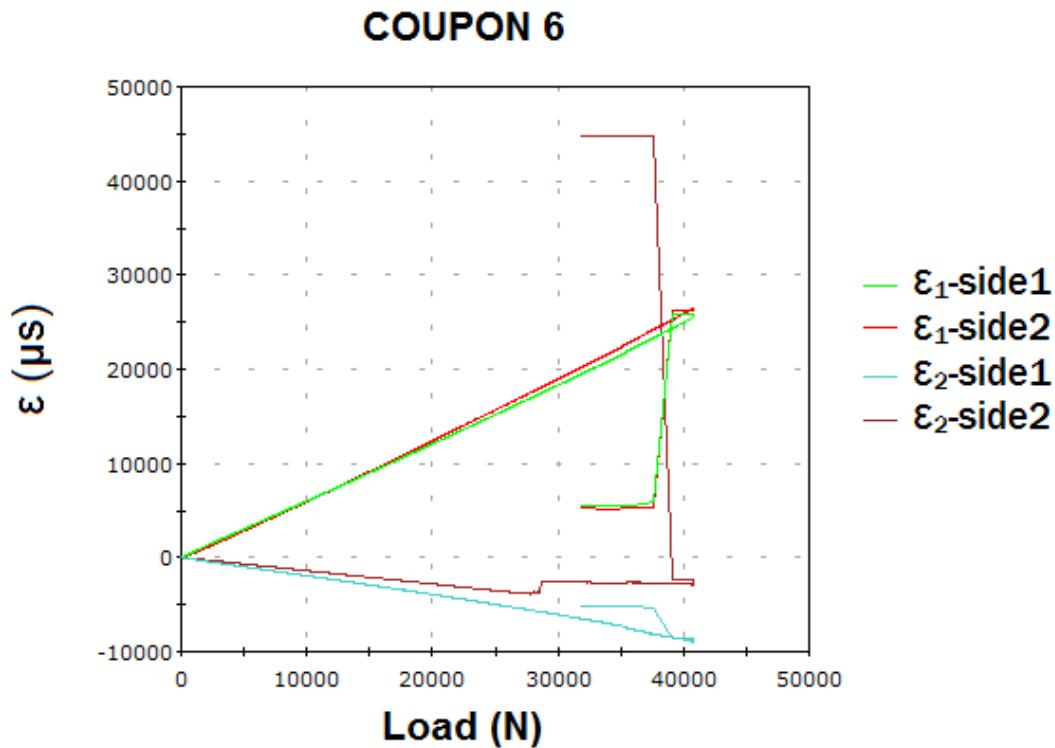


Figure 19 IWES coupons. Strain Measurements. Coupon 6

Pictures of the damaged coupons are shown in Appendix 8.1.5.

2.2.2.2 Coupons manufactured by CENER

These coupons were manufactured and tested at CENER.

The test results are shown in Table 12.

| | width (mm) | Thickness (mm) | F_{max} (N) | δ_{max} (mm) | σ_{max} (MPa) | E_{side1} (MPa) | E_{side2} (MPa) | U_{side1} | U_{side2} |
|------|---------------|-------------------|------------------|------------------------|-------------------------|----------------------|----------------------|-------------|-------------|
| 1 | 15,3 | 2,35 | 40700 | 4,95 | 1130 | 48700 | 47400 | 0,229 | 0,235 |
| 2 | 15,3 | 2,35 | 40500 | 4,91 | 1120 | 51100 | 49800 | 0,274 | 0,28 |
| 3 | 15,7 | 2,28 | 37800 | 4,68 | 1060 | 52200 | 48400 | 0,26 | 0,257 |
| 4 | 15,6 | 2,32 | 41400 | 5,00 | 1150 | 54500 | - | 0,279 | - |
| 5 | 15,9 | 2,31 | 41100 | 4,84 | 1120 | 55100 | 45200 | 0,307 | 0,274 |
| Mean | 15,6 | 2,32 | 40300 | 4,88 | 1116 | 52320 | 47700 | 0,270 | 0,262 |
| Std | 0,3 | 0,03 | 1440 | 0,12 | 33,6 | 2602 | 1936 | 0,028 | 0,020 |
| COV | 1,7 | 1,27 | 3,6 | 2,5 | 3,0 | 5,0 | 4,1 | 10,6 | 7,7 |

Table 12. Test summary

(- strain gauges invalid measurements)

The following figures show the strain gauges measurements (in longitudinal ϵ_1 and transversal ϵ_2 direction) vs. load, for both sides of the coupons.

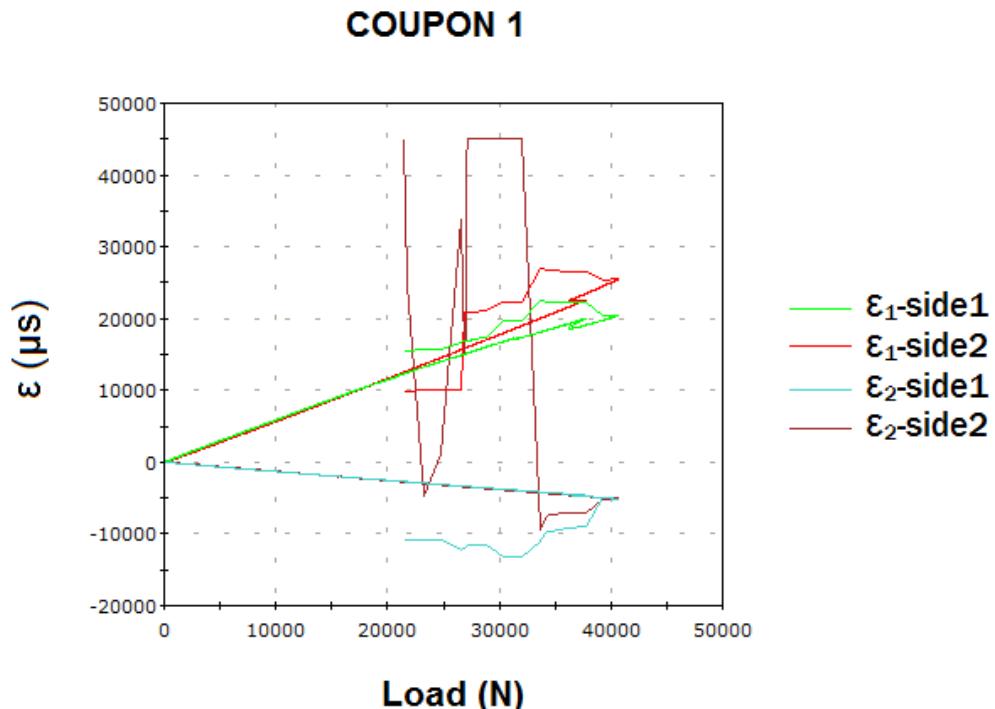


Figure 20 CENER coupons. Strain Measurements. Coupon 1

COUPON 2

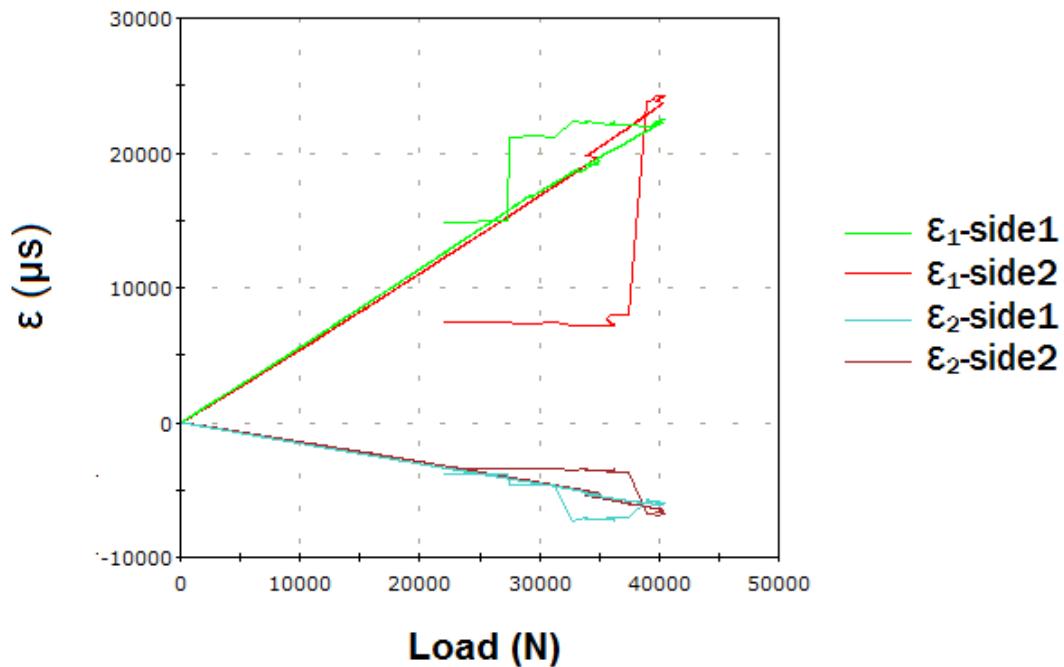


Figure 21 CENER coupons. Strain Measurements. Coupon 2

COUPON 3

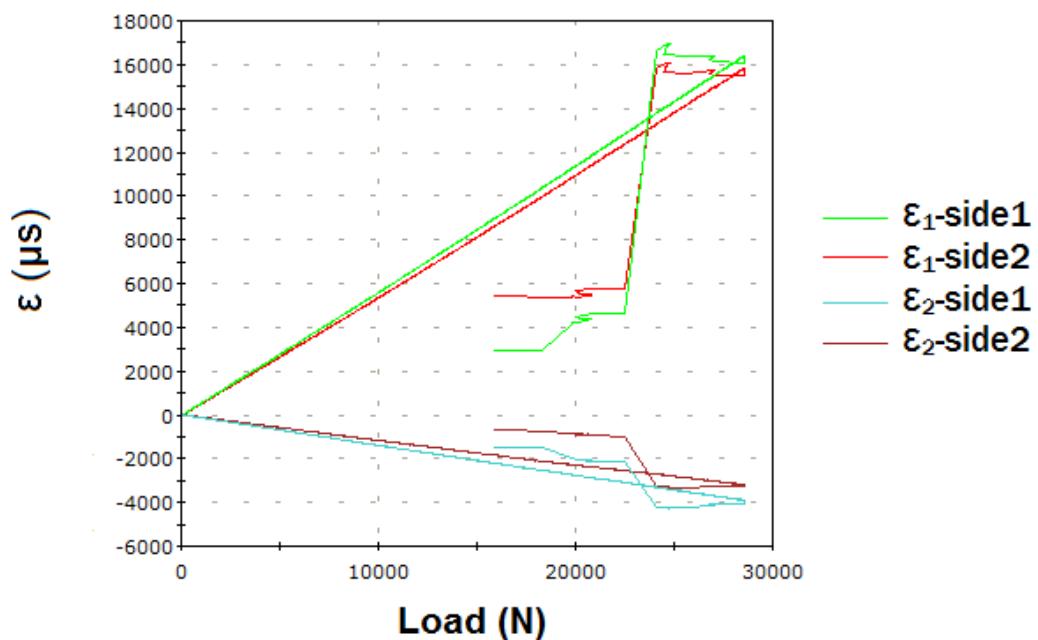


Figure 22 CENER coupons. Strain Measurements. Coupon 3

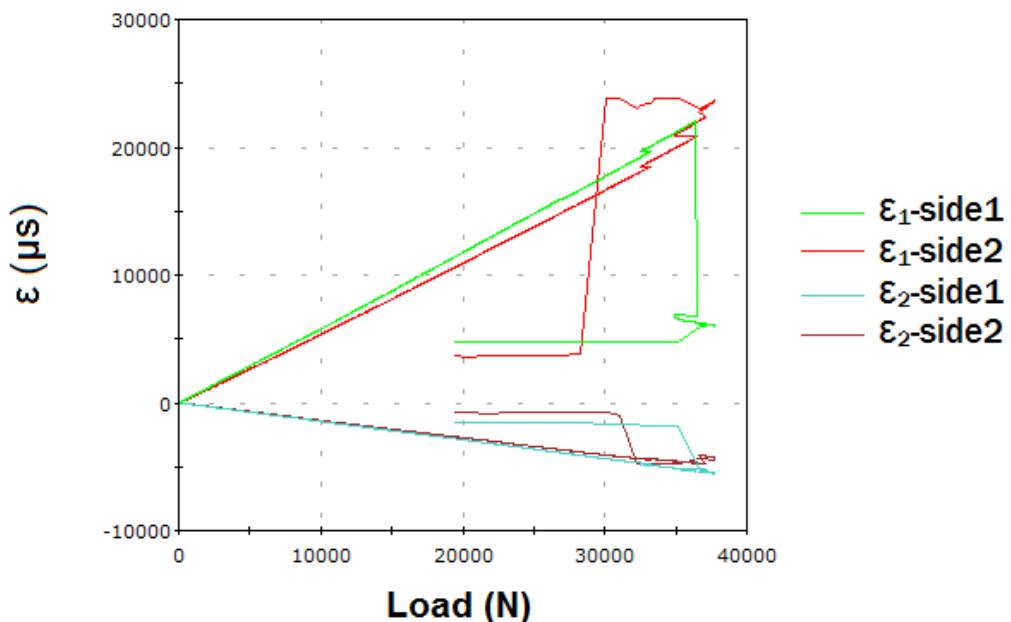
COUPON 4


Figure 23 CENER coupons. Strain Measurements. Coupon 4

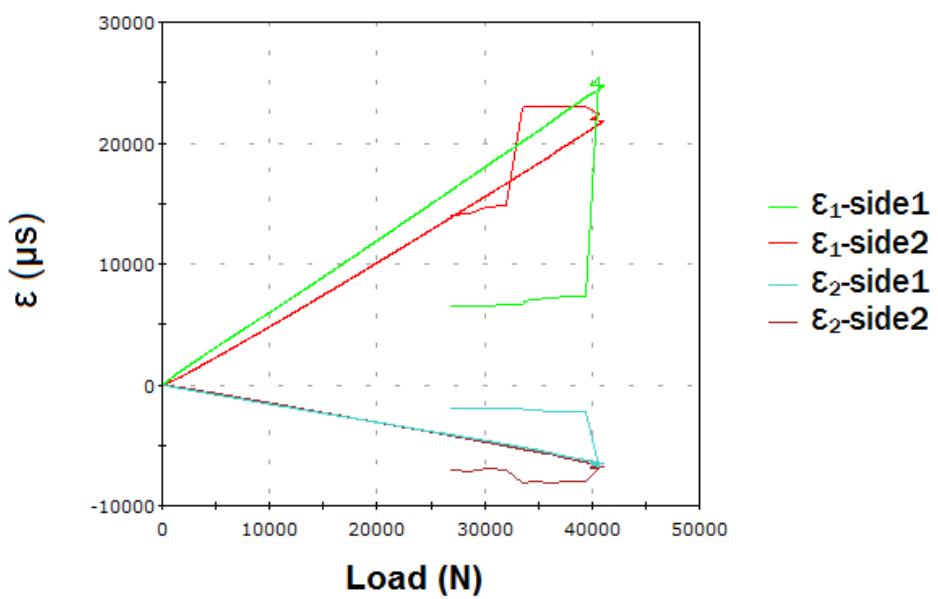
COUPON 5


Figure 24 CENER coupons. Strain Measurements. Coupon 5

Pictures of the damaged coupons are shown in Appendix 8.1.6.

3. IWES test description

3.1 Work Package 1 (WP1)

Coupons were manufactured according CENERS' specification [4] for compression-compression tests with an r ration R=10. Constant amplitude force controlled tests were performed in room temperature. The coupons were installed in an ASTM D6641 [5] test jig see Figure 25.

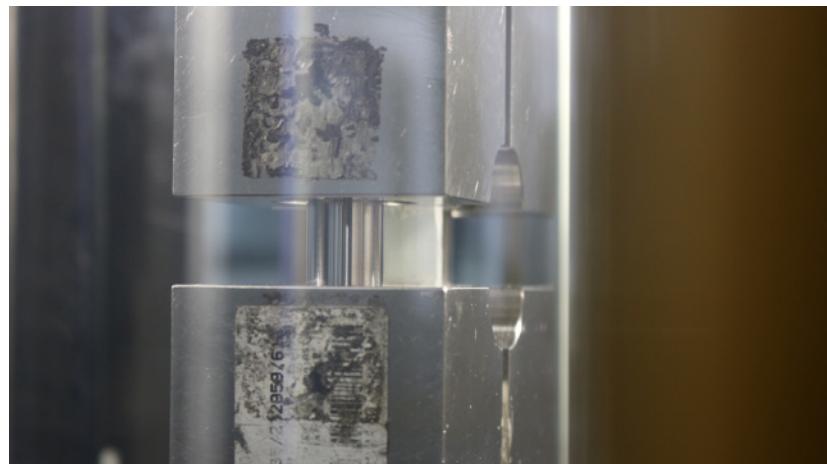


Figure 25 Test jig

Test results are summarized in the following Table.

| Specimen ID | Max. Stress | Test Frequency | Bolts Torque | Cycles to Failure |
|-------------------|-------------|----------------|--------------|-------------------|
| | [MPa] | [Hz] | [Nm] | [-] |
| 111333_001_01_004 | 563 | 1/2/1,5/2,5 | 12 | 1024703 |
| 111333_001_01_006 | 592 | 1 | 12 | 503480 |
| 111333_001_01_007 | 660 | 1 | 12 | 7 |
| 111333_001_01_008 | 630 | 1 | 12 | 76930 |
| 111333_001_01_009 | 611 | 1 | 12 | 131960 |
| 111333_001_01_010 | 607 | 1 | 12 | 31373 |
| 111333_001_01_011 | 611 | 1 | 12 | 13547 |
| 111333_001_01_012 | 585 | 1,8/1,6 | 12 | 24519 |
| 111333_001_01_013 | 620 | 1 | 12 | 8634 |

Table 13. Test results UDO fatigue R=10

The results are graphically presented in Figure 26.

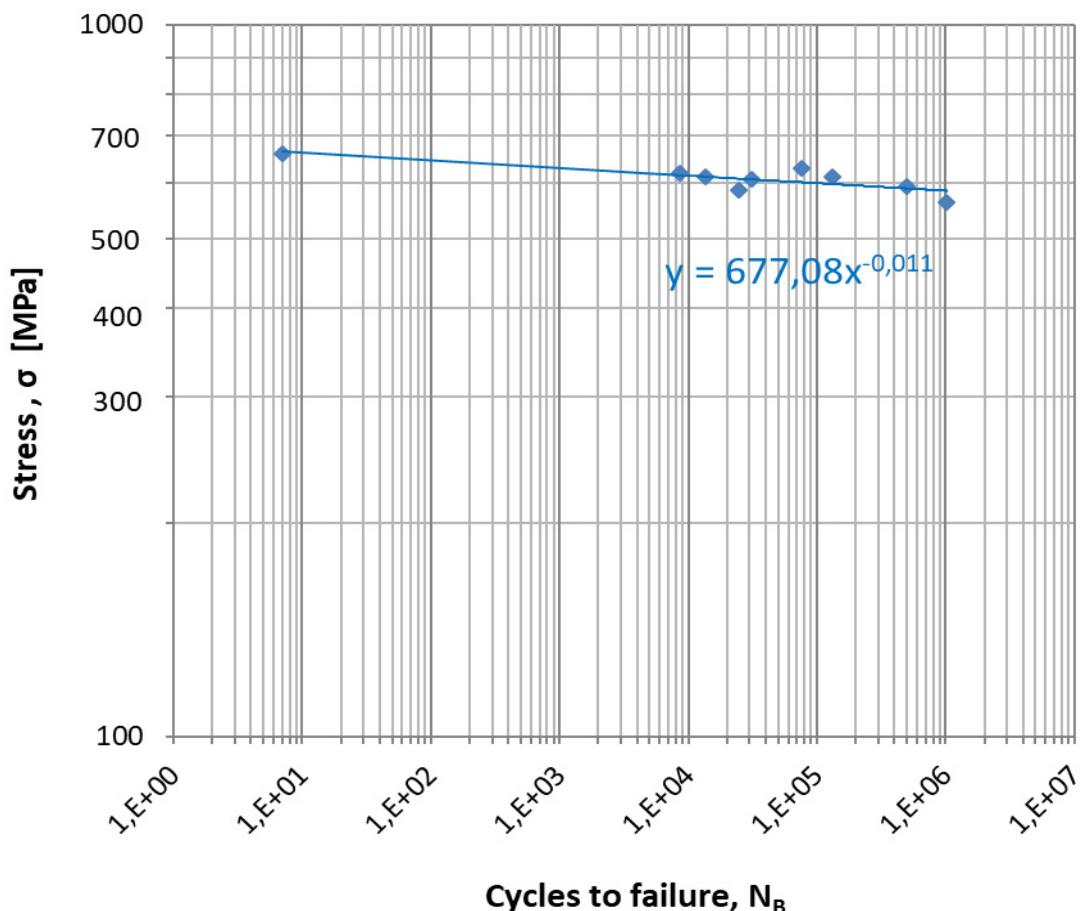


Figure 26 UDO fatigue results R=10

The fatigue performance in a double logarithmic diagram is described with the following formula:

$$y = ax^b \quad (1)$$

where $a=677,08$ and $b=-0,011$.

3.2 Work Package 2 (WP2)

Two [UD]_{2s} plates were manufactured and then off-axis coupons at 5° and 10° degrees were cut out with respect to the fibres orientation. The nominal coupon geometry i.e. 250mm long and 150mm gauge length prohibited fibre bridging from tabs to tabs area. A series of fatigue tests were performed under force control. The results for both tension-tension R=0.1 off-axis coupons are summarized in the following Tables. Static tests are included for completeness.

| Specimen ID | Max. Stress | Test Frequency | Clamps Pressure | Cycles to Failure |
|-------------------|-------------|----------------|-----------------|-------------------|
| | [MPa] | [Hz] | [bar] | [\cdot] |
| 111333_002_01_004 | 426 | 1 | 30 | 204 |
| 111333_002_01_006 | 265 | 1,5 | 30 | 119331 |
| 111333_002_01_007 | 212 | 2 | 30 | 316906 |
| 111333_002_01_010 | 200 | 3 | 20 | 640937 |
| 111333_002_01_011 | 304 | 1 | 30 | 10262 |
| 111333_002_01_012 | 350 | 1 | 30 | 4167 |
| 111333_002_01_013 | 190 | 3 | 20 | 844107 |
| 111333_002_01_015 | 178 | 4 | 20 | 1997520 |
| 111333_002_01_001 | 540 | Quasi-static | 50 | 0,25 |
| 111333_002_01_002 | 522 | Quasi-static | 50 | 0,25 |

Table 14. 5° off-axis specimens

| Specimen ID | Max. Stress | Test Frequency | Clamps Pressure | Cycles to Failure |
|-------------------|-------------|----------------|-----------------|-------------------|
| | [MPa] | [Hz] | [bar] | [\cdot] |
| 111333_003_01_004 | 160 | 1,5 | 30 | 26305 |
| 111333_003_01_005 | 170 | 1,5 | 30 | 15316 |
| 111333_003_01_007 | 150 | 1,5 | 30 | 96906 |
| 111333_003_01_008 | 134 | 2,5 | 30 | 116840 |
| 111333_003_01_009 | 126 | 2,5 | 30 | 312000 |
| 111333_003_01_010 | 118 | 5 | 30 | 5724659 |
| 111333_003_01_001 | 291 | Quasi-static | 50 | 0,25 |
| 111333_003_01_002 | 274 | Quasi-static | 50 | 0,25 |

Table 15. 10° off-axis specimens

The results are graphically presented in the following Figure 27. UDO results are included for completeness (tested from CENER).

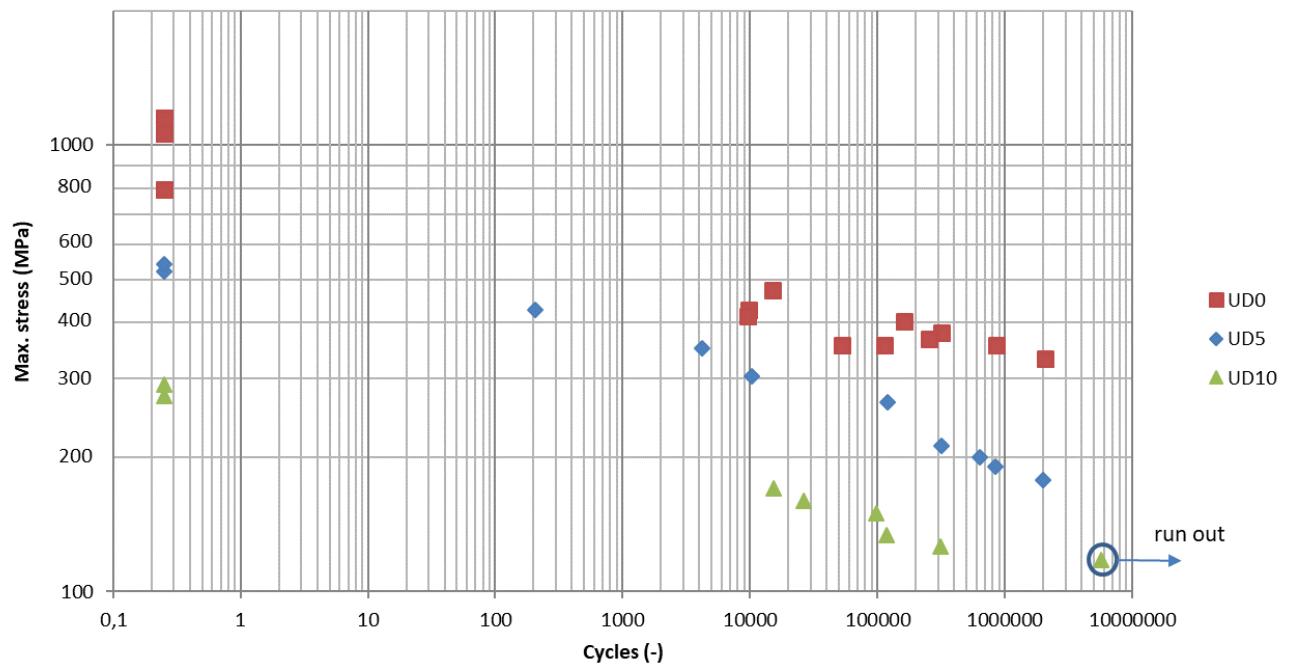


Figure 27 UDO, UD5 and UD10 tension tension results R=0.1

4. WMC test description

4.1 UD-45-STT tension test

| Test specifications | |
|---------------------------------|--|
| Test standard: | ASTM D3039 |
| Fibre direction w.r.t. loading: | UD ± 45 layup [0,90 90,0] |
| Test machine: | MTS 100 kN |
| Grip pressure settings: | 100bar |
| Special fixture: | Test machine grips |
| Strain sensors: | Back to back 2mm cross strain gauges |
| Test speed: | 2 mm/min |
| Test conditions: | Ambient temperature ($23 \pm 2^\circ\text{C}$) |
| Test date & operator: | 15-08-2017, FL, FK |

| Material specifications |
|---|
| UD 1800 gsm, FV HM 3B W2020 |
| MOMENTIVE EPIKOTE MGS RIMR 135 / 035c (Ratio 100:30) |
| MOMENTIVE EPIKURE MGS RIMH 137 |
| Plate 3374 FWR: 73.41% FVC: 54.8% Void content: 0.52% |



Figure 28: Test setup front

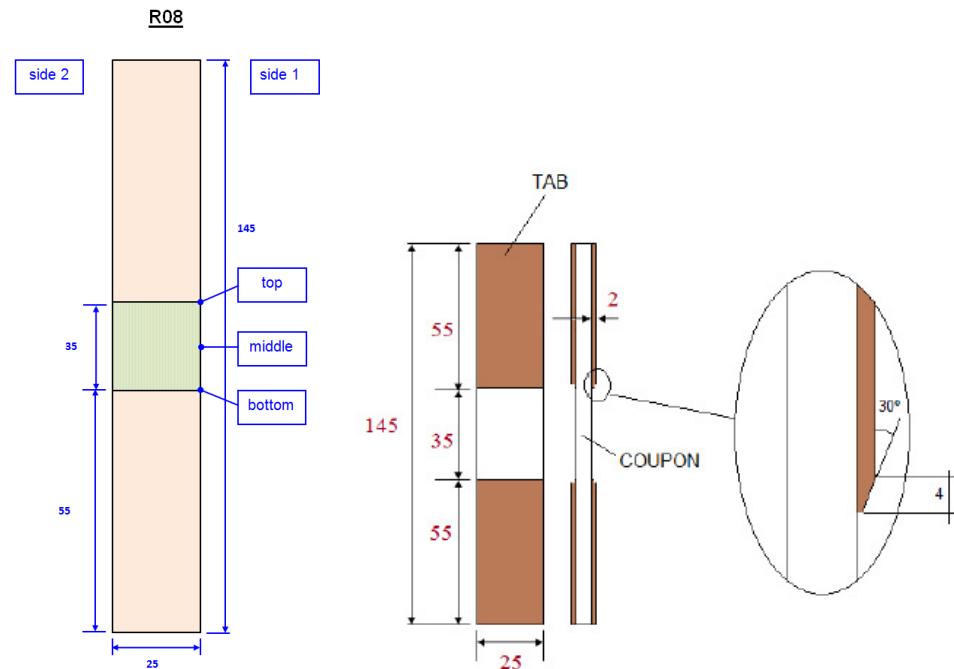


Figure 29: Coupon geometry diagram

| Id | Width | | | Thickness | | | Length | | Area |
|------------|--------|--------|-------|-----------|--------|-------|--------|--------|--------|
| | bottom | middle | top | bottom | middle | top | gauge | total | |
| | [mm] | [mm] | [mm] | [mm] | [mm] | [mm] | [mm] | [mm] | |
| UD-45-16 | 25.05 | 25.20 | 25.02 | 4.91 | 4.94 | 4.94 | 34.30 | 146.1 | 124.4 |
| UD-45-17 | 25.27 | 25.18 | 25.05 | 4.97 | 4.98 | 4.92 | 34.88 | 146.1 | 125.4 |
| UD-45-18 | 25.16 | 25.11 | 25.15 | 4.95 | 4.95 | 4.97 | 35.04 | 146.1 | 124.2 |
| UD-45-19 | 25.29 | 25.01 | 25.07 | 4.93 | 4.95 | 4.96 | 35.37 | 146.1 | 123.7 |
| UD-45-20 | 25.83 | 25.72 | 25.85 | 4.91 | 4.88 | 4.93 | 34.49 | 146.0 | 125.5 |
| Average | 25.32 | 25.24 | 25.23 | 4.93 | 4.94 | 4.94 | 34.82 | 146.08 | 124.62 |
| Deviation | 1.19 | 1.09 | 1.39 | 0.52 | 0.73 | 0.44 | 1.23 | 0.03 | 0.64 |
| Tolerances | ±0.83 | ±0.72 | ±0.85 | ±0.10 | ±0.12 | ±0.08 | ±0.70 | ±1.14 | ±1.33 |
| Nominal | 25 | 25 | 25 | 5 | 5 | 5 | 35 | 145 | 125 |

Table 16: Coupons dimensions

Where amb: ambient, E: elastic modulus, max: ultimate, F: force, δ : displacement, v: Poisson coefficient, T: temperature, amb: ambient

| ID | F _{max} | δ_{max} | σ_{max} | E _{side1} | E _{side2} | v _{side1} | v _{side2} | T _{amb} |
|----------|------------------|-----------------------|-----------------------|--------------------|--------------------|--------------------|--------------------|------------------|
| | [kN] | [mm] | [Mpa] | [GPa] | [GPa] | [-] | [-] | [°C] |
| UD-45-16 | 12.8 | 2.13 | 103.0 | 13.8 | 16.9 | 0.643 | 0.592 | 22.4 |
| UD-45-17 | 12.1 | 1.44 | 96.8 | 12.6 | 11.7 | 0.648 | 0.605 | 23.0 |
| UD-45-18 | 12.3 | 1.63 | 98.7 | 13.1 | 12.3 | 0.685 | 0.599 | 23.2 |
| UD-45-19 | 12.5 | 1.66 | 100.8 | 12.6 | 12.8 | 0.665 | 0.612 | 23.0 |
| UD-45-20 | 14.0 | 2.31 | 111.5 | 12.9 | 13.9 | 0.623 | 0.671 | 23.3 |
| | | | | | | | | |
| Mean | 12.7 | 1.83 | 102.2 | 13.0 | 13.5 | 0.653 | 0.616 | 23.0 |
| Std | 0.75 | 0.369 | 5.7 | 0.47 | 2.03 | 0.023 | 0.032 | 0.38 |
| COV | 6% | 20% | 6% | 4% | 15% | 4% | 5% | 2% |

Table 17: Test summary

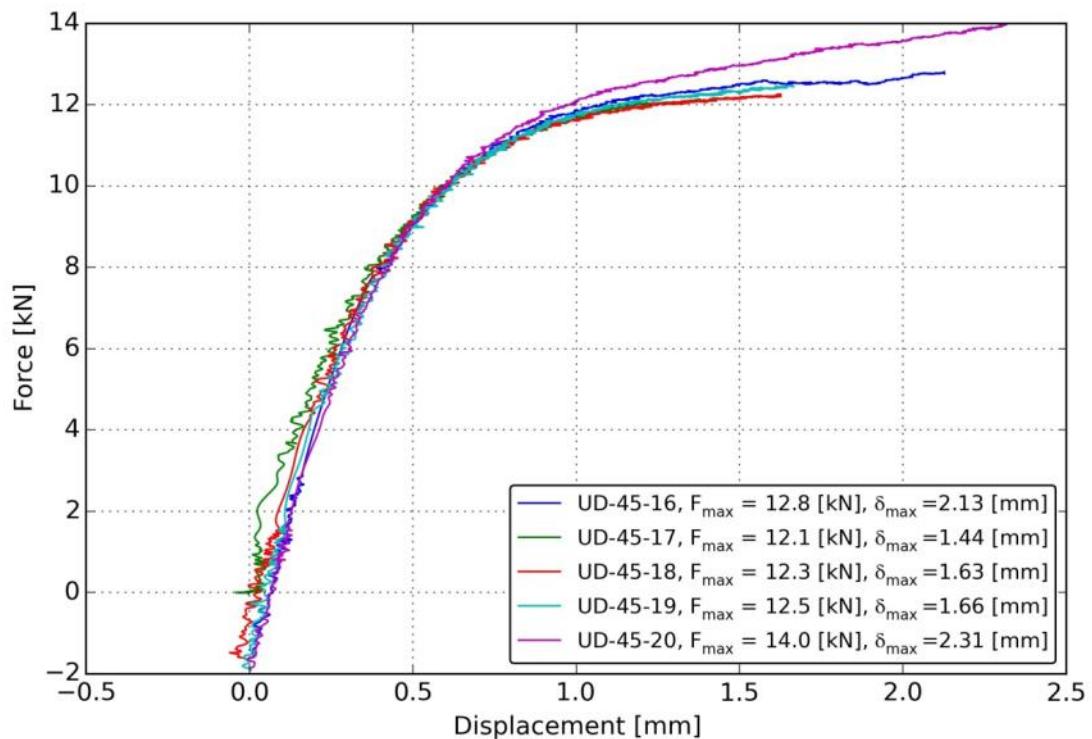


Figure 30: Force versus displacement

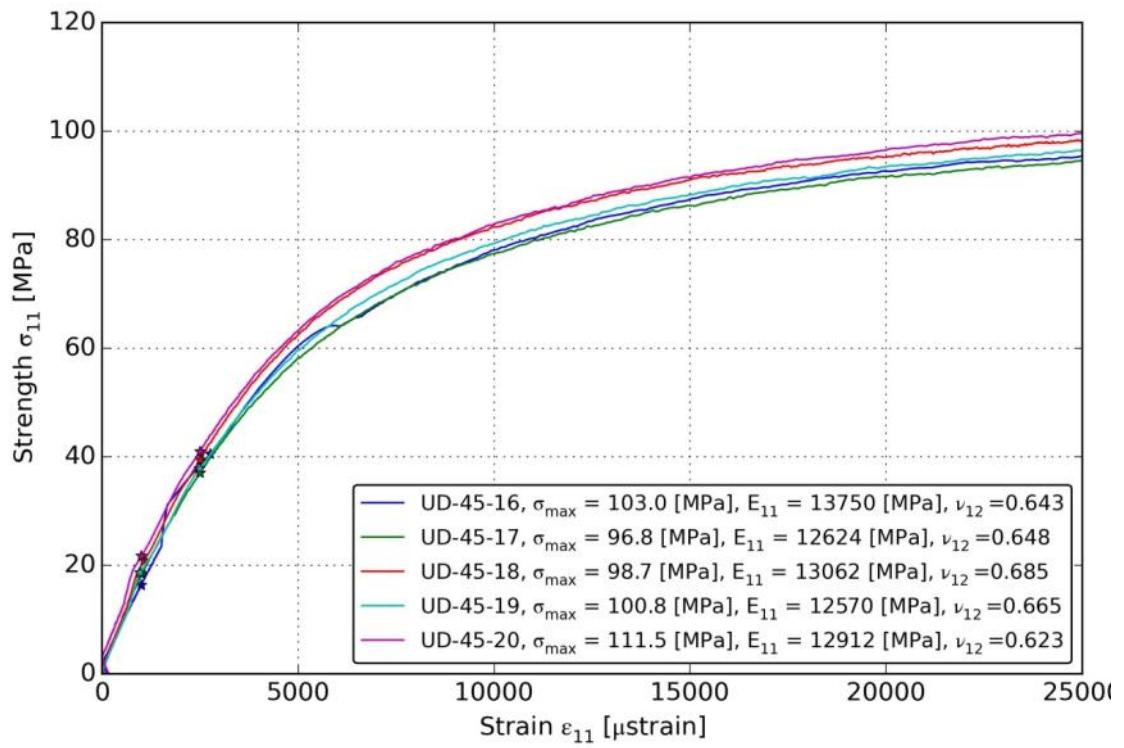


Figure 31: Stress versus strain

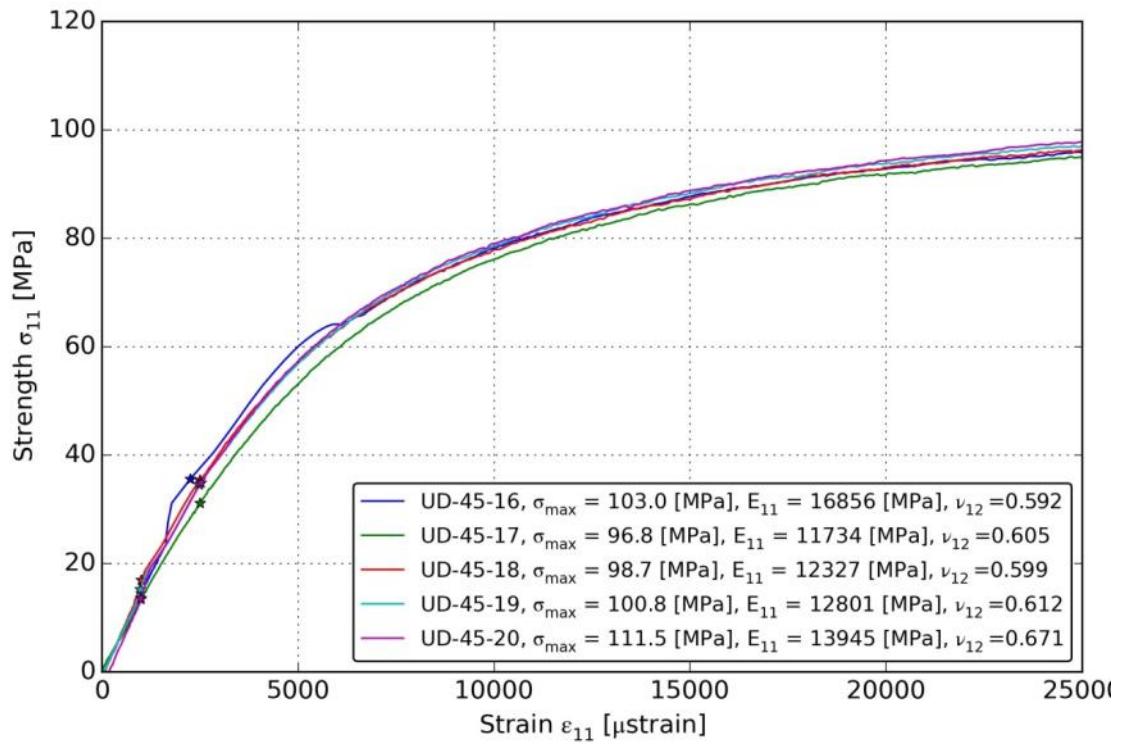


Figure 32: Stress versus strain side 2

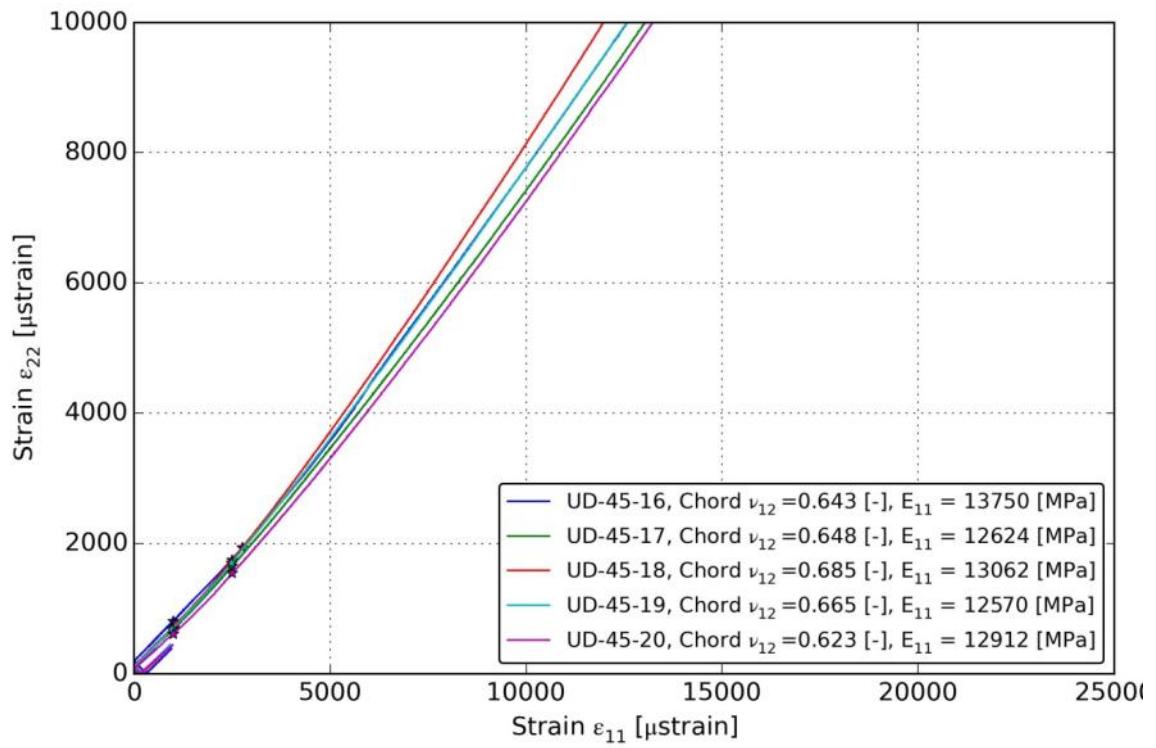


Figure 33: Strain 1 versus strain 2, side 1

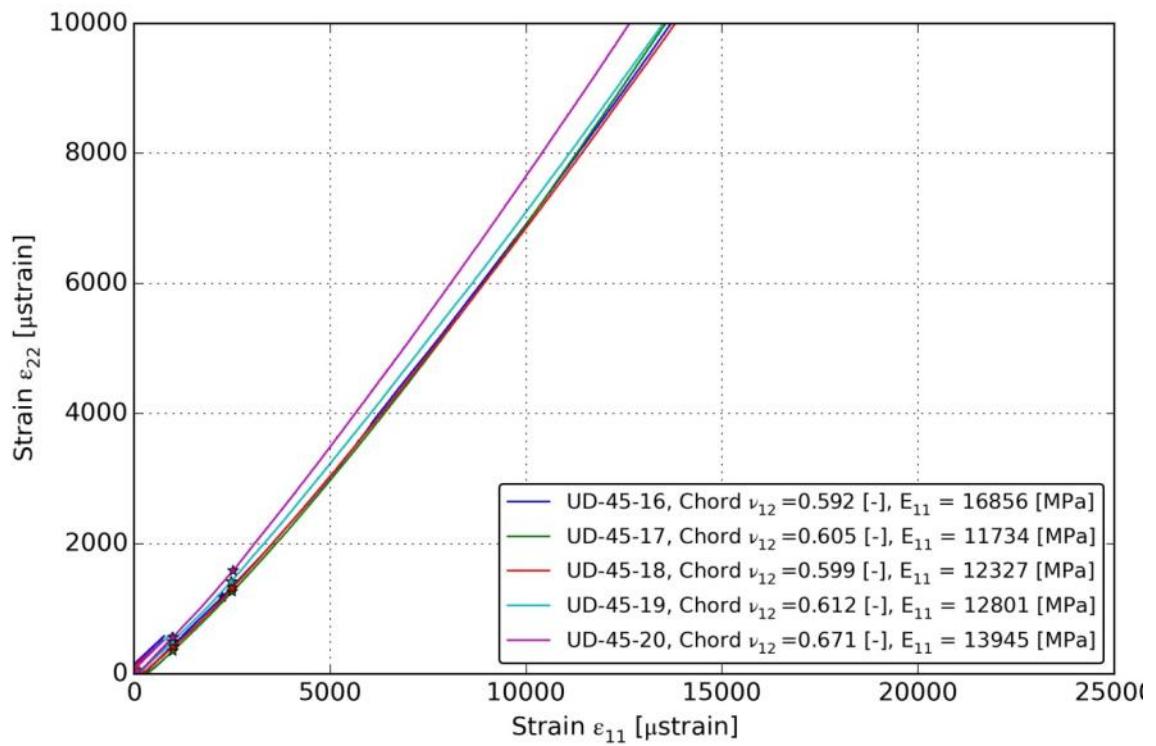


Figure 34: Strain 1 versus strain 2, side 2

4.2 UD ±45 layup test CA R=0.1

| Test specifications | |
|---------------------------------|--|
| Test standard: | Fatigue ASTM D3479 accommodated to compression (change in coupon geometry) R=0.1 |
| Fibre direction w.r.t. loading: | UD ±45 layup [0,90 90,0] |
| Test machine: | MTS 100 kN |
| Grip pressure settings: | 100bar |
| Special fixture: | Test machine grips |
| Strain sensors: | None |
| Test speed: | 2 to 3 Hz |
| Test conditions: | Ambient temperature (23±2 °C) |
| Test date & operator: | 15-08-2017, FL, FK |

| Material specifications |
|---|
| UD 1800 gsm, FV HM 3B W2020 |
| MOMENTIVE EPIKOTE MGS RIMR 135 / 035c (Ration 100:30) |
| MOMENTIVE EPIKURE MGS RIMH 137 |
| Plate 3374 FWR: 73.41% FVC: 54.8 Void content:0.52% |

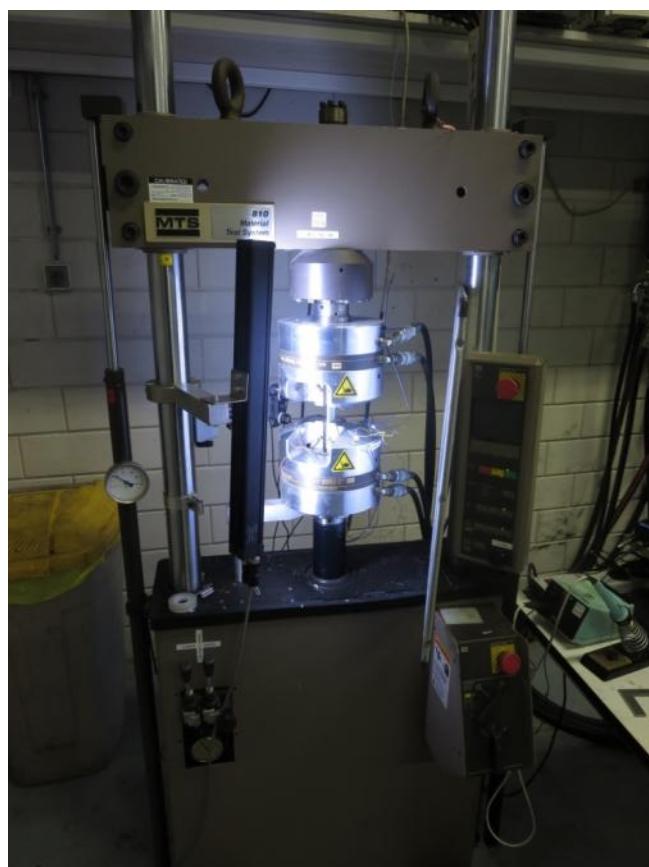


Figure 35: Test setup front

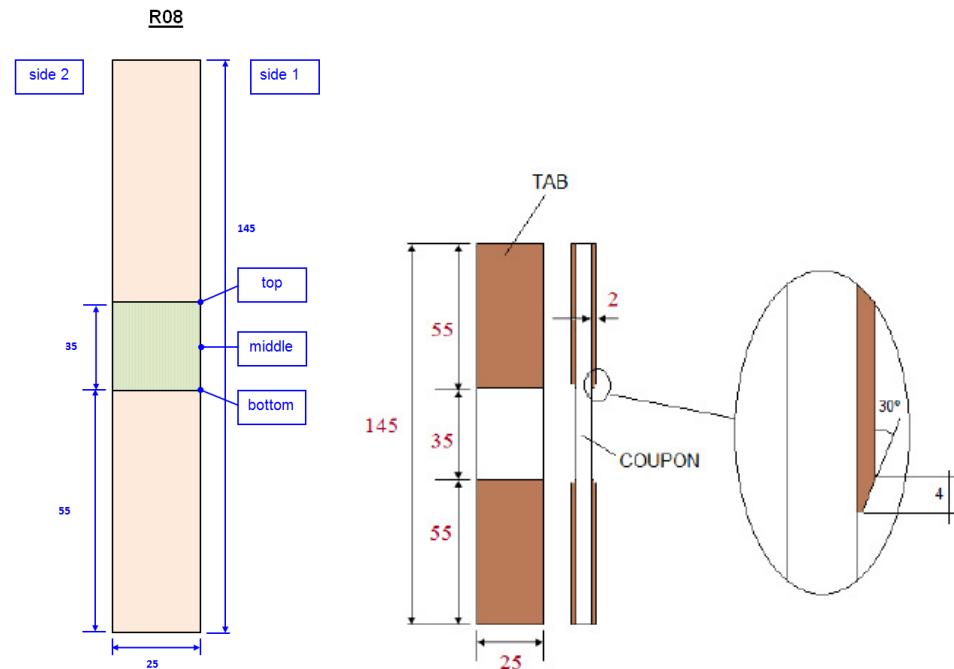


Figure 36: Coupon geometry diagram

| Id | Width | | | Thickness | | | Length | | Area |
|------------|--------|--------|-------|-----------|--------|-------|--------|--------|--------|
| | bottom | middle | top | bottom | middle | top | gauge | total | |
| | [mm] | [mm] | [mm] | [mm] | [mm] | [mm] | [mm] | [mm] | |
| UD-45-06 | 24.97 | 24.96 | 24.97 | 4.91 | 5.01 | 5.03 | 34.11 | 146.2 | 124.9 |
| UD-45-07 | 25.02 | 24.99 | 24.99 | 4.97 | 5.14 | 5.08 | 34.42 | 146.2 | 128.3 |
| UD-45-08 | 24.94 | 24.98 | 24.96 | 4.98 | 5.01 | 4.98 | 34.37 | 146.2 | 125.1 |
| UD-45-09 | 25.10 | 24.95 | 24.95 | 4.94 | 4.97 | 5.01 | 34.71 | 146.0 | 123.9 |
| UD-45-10 | 24.92 | 24.91 | 24.93 | 4.96 | 4.91 | 5.02 | 33.99 | 146.2 | 122.3 |
| UD-45-11 | 24.97 | 24.91 | 24.91 | 4.99 | 5.08 | 5.13 | 34.13 | 146.2 | 126.4 |
| UD-45-12 | 24.94 | 24.97 | 24.95 | 4.94 | 4.99 | 4.93 | 33.70 | 146.3 | 124.6 |
| UD-45-13 | 24.95 | 24.95 | 24.99 | 5.00 | 5.01 | 5.02 | 34.18 | 146.3 | 124.9 |
| UD-45-14 | 24.97 | 24.94 | 24.96 | 5.03 | 5.03 | 5.01 | 34.50 | 146.0 | 125.3 |
| Average | 24.98 | 24.95 | 24.96 | 4.97 | 5.01 | 5.02 | 34.23 | 146.17 | 125.09 |
| Deviation | 0.22 | 0.11 | 0.10 | 0.72 | 1.27 | 1.14 | 0.88 | 0.06 | 1.32 |
| Tolerances | ±0.10 | ±0.09 | ±0.09 | ±0.09 | ±0.14 | ±0.13 | ±1.30 | ±1.31 | ±3.32 |
| Nominal | 25 | 25 | 25 | 5 | 5 | 5 | 35 | 145 | 125 |

Table 18: Coupons dimensions

Where amb: ambient, E: elastic modulus, max: ultimate, F: force, δ : displacement, v: Poisson coefficient, T: temperature, amb: ambient

| ID | F _{max} | F _{min} | σ_{\max} | σ_{\min} | δ_{\min} | δ_{\max} | N | T _{avg} Ambient | T _{max} Surface | RunOut |
|----------|------------------|------------------|-----------------|-----------------|-----------------|-----------------|----------|-----------------------------|-----------------------------|--------|
| | [kN] | [kN] | [MPa] | [MPa] | [mm] | [mm] | [cycles] | [°C] | [°C] | |
| UD-45-07 | 8.68 | 0.87 | 67.6 | 6.8 | 0.27 | 0.69 | 4310 | 22.6 | 23.4 | FALSE |
| UD-45-08 | 7.44 | 0.74 | 59.4 | 5.9 | 0.13 | 0.47 | 29434 | 22.7 | 23.5 | FALSE |
| UD-45-09 | 7.44 | 0.74 | 60.1 | 6.0 | 0.12 | 0.46 | 20051 | 22.7 | 23.5 | FALSE |
| UD-45-10 | 6.20 | 0.62 | 50.7 | 5.1 | 0.95 | 1.24 | 223204 | 22.5 | 23.4 | FALSE |
| UD-45-11 | 6.20 | 0.62 | 49.0 | 4.9 | | | 171375 | 22.9 | 23.5 | FALSE |
| UD-45-12 | 4.96 | 0.54 | 39.8 | 4.3 | 0.03 | 0.27 | 3768610 | 22.5 | 23.4 | FALSE |
| UD-45-13 | 4.96 | 0.50 | 39.7 | 4.0 | | | 2697305 | 22.1 | 23.2 | FALSE |

Table 19: Test summary

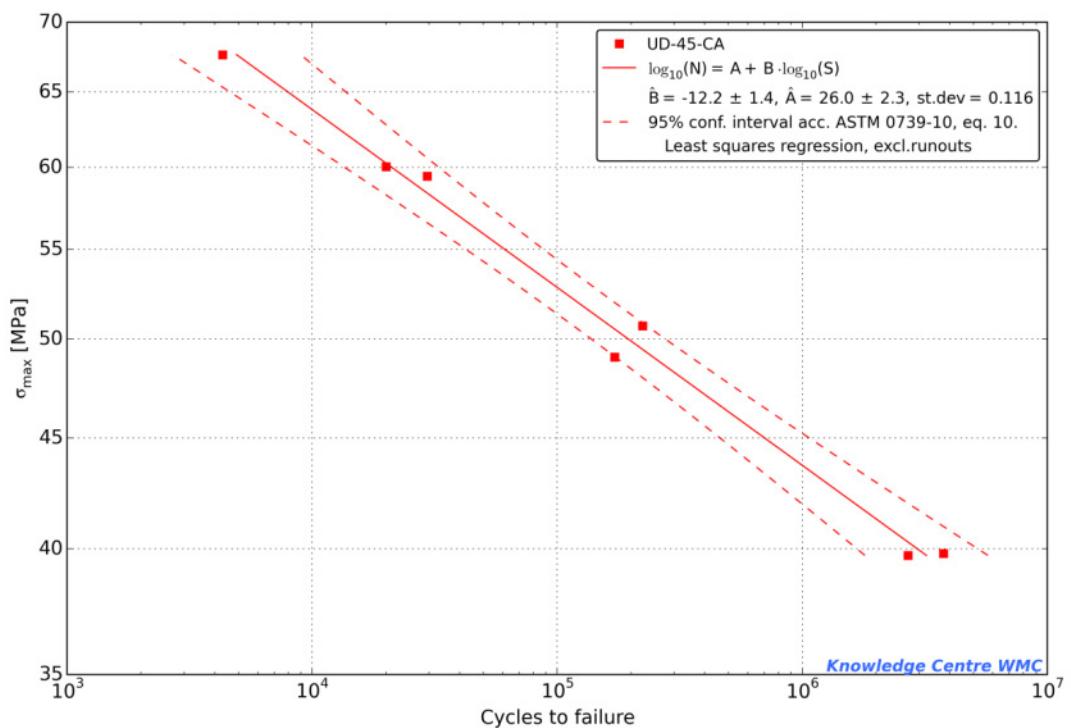


Figure 37: S-N curve

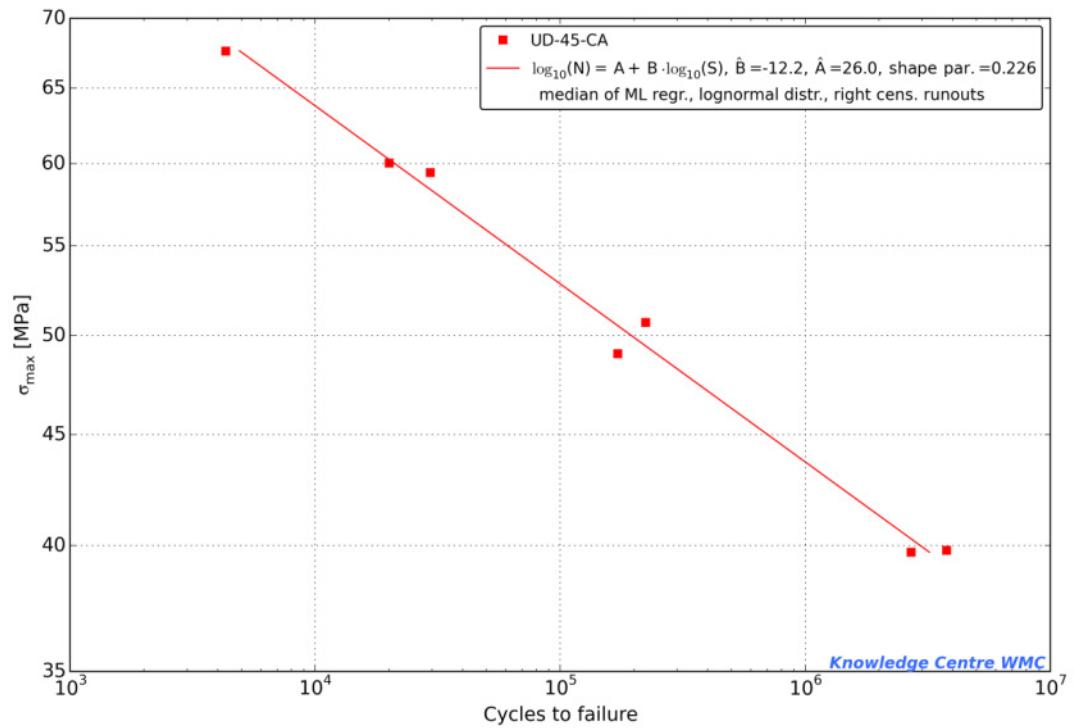


Figure 38: S-N curve (likelihood model)

4.3 UD 90 layup test CA R=0.1

| Test specifications | |
|------------------------------------|--------------------------------------|
| Test standard: | ASTM D3039 |
| Fibre direction w.r.t. loading: | UD 90 layup [0,0] |
| Test machine: | MTS 100 kN |
| Grip pressure settings: | 100bar |
| Special fixture: | Test machine grips |
| Strain sensors: | Back to back 2mm cross strain gauges |
| Test speed: | 2 mm/min |
| Test conditions: | Ambient temperature (23±2 °C) |
| Test date & operator: | 15-08-2017, FL, FK |

| Material specifications | |
|--|--|
| UD 1800 gsm, FV HM 3B W2020 | |
| MOMENTIVE EPIKOTE MGS RIMR 135 / 035c (Ratio 100:30) | |
| MOMENTIVE EPIKURE MGS RIMH 137 | |
| Plate 3373 FWR: 73.2% FVC: 55.5 Void content:-0.3% | |

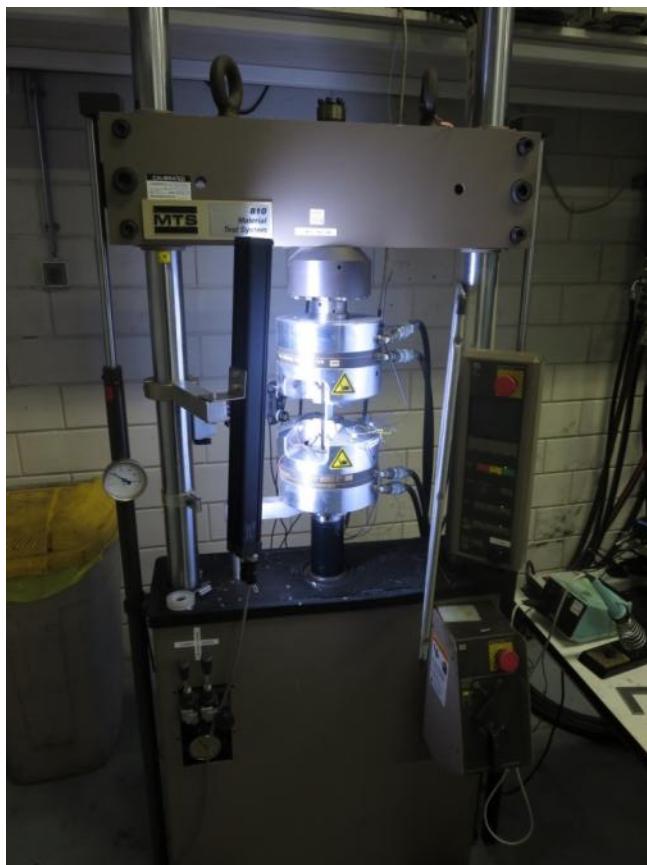


Figure 39: Test setup front

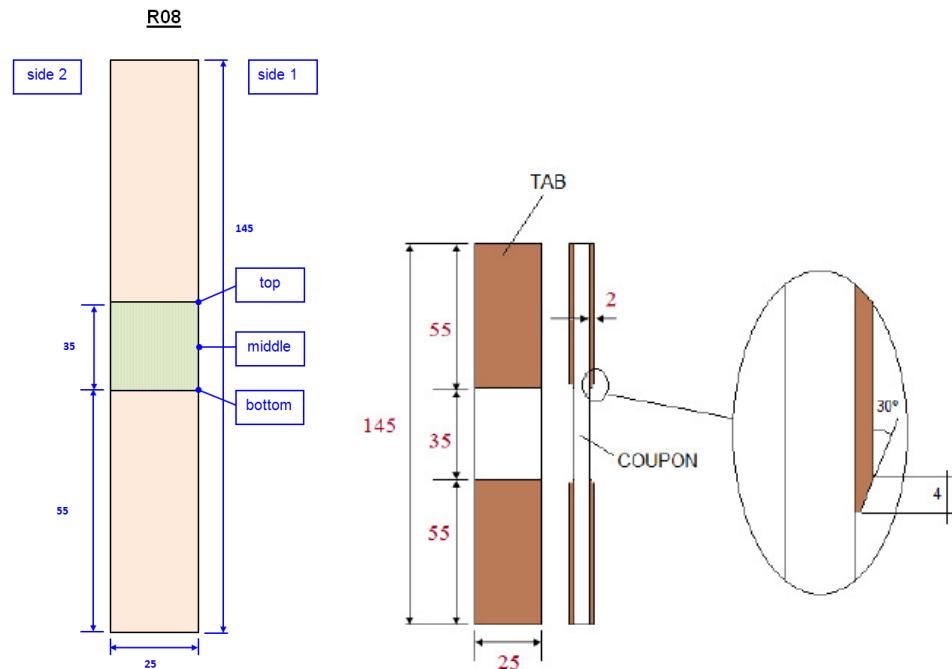


Figure 40: Coupon geometry diagram

| Id | Width | | | Thickness | | | Length | | Area |
|------------|--------|--------|-------|-----------|--------|-------|--------|--------|-------|
| | bottom | middle | top | bottom | middle | top | gauge | total | |
| | [mm] | [mm] | [mm] | [mm] | [mm] | [mm] | [mm] | [mm] | |
| UD-90-15 | 25.04 | 25.08 | 25.05 | 2.55 | 2.59 | 2.67 | 34.44 | 145.0 | 65.0 |
| UD-90-19 | 25.04 | 25.04 | 25.04 | 2.48 | 2.55 | 2.57 | 34.80 | 144.9 | 63.7 |
| UD-90-20 | 25.07 | 25.05 | 25.07 | 2.51 | 2.63 | 2.56 | 33.65 | 144.9 | 65.9 |
| UD-90-21 | 25.03 | 24.93 | 25.01 | 2.55 | 2.56 | 2.53 | 34.08 | 144.9 | 63.7 |
| UD-90-22 | 25.10 | 25.04 | 25.08 | 2.56 | 2.60 | 2.53 | 34.19 | 144.8 | 65.0 |
| UD-90-23 | 25.37 | 25.21 | 25.09 | 2.54 | 2.53 | 2.53 | 33.58 | 144.9 | 63.8 |
| Average | 25.11 | 25.06 | 25.06 | 2.53 | 2.57 | 2.56 | 34.12 | 144.90 | 64.50 |
| Deviation | 0.52 | 0.36 | 0.12 | 1.18 | 1.45 | 2.13 | 1.37 | 0.05 | 1.41 |
| Tolerances | ±0.37 | ±0.21 | ±0.09 | ±0.06 | ±0.13 | ±0.17 | ±1.42 | ±0.17 | ±3.38 |
| Nominal | 25 | 25 | 25 | 2.5 | 2.5 | 2.5 | 35 | 145 | 62.5 |

Table 20: Coupons dimensions

Where amb: ambient, E: elastic modulus, max: ultimate, F: force, δ : displacement, v: Poisson coefficient, T: temperature, amb: ambient

| ID | F_{max} | δ_{max} | σ_{max} | E_{side1} | E_{side2} | v_{side1} | v_{side2} | T_{amb} |
|----------|-----------|----------------|----------------|-------------|-------------|-------------|-------------|-----------|
| | [kN] | [mm] | [Mpa] | [GPa] | [GPa] | [-] | [-] | [°C] |
| UD-90-19 | 3.5 | 0.43 | 55.4 | 15.8 | | 0.081 | 0.104 | 22.0 |
| UD-90-20 | 3.4 | 0.71 | 52.2 | | 10.7 | 0.306 | 0.093 | 23.1 |
| UD-90-21 | 3.1 | 0.56 | 49.1 | | 32.3 | 0.216 | 0.096 | 23.0 |
| UD-90-23 | 3.8 | 0.91 | 59.2 | 15.7 | 32.9 | 0.080 | 0.089 | 23.3 |
| | | | | | | | | |
| Mean | 3.5 | 0.65 | 54.0 | 15.7 | 25.3 | 0.171 | 0.096 | 22.8 |
| Std | 0.27 | 0.206 | 4.3 | 0.05 | 12.61 | 0.110 | 0.006 | 0.58 |
| COV | 8% | 32% | 8% | 0% | 50% | 65% | 7% | 3% |

Table 21: Test summary

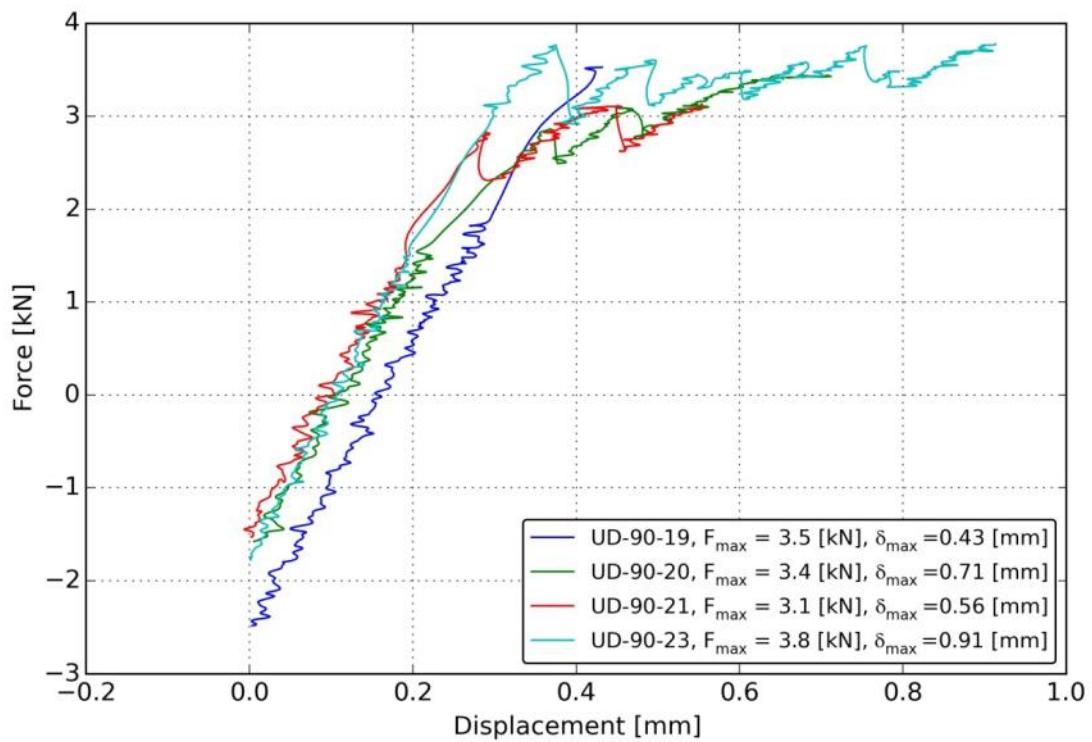


Figure 41: Force versus displacement

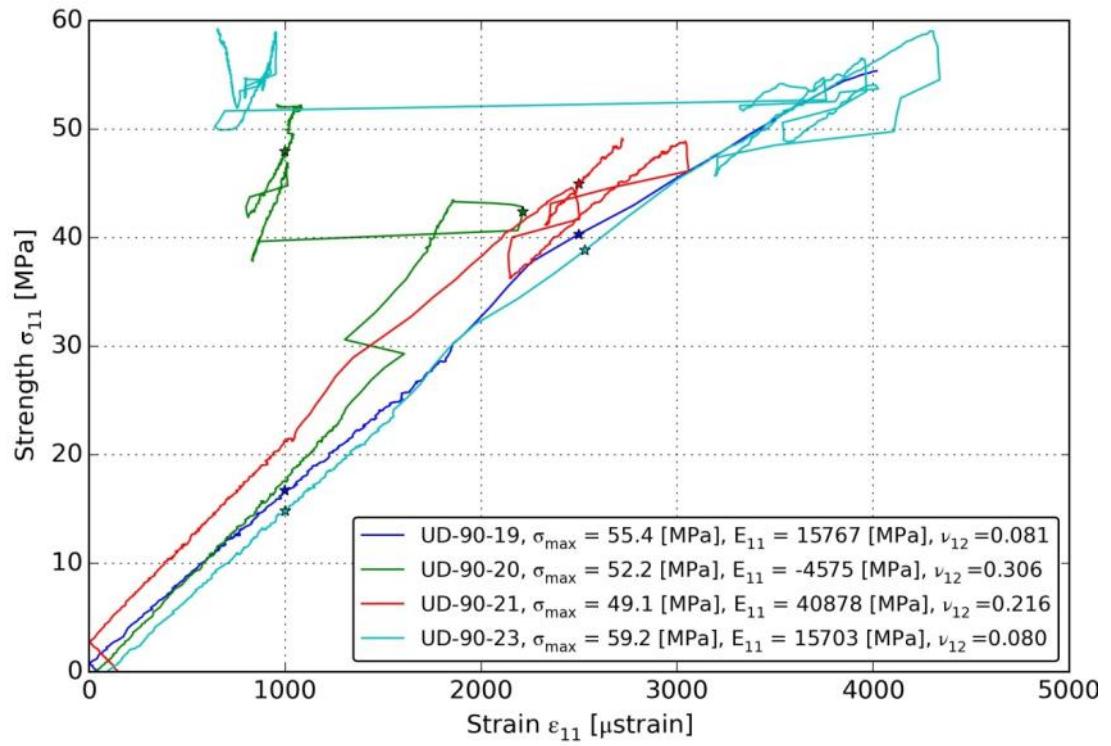


Figure 42: Stress versus strain

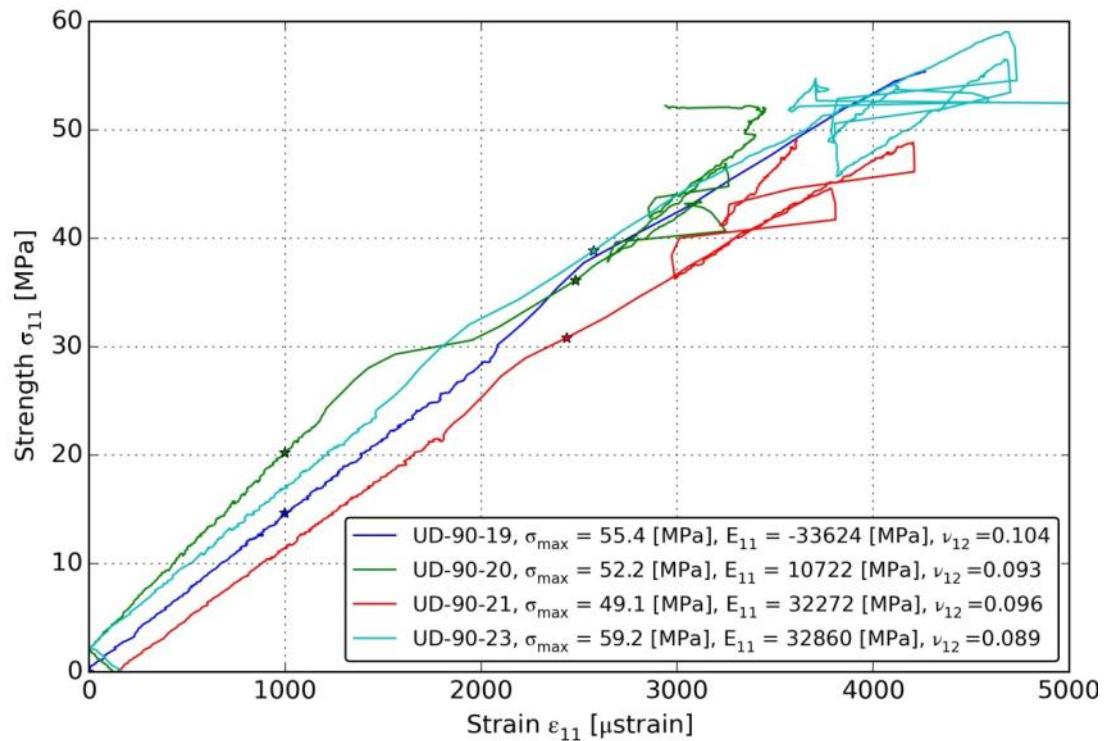


Figure 43: Stress versus strain side 2

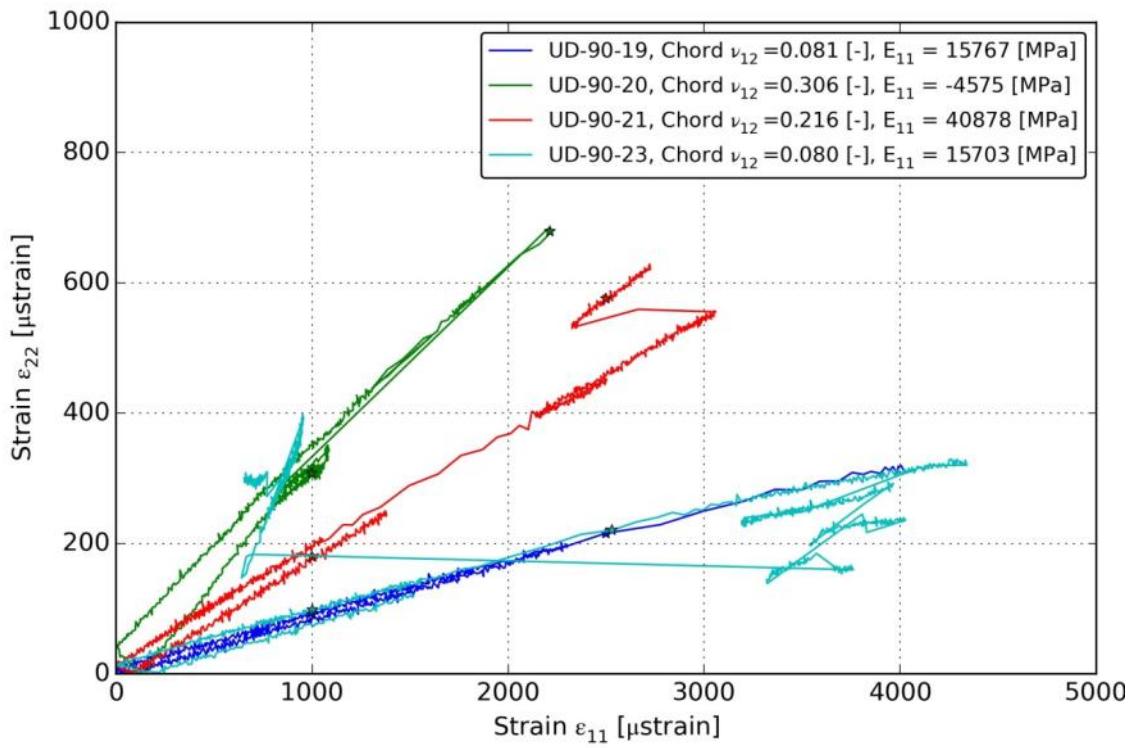


Figure 44: Strain 1 versus strain 2, side 1

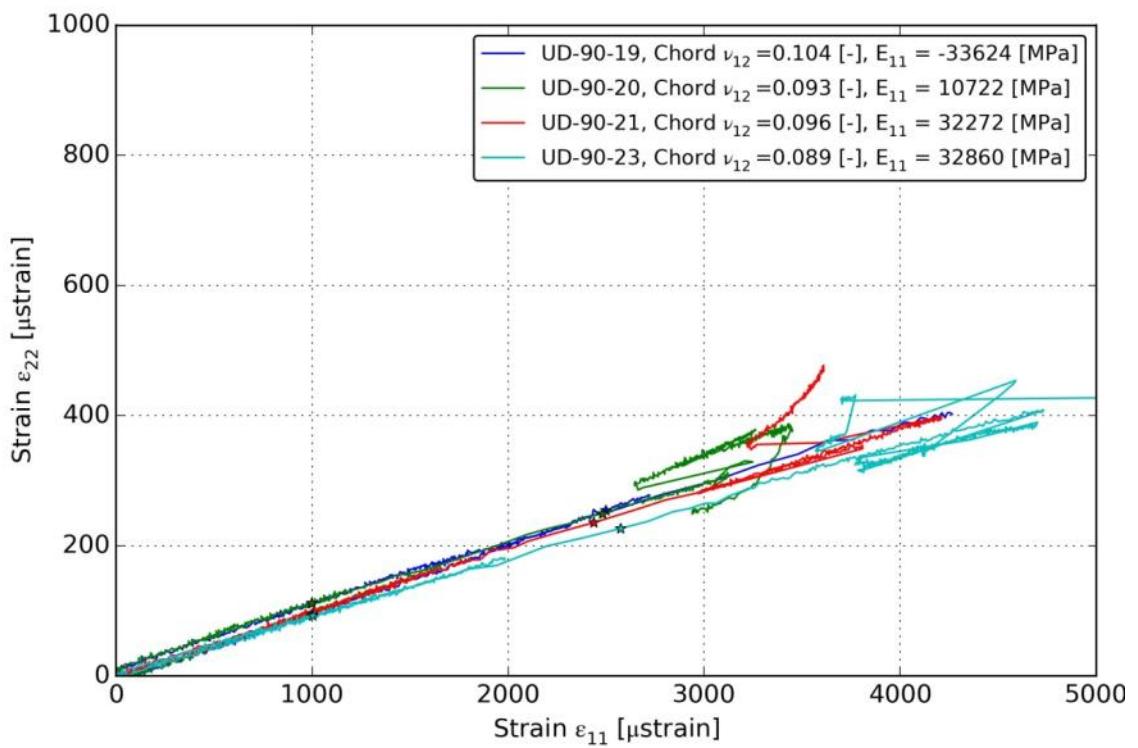


Figure 45: Strain 1 versus strain 2, side 2

4.4 UD 90 layup test CA R=0.1

| Test specifications | |
|---------------------------------|--|
| Test standard: | Fatigue ASTM D3479 accommodated to compression (change in coupon geometry) R=0.1 |
| Fibre direction w.r.t. loading: | UD 90 layup [0,0] |
| Test machine: | MTS 100 kN |
| Grip pressure settings: | 100bar |
| Special fixture: | Test machine grips |
| Strain sensors: | None |
| Test speed: | 2 to 3 Hz |
| Test conditions: | Ambient temperature (23±2 °C) |
| Test date & operator: | 15-08-2017, FL, FK |

| Material specifications |
|--|
| UD 1800 gsm, FV HM 3B W2020 |
| MOMENTIVE EPIKOTE MGS RIMR 135 / 035c (Ration 100:30) |
| MOMENTIVE EPIKURE MGS RIMH 137 |
| Plate 3373 FWR: 73.2% FVC: 55.5 Void content:-0.3% |



Figure 46: Test setup front

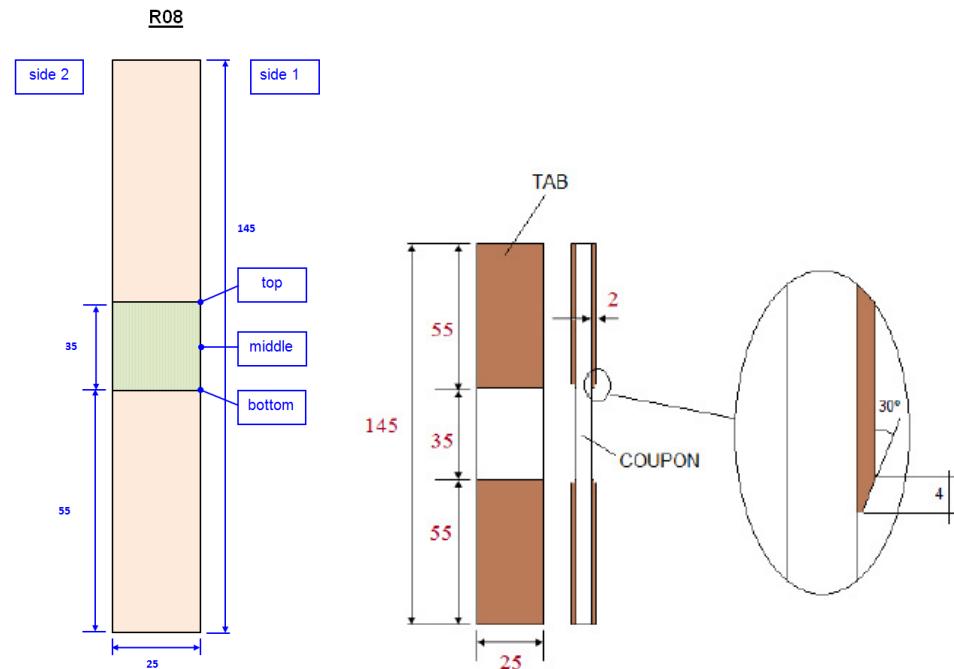


Figure 47: Coupon geometry diagram

| Id | Width | | | Thickness | | | Length | | Area |
|------------|--------|--------|-------|-----------|--------|-------|--------|--------|-------|
| | bottom | middle | top | bottom | middle | top | gauge | total | |
| | [mm] | [mm] | [mm] | [mm] | [mm] | [mm] | [mm] | [mm] | |
| UD-90-06 | 25.00 | 25.01 | 25.02 | 2.59 | 2.75 | 2.57 | 34.44 | 145.1 | 68.7 |
| UD-90-07 | 25.00 | 24.99 | 25.03 | 2.54 | 2.68 | 2.60 | 33.96 | 145.2 | 66.8 |
| UD-90-08 | 24.99 | 24.98 | 25.01 | 2.60 | 2.67 | 2.61 | 34.35 | 145.1 | 66.6 |
| UD-90-09 | 24.94 | 24.94 | 24.96 | 2.56 | 2.66 | 2.51 | 34.24 | 145.1 | 66.3 |
| UD-90-10 | 24.98 | 24.99 | 24.98 | 2.60 | 2.59 | 2.50 | 34.29 | 145.1 | 64.6 |
| UD-90-11 | 24.96 | 24.96 | 24.96 | 2.60 | 2.58 | 2.54 | 34.47 | 145.1 | 64.4 |
| UD-90-12 | 24.98 | 24.98 | 25.00 | 2.55 | 2.60 | 2.51 | 34.18 | 145.0 | 64.8 |
| UD-90-13 | 25.00 | 25.00 | 25.02 | 2.57 | 2.73 | 2.63 | 34.31 | 145.0 | 68.1 |
| UD-90-14 | 24.98 | 24.97 | 24.97 | 2.54 | 2.60 | 2.58 | 34.52 | 145.0 | 64.9 |
| UD-90-16 | 24.98 | 25.03 | 25.00 | 2.79 | 2.60 | 2.68 | 35.05 | 145.0 | 65.0 |
| UD-90-17 | 24.96 | 25.07 | 24.97 | 2.66 | 2.62 | 2.68 | 34.72 | 145.0 | 65.7 |
| UD-90-18 | 25.29 | 25.13 | 25.30 | 2.52 | 2.56 | 2.64 | 34.84 | 145.0 | 64.3 |
| | | | | | | | | | |
| Average | 25.01 | 25.00 | 25.02 | 2.59 | 2.63 | 2.59 | 34.45 | 145.05 | 65.85 |
| Deviation | 0.37 | 0.21 | 0.37 | 2.83 | 2.26 | 2.49 | 0.88 | 0.04 | 2.22 |
| Tolerances | ±0.29 | ±0.13 | ±0.30 | ±0.29 | ±0.25 | ±0.18 | ±1.04 | ±0.16 | ±6.15 |
| | | | | | | | | | |
| Nominal | 25 | 25 | 25 | 2.5 | 2.5 | 2.5 | 35 | 145 | 62.5 |

Table 22: Coupons dimensions

Where amb: ambient, E: elastic modulus, max: ultimate, F: force, δ : displacement, v: Poisson coefficient, T: temperature, amb: ambient

| ID | F _{max} | F _{min} | σ_{\max} | σ_{\min} | δ_{\min} | δ_{\max} | N | T _{avg} Ambient | T _{max} Surface | RunOut |
|----------|------------------|------------------|-----------------|-----------------|-----------------|-----------------|----------|-----------------------------|-----------------------------|--------|
| | [kN] | [kN] | [MPa] | [MPa] | [mm] | [mm] | [cycles] | [°C] | [°C] | |
| UD-90-07 | 2.80 | 0.28 | 41.9 | 4.2 | 3.48 | 3.79 | 1043 | 26.4 | 23.3 | FALSE |
| UD-90-08 | 2.77 | 0.28 | 41.7 | 4.2 | 1.91 | 2.27 | 1392 | 25.9 | 23.0 | FALSE |
| UD-90-09 | 2.40 | 0.24 | 36.2 | 3.6 | -0.01 | 0.24 | 7192 | 26.5 | 23.5 | FALSE |
| UD-90-10 | 2.40 | 0.24 | 37.1 | 3.7 | 0.08 | 0.54 | 60320 | 25.7 | 22.8 | FALSE |
| UD-90-11 | 2.00 | 0.20 | 31.0 | 3.1 | 0.04 | 0.35 | 98455 | 24.4 | 22.3 | FALSE |
| UD-90-13 | 1.68 | 0.17 | 24.7 | 2.5 | | | 508037 | 23.4 | 22.0 | FALSE |
| UD-90-16 | 2.00 | 0.20 | 30.7 | 3.1 | 0.09 | 0.52 | 150607 | 24.6 | 22.7 | FALSE |
| UD-90-17 | 2.00 | 0.20 | 30.5 | 3.1 | 0.04 | 0.32 | 242316 | 24.0 | 22.1 | FALSE |
| UD-90-18 | 1.68 | 0.17 | 26.1 | 2.6 | 0.11 | 0.47 | 3504083 | 22.4 | 27.7 | FALSE |

Table 23: Test summary

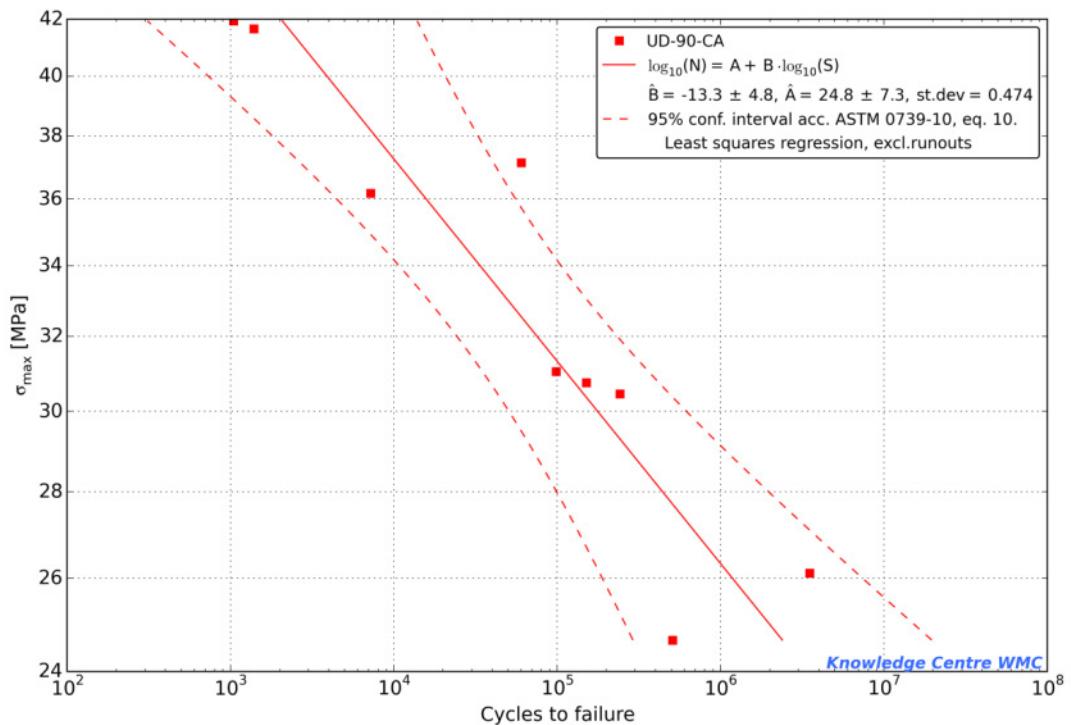


Figure 48: S-N curve

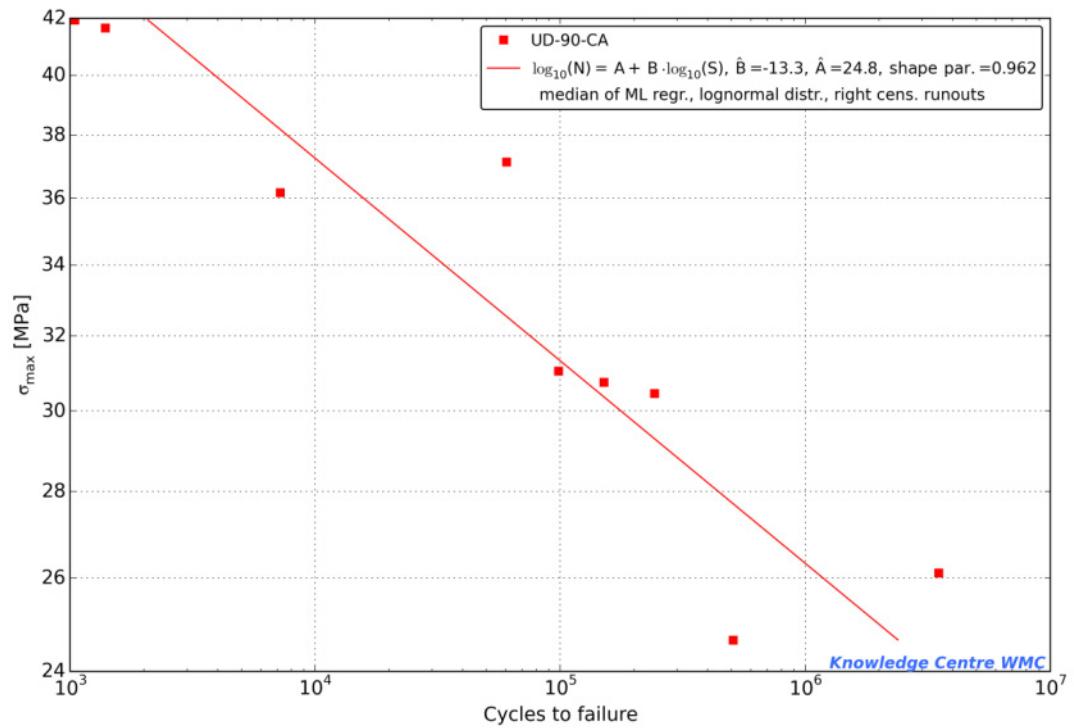


Figure 49: S-N curve (likelihood model)

4.5 MU-045-STT tension test

| Test specifications | |
|------------------------------------|--------------------------------------|
| Test standard: | ASTM D3039 |
| Fibre direction w.r.t. loading: | UD multiaxial [+45,-45,0 0,-45,+45] |
| Test machine: | MTS 100 kN |
| Grip pressure settings: | 100bar |
| Special fixture: | Test machine grips |
| Strain sensors: | Back to back 2mm cross strain gauges |
| Test speed: | 2 mm/min |
| Test conditions: | Ambient temperature (23±2 °C) |
| Test date & operator: | 15-08-2017, FL, FK |

| Material specifications |
|--|
| UD 1800 gsm, FV HM 3B W2020 |
| MOMENTIVE EPIKOTE MGS RIMR 135 / 035c (Ratio 100:30) |
| MOMENTIVE EPIKURE MGS RIMH 137 |
| Plate 3384 - 3385 |

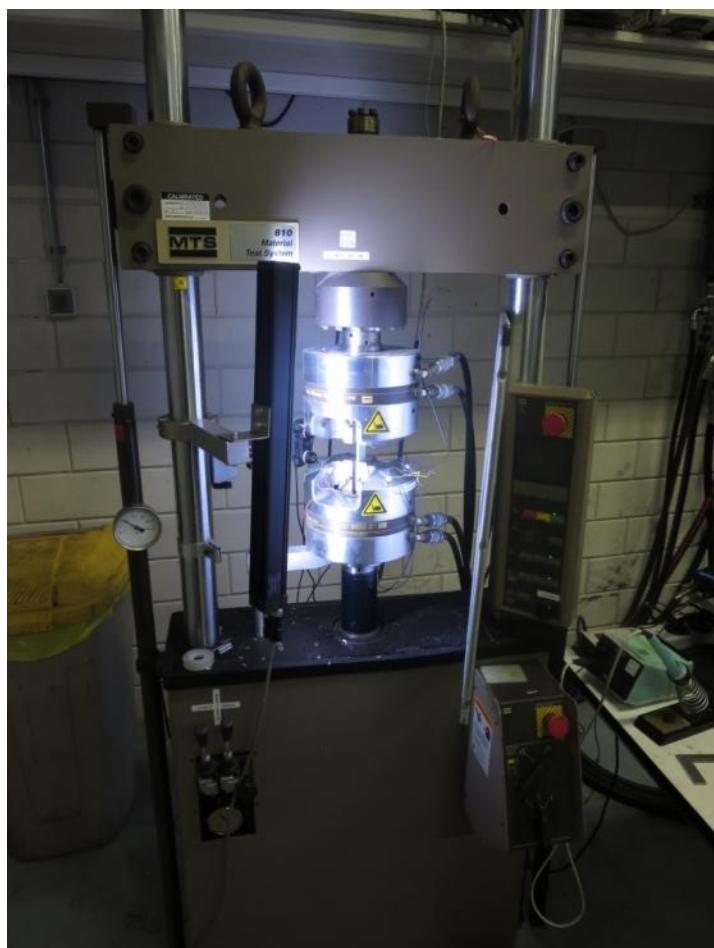


Figure 50: Test setup front

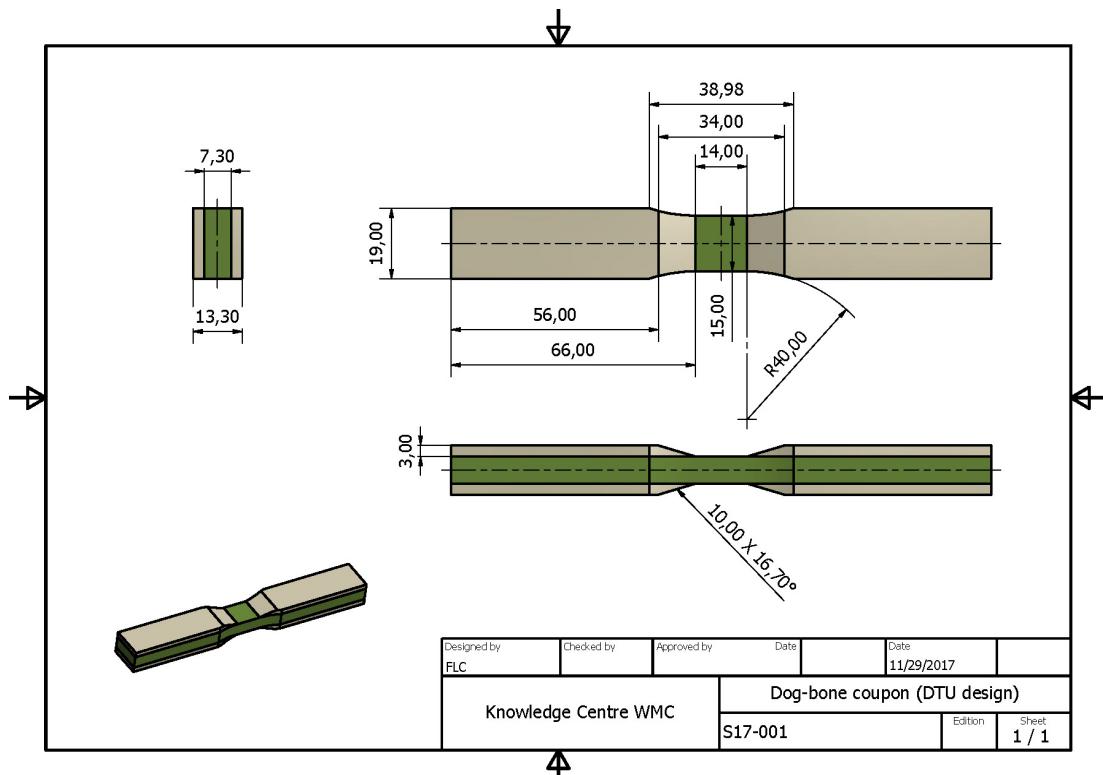


Figure 51: Coupon geometry diagram

| Id | Width | | | Thickness | | | Length | | Area |
|------------|--------|--------|-------|-----------|--------|-------|--------|--------|--------|
| | bottom | middle | top | bottom | middle | top | gauge | total | |
| | [mm] | [mm] | [mm] | [mm] | [mm] | [mm] | [mm] | [mm] | |
| MU-045-01 | 13.56 | 13.57 | 13.56 | 7.41 | 7.30 | 7.34 | 13.46 | 144.4 | 99.0 |
| MU-045-02 | 13.55 | 13.56 | 13.58 | 7.40 | 7.35 | 7.34 | 13.38 | 144.3 | 99.6 |
| MU-045-03 | 13.54 | 13.53 | 13.54 | 7.36 | 7.36 | 7.35 | 13.53 | 144.4 | 99.5 |
| MU-045-04 | 13.53 | 13.53 | 13.53 | 7.40 | 7.36 | 7.40 | 13.30 | 144.2 | 99.6 |
| Average | 13.55 | 13.55 | 13.55 | 7.39 | 7.34 | 7.36 | 13.42 | 144.31 | 99.42 |
| Deviation | 0.10 | 0.15 | 0.16 | 0.31 | 0.41 | 0.37 | 0.75 | 0.04 | 0.29 |
| Tolerances | ±1.47 | ±1.47 | ±1.47 | ±0.15 | ±0.21 | ±0.17 | ±0.70 | ±0.76 | ±13.51 |
| Nominal | 15 | 15 | 15 | 7.5 | 7.5 | 7.5 | 14 | 145 | 112.5 |

Table 24: Coupons dimensions

Where amb: ambient, E: elastic modulus, max: ultimate, F: force, δ : displacement, v: Poisson coefficient, T: temperature, amb: ambient

| ID | F _{max} | δ_{\max} | σ_{\max} | E _{side1} | E _{side2} | v _{side1} | v _{side2} | T _{amb} |
|-----------|------------------|-----------------|-----------------|--------------------|--------------------|--------------------|--------------------|------------------|
| | [kN] | [mm] | [Mpa] | [GPa] | [GPa] | [-] | [-] | [°C] |
| MU-045-01 | 42.6 | 2.17 | 430.6 | 22.4 | 22.7 | 0.598 | 0.635 | 23.0 |
| MU-045-02 | 45.2 | 2.45 | 454.0 | 23.2 | 20.9 | 0.542 | 0.609 | 21.4 |
| MU-045-03 | 43.9 | 2.21 | 440.9 | 23.5 | 27.2 | 0.552 | 0.532 | 21.4 |
| MU-045-04 | 45.7 | 2.44 | 458.7 | 24.6 | 23.5 | 0.597 | 0.559 | 22.9 |
| Mean | 44.3 | 2.32 | 446.0 | 23.4 | 23.6 | 0.572 | 0.584 | 22.2 |
| Std | 1.38 | 0.149 | 12.75 | 0.91 | 2.67 | 0.030 | 0.047 | 0.91 |
| COV | 3% | 6% | 3% | 4% | 11% | 5% | 8% | 4% |

Table 25: Test summary

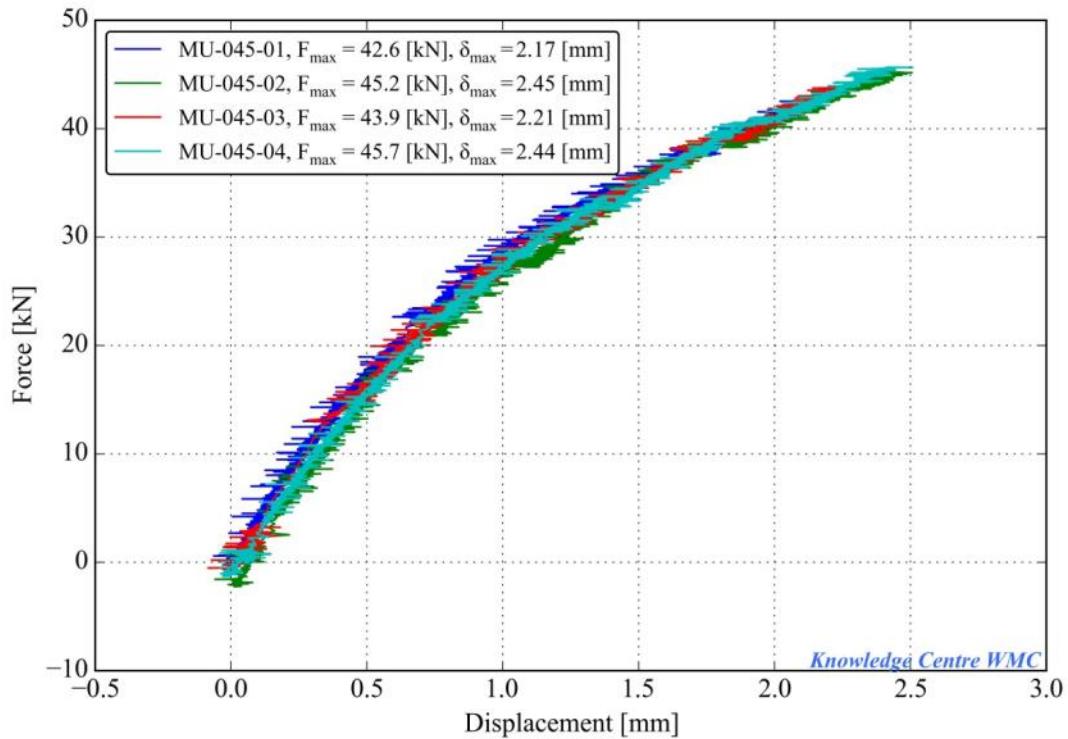


Figure 52: Force versus displacement

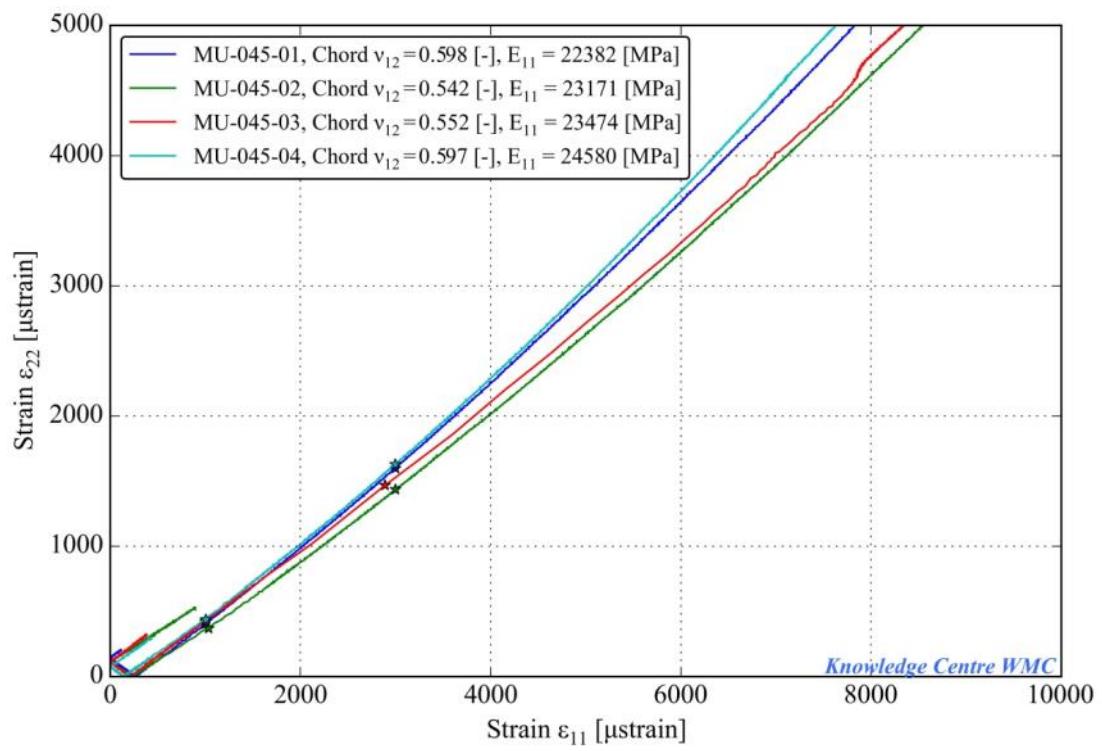


Figure 53: Stress versus strain

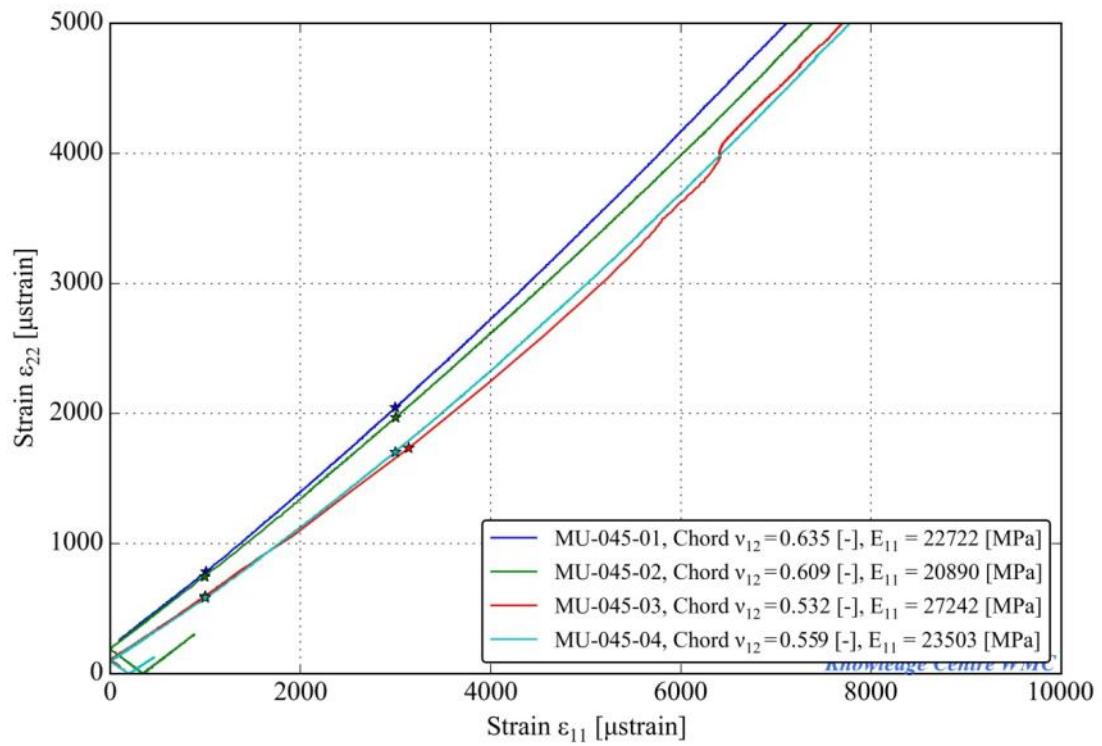


Figure 54: Stress versus strain side 2

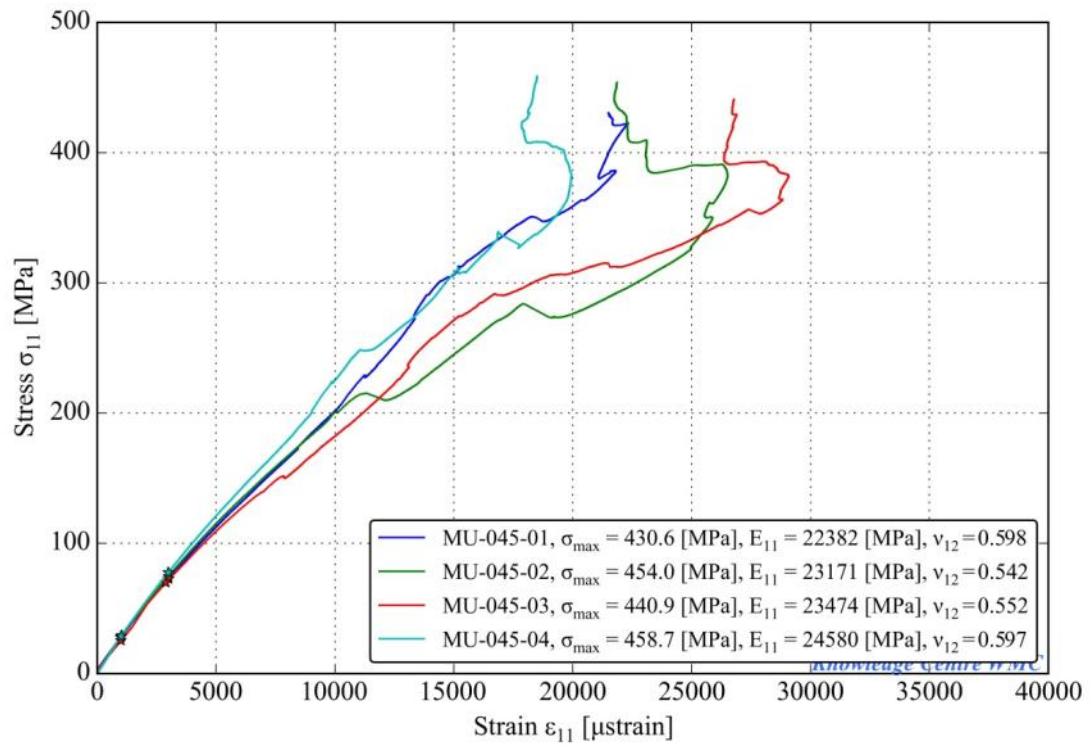


Figure 55: Strain 1 versus strain 2, side 1

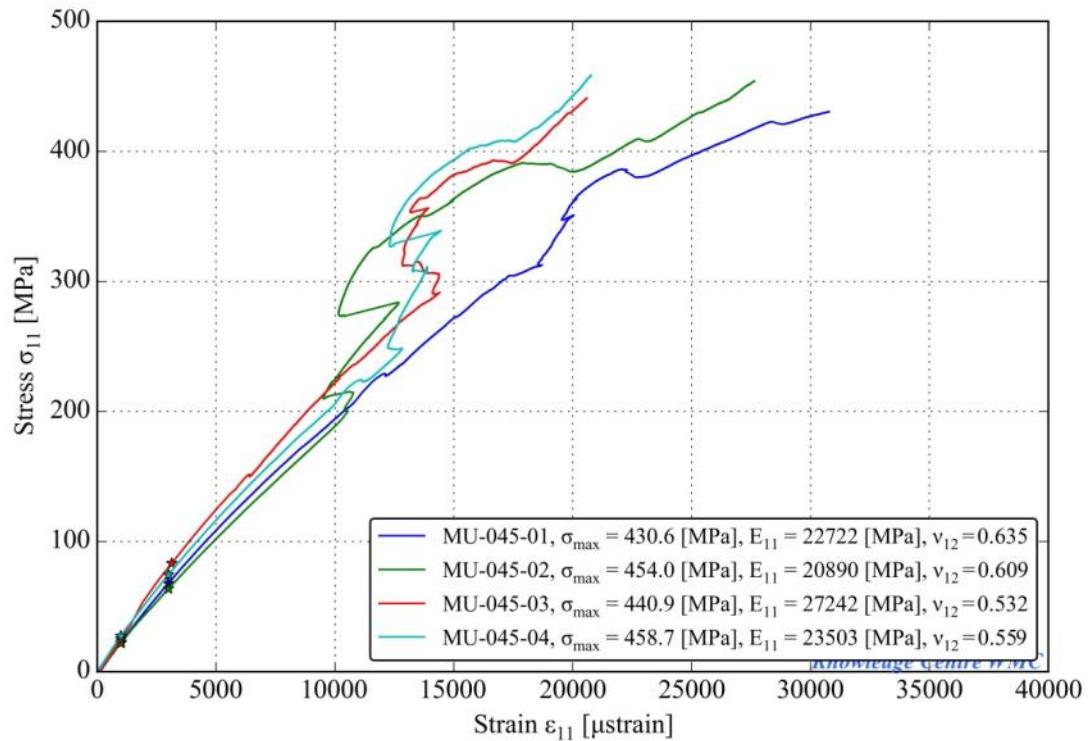


Figure 56: Strain 1 versus strain 2, side 2

4.6 UD Multiaxial layup test CA R=-1

| Test specifications | |
|---------------------------------|---|
| Test standard: | Fatigue ASTM D3479 accommodated to compression (change in coupon geometry) R=-1 |
| Fibre direction w.r.t. loading: | UD multiaxial [+45,-45,0 0,-45,+45] |
| Test machine: | MTS 100 kN |
| Grip pressure settings: | 100bar |
| Special fixture: | Test machine grips |
| Strain sensors: | None |
| Test speed: | 2 to 3 Hz |
| Test conditions: | Ambient temperature (23±2 °C) |
| Test date & operator: | 15-08-2017, FL, FK |

| Material specifications |
|---|
| UD 1800 gsm, FV HM 3B W2020 |
| MOMENTIVE EPIKOTE MGS RIMR 135 / 035c (Ration 100:30) |
| MOMENTIVE EPIKURE MGS RIMH 137 |
| Plate 3384 - 3385 |

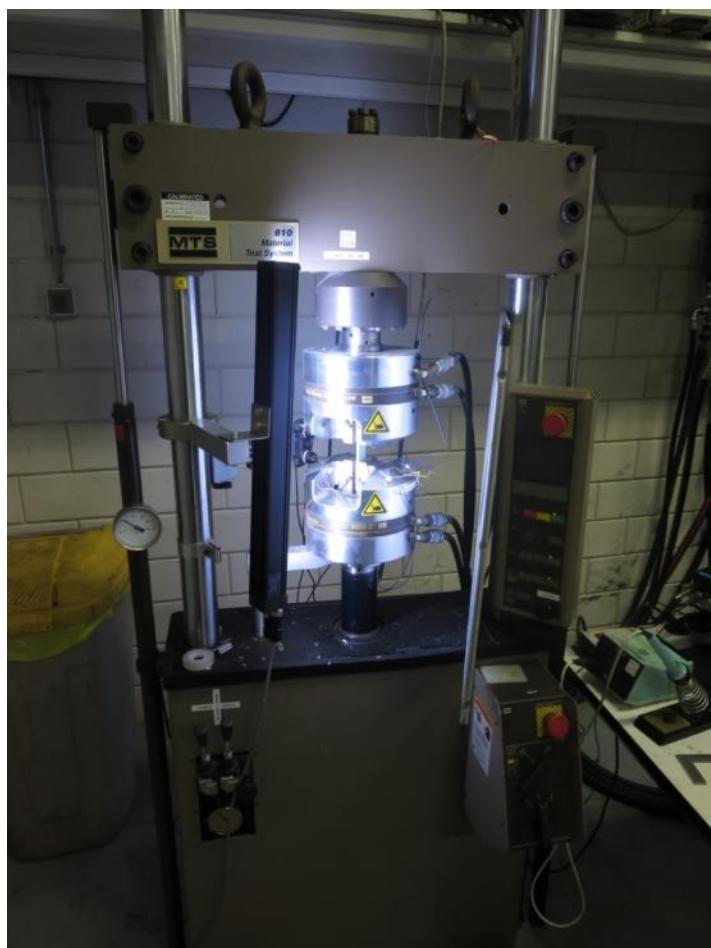


Figure 57: Test setup front

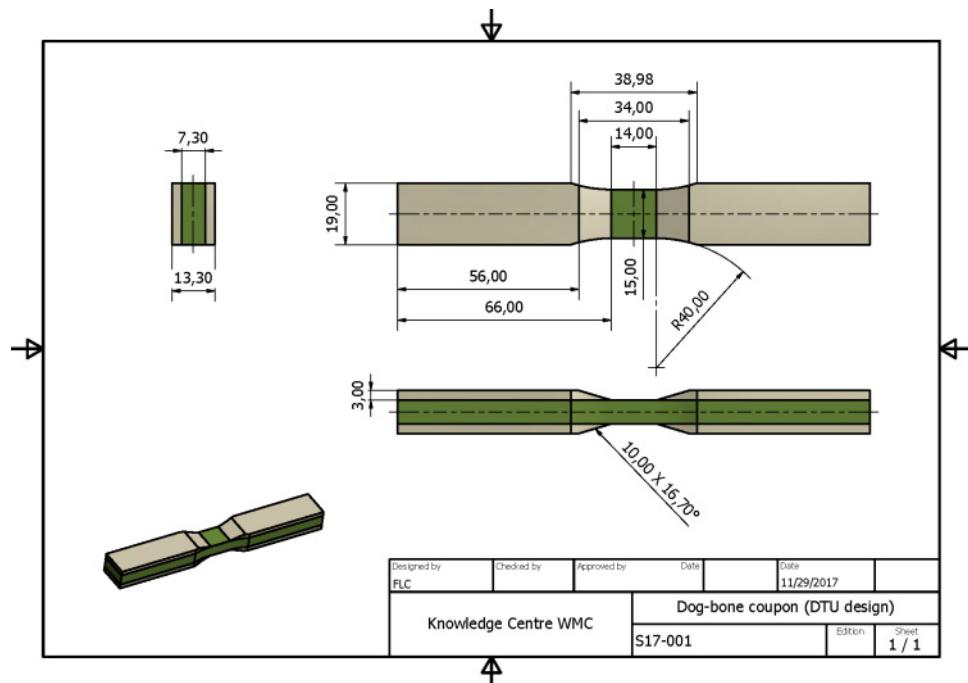


Figure 58: Coupon geometry diagram

| Id | Width | | | Thickness | | | Length | | Area |
|------------|--------|--------|-------|-----------|--------|-------|--------|--------|--------|
| | bottom | middle | top | bottom | middle | top | gauge | total | |
| | [mm] | [mm] | [mm] | [mm] | [mm] | [mm] | [mm] | [mm] | |
| MU-045-09 | 14.83 | 14.82 | 14.81 | 7.36 | 7.35 | 7.36 | 13.74 | 145.9 | 108.9 |
| MU-045-10 | 14.80 | 14.80 | 14.80 | 7.37 | 7.37 | 7.39 | 13.45 | 145.7 | 109.1 |
| MU-045-11 | 14.60 | 14.56 | 14.62 | 7.43 | 7.43 | 7.44 | 13.08 | 145.3 | 108.1 |
| MU-045-12 | 14.64 | 14.59 | 14.62 | 7.31 | 7.30 | 7.38 | 13.21 | 145.2 | 106.4 |
| MU-045-13 | 14.69 | 14.69 | 14.68 | 7.37 | 7.40 | 7.43 | 14.04 | 145.6 | 108.7 |
| MU-045-14 | 14.70 | 14.72 | 14.86 | 7.51 | 7.52 | 7.49 | 13.96 | 145.7 | 110.6 |
| MU-045-15 | 14.71 | 14.71 | 14.72 | 7.35 | 7.38 | 7.36 | 13.96 | 145.6 | 108.6 |
| MU-045-16 | 14.72 | 14.75 | 14.80 | 7.36 | 7.35 | 7.39 | 14.14 | 145.6 | 108.4 |
| MU-045-17 | 14.77 | 14.76 | 14.78 | 7.48 | 7.45 | 7.35 | 14.26 | 145.7 | 109.9 |
| MU-045-18 | 14.76 | 14.76 | 14.75 | 7.36 | 7.36 | 7.38 | 14.38 | 145.7 | 108.6 |
| MU-045-19 | 14.81 | 14.81 | 14.82 | 7.33 | 7.34 | 7.34 | 14.23 | 145.7 | 108.6 |
| MU-045-20 | 14.82 | 14.82 | 14.82 | 7.38 | 7.33 | 7.34 | 14.08 | 145.7 | 108.6 |
| MU-045-21 | 14.81 | 14.81 | 14.80 | 7.27 | 7.38 | 7.39 | 14.21 | 145.7 | 109.2 |
| MU-045-22 | 14.84 | 14.84 | 14.83 | 7.41 | 7.36 | 7.31 | 14.44 | 145.7 | 109.2 |
| Average | 14.75 | 14.75 | 14.77 | 7.38 | 7.38 | 7.38 | 13.94 | 145.62 | 108.78 |
| Deviation | 0.51 | 0.58 | 0.52 | 0.85 | 0.75 | 0.63 | 3.04 | 0.12 | 0.86 |
| Tolerances | ±0.40 | ±0.44 | ±0.38 | ±0.14 | ±0.12 | ±0.10 | ±0.93 | ±0.79 | ±4.57 |
| Nominal | 15 | 15 | 15 | 7.4 | 7.4 | 7.4 | 14 | 146 | 111 |

Table 26: Coupons dimensions

Where amb: ambient, E: elastic modulus, max: ultimate, F: force, δ: displacement, v: Poisson coefficient, T: temperature, amb: ambient

| ID | F _{max} | F _{min} | σ _{max} | σ _{min} | δ _{min} | δ _{max} | N | T _{avg} Ambient | T _{max} Surface | RunOut |
|-----------|------------------|------------------|------------------|------------------|------------------|------------------|----------|-----------------------------|-----------------------------|--------|
| | [kN] | [kN] | [MPa] | [MPa] | [mm] | [mm] | [cycles] | [°C] | [°C] | |
| MU-045-09 | 19.71 | -13.73 | 181.0 | -126.1 | -0.36 | 0.69 | 79 | 23.3 | 25.0 | FALSE |
| MU-045-10 | 17.45 | -16.96 | 160.0 | -155.5 | -0.40 | 0.61 | 219 | 23.5 | 25.2 | FALSE |
| MU-045-11 | 16.75 | -16.15 | 154.9 | -149.4 | -0.42 | 0.56 | 459 | 22.6 | 25.4 | FALSE |
| MU-045-12 | 15.22 | -15.22 | 143.0 | -143.0 | -0.40 | 0.47 | 688 | 22.9 | 25.4 | FALSE |
| MU-045-13 | 10.19 | -10.07 | 93.8 | -92.6 | -0.33 | 0.42 | 2412274 | 22.1 | 24.9 | TRUE |
| MU-045-14 | 16.51 | -16.50 | 149.3 | -149.2 | -0.40 | 0.51 | 531 | 23.2 | 25.7 | FALSE |
| MU-045-15 | 17.38 | -17.37 | 160.1 | -160.0 | -0.48 | 0.50 | 497 | 23.3 | 25.3 | FALSE |
| MU-045-16 | 15.22 | -15.22 | 140.4 | -140.4 | -0.39 | 0.47 | 778 | 22.0 | 25.4 | FALSE |
| MU-045-17 | 16.51 | -16.51 | 150.3 | -150.2 | -0.43 | 0.50 | 567 | 23.3 | 25.3 | FALSE |
| MU-045-18 | 10.88 | -10.88 | 100.1 | -100.2 | -0.47 | 0.32 | 1048192 | 22.4 | 25.6 | FALSE |
| MU-045-19 | 13.49 | -13.49 | 124.2 | -124.2 | -0.41 | 0.61 | 204423 | 22.3 | 25.5 | FALSE |
| MU-045-20 | 11.31 | -11.31 | 104.2 | -104.2 | -0.43 | 0.41 | 889419 | 22.0 | 25.5 | FALSE |

Table 27: Test summary

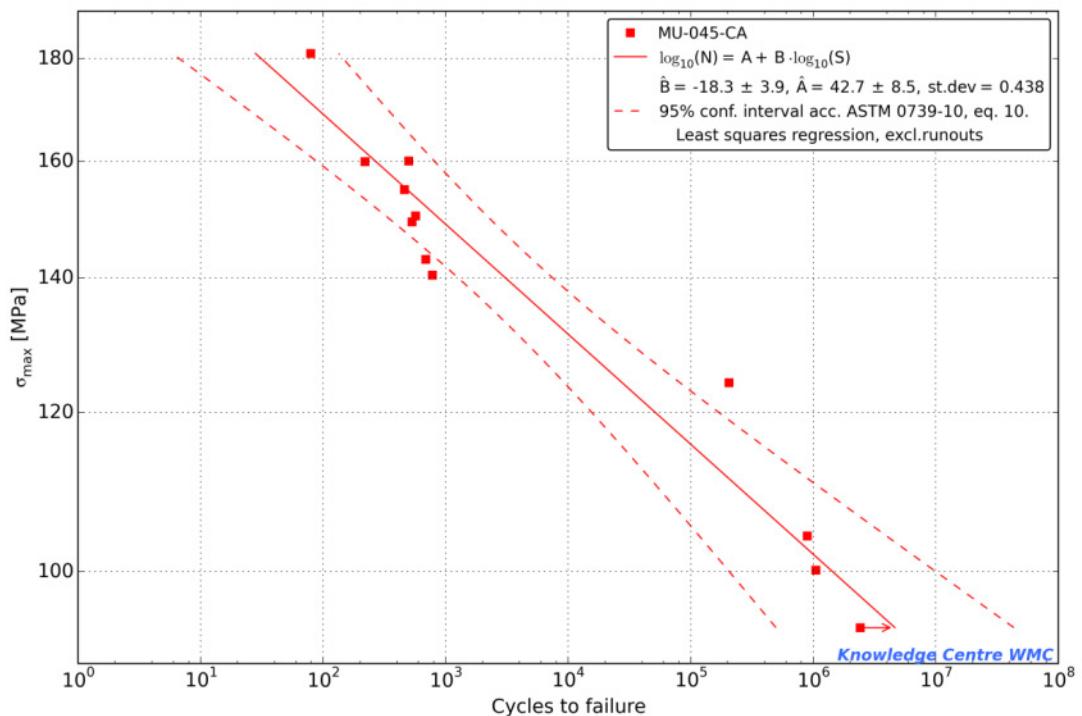


Figure 59: S-N curve

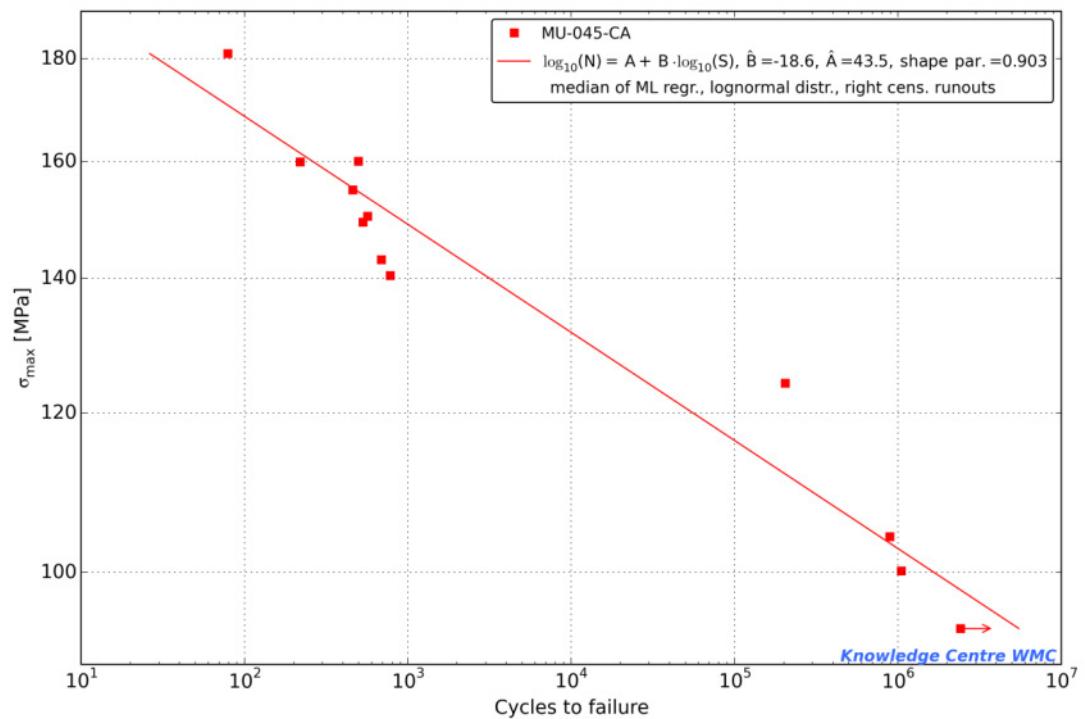


Figure 60: S-N curve (likelihood model)

4.7 UD-0-STT tension test. Benchmark test.

| Test specifications | |
|---------------------------------|--------------------------------------|
| Test standard: | ASTM D3039 |
| Fibre direction w.r.t. loading: | UD 0 degrees main direction |
| Test machine: | MTS 100 kN |
| Grip pressure settings: | 100bar |
| Special fixture: | Test machine grips |
| Strain sensors: | Back to back 2mm cross strain gauges |
| Test speed: | 2 mm/min |
| Test conditions: | Ambient temperature (23±2 °C) |
| Test date & operator: | 15-08-2017, FL, FK |

| Material specifications | |
|---|--|
| UD 1800 gsm, FV HM 3B W2020 | |
| MOMENTIVE EPIKOTE MGS RIMR 135 / 035c (Ratio 100:30) | |
| MOMENTIVE EPIKURE MGS RIMH 137 | |
| Plate 3373 FWC: 73.3 [%] FVC: 56.21 [%] Void content: -0.3[%] | |



Figure 61: Test setup front

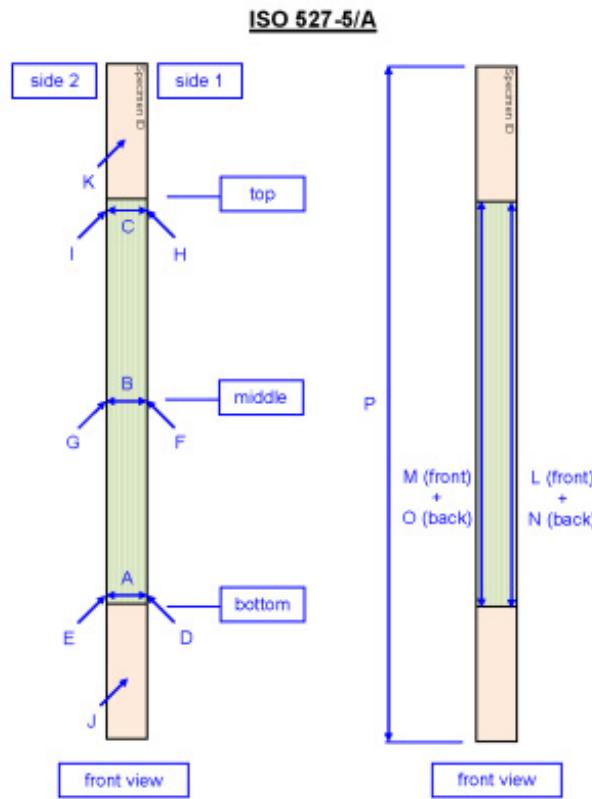


Figure 62: Coupon geometry diagram

| Id | Width | | | Thickness | | | Length | | Area |
|------------|--------|--------|-------|-----------|--------|-------|--------|--------|-------|
| | bottom | middle | top | bottom | middle | top | gauge | total | |
| | [mm] | [mm] | [mm] | [mm] | [mm] | [mm] | [mm] | [mm] | |
| UD-0-01 | 14.91 | 14.92 | 14.91 | 2.56 | 2.64 | 2.64 | 129.92 | 250.0 | 39.4 |
| UD-0-02 | 14.89 | 14.87 | 14.86 | 2.61 | 2.61 | 2.56 | 129.94 | 250.0 | 38.8 |
| UD-0-03 | 14.90 | 14.89 | 14.94 | 2.50 | 2.52 | 2.61 | 129.56 | 250.0 | 37.5 |
| UD-0-04 | 14.85 | 14.84 | 14.87 | 2.56 | 2.58 | 2.57 | 129.79 | 250.0 | 38.2 |
| UD-0-05 | 14.88 | 14.88 | 14.88 | 2.54 | 2.57 | 2.58 | 129.88 | 250.0 | 38.2 |
| Average | 14.89 | 14.88 | 14.89 | 2.55 | 2.58 | 2.59 | 129.82 | 250.00 | 38.42 |
| Deviation | 0.15 | 0.20 | 0.22 | 1.57 | 1.77 | 1.32 | 0.12 | 0.00 | 1.84 |
| Tolerances | ±0.15 | ±0.16 | ±0.14 | ±0.50 | ±0.48 | ±0.44 | ±20.44 | ±0.00 | ±7.48 |
| Nominal | 15 | 15 | 15 | 3 | 3 | 3 | 150 | 250 | 45 |

Table 28: Coupons dimensions

Where amb: ambient, E: elastic modulus, max: ultimate, F: force, δ : displacement, v: Poisson coefficient, T: temperature, amb: ambient

| ID | F_{max} | δ_{max} | σ_{max} | E_{side1} | E_{side2} | v_{side1} | v_{side2} | T_{amb} | $\epsilon_{max,1}$ | $\epsilon_{max,2}$ |
|---------|-----------|----------------|----------------|-------------|-------------|-------------|-------------|-----------|--------------------|--------------------|
| | [kN] | [mm] | [Mpa] | [GPa] | [GPa] | [-] | [-] | [°C] | [micStrain] | [micStrain] |
| UD-0-01 | 47.0 | 5.52 | 1193.9 | 45.9 | 46.2 | 0.314 | 0.303 | 25.0 | 28664 | 29059 |
| UD-0-02 | 46.2 | 5.35 | 1190.9 | 48.0 | 49.2 | 0.242 | 0.314 | 24.9 | 27053 | 26300 |
| UD-0-03 | 47.2 | 5.69 | 1258.9 | 45.1 | 49.1 | 0.254 | 0.321 | 24.7 | 30969 | 27996 |
| UD-0-04 | 45.6 | 5.47 | 1193.6 | 45.7 | 42.3 | 0.262 | 0.216 | 24.5 | 28250 | 29654 |
| UD-0-05 | 42.1 | 5.03 | 1103.6 | 46.7 | 45.9 | 0.255 | 0.278 | 24.5 | 26282 | 27409 |
| Mean | 45.6 | 5.41 | 1188.2 | 46.3 | 46.6 | 0.265 | 0.286 | 24.7 | 28244 | 28083 |
| Std | 2.07 | 0.245 | 55.3 | 1.11 | 2.82 | 0.028 | 0.043 | 0.23 | 1793.93 | 1328.73 |
| COV | 5% | 5% | 5% | 2% | 6% | 11% | 15% | 1% | 6% | 5% |

Table 29: Test summary

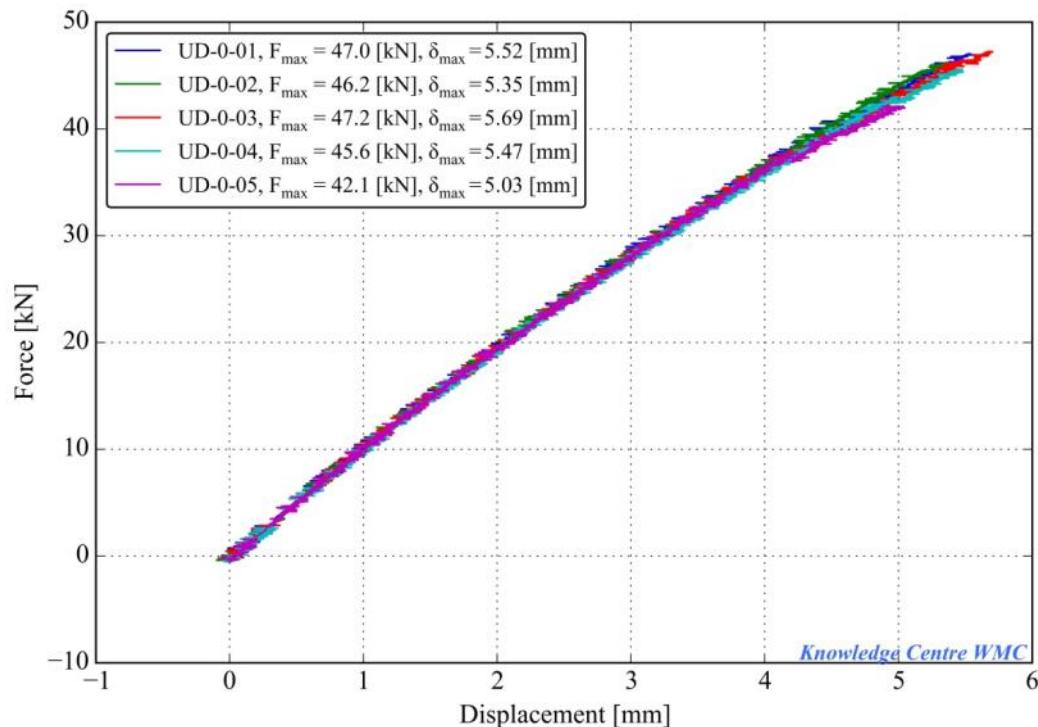


Figure 63: Force versus displacement

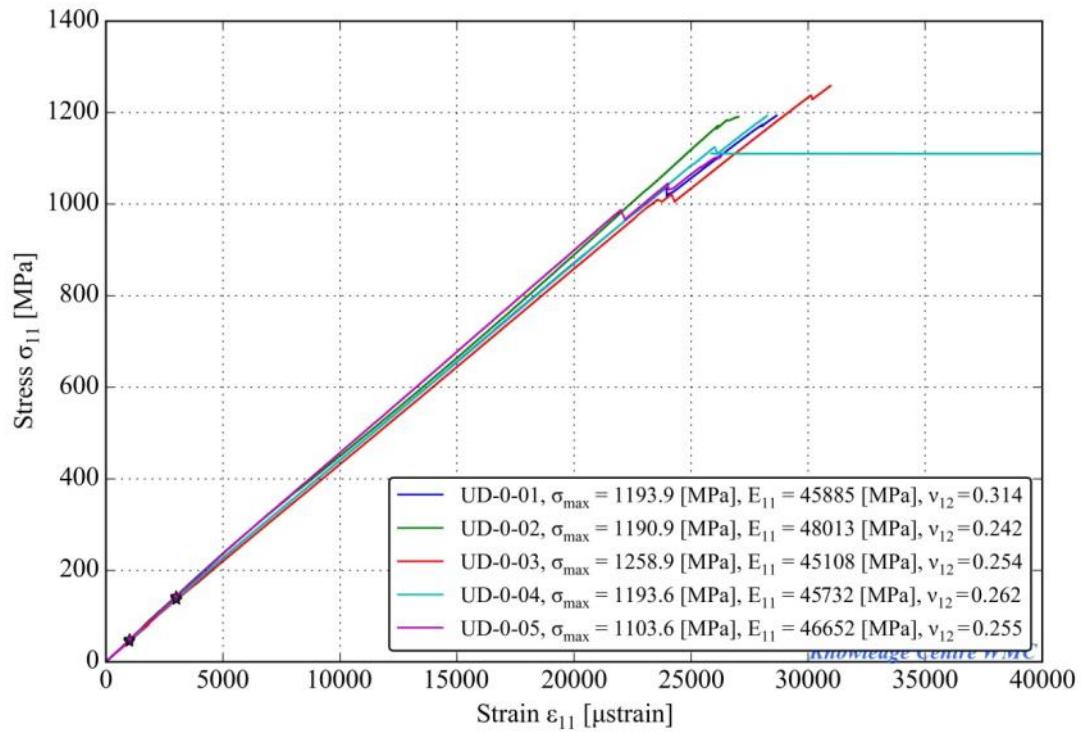


Figure 64: Stress versus strain

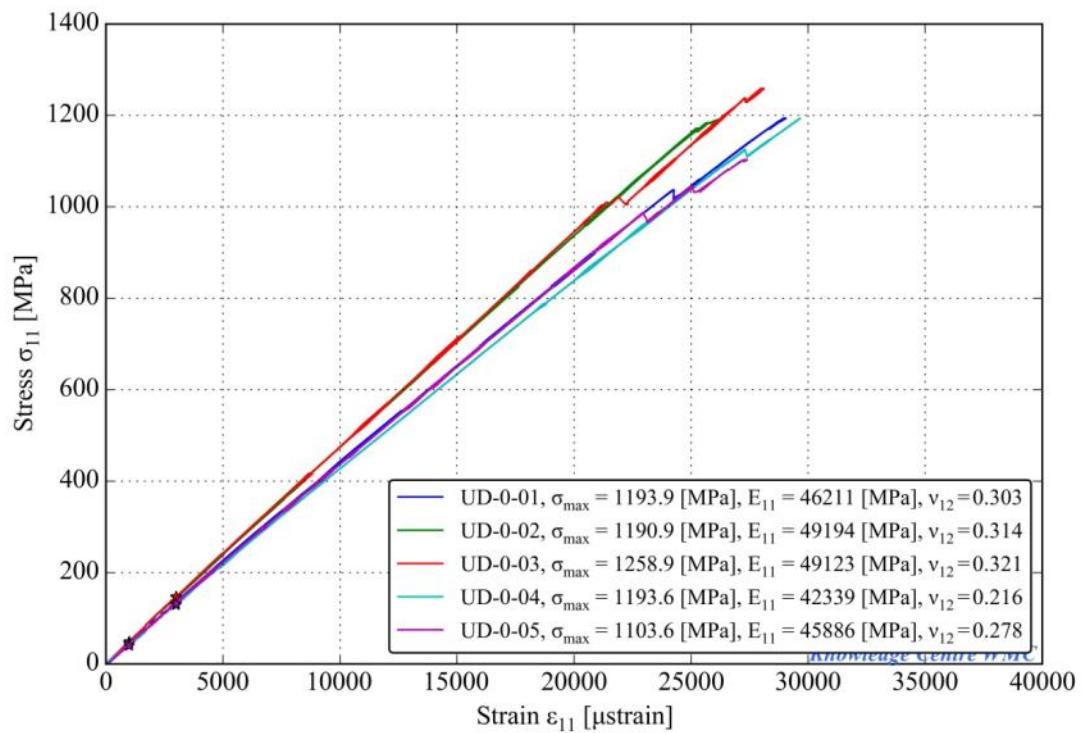


Figure 65: Stress versus strain side 2

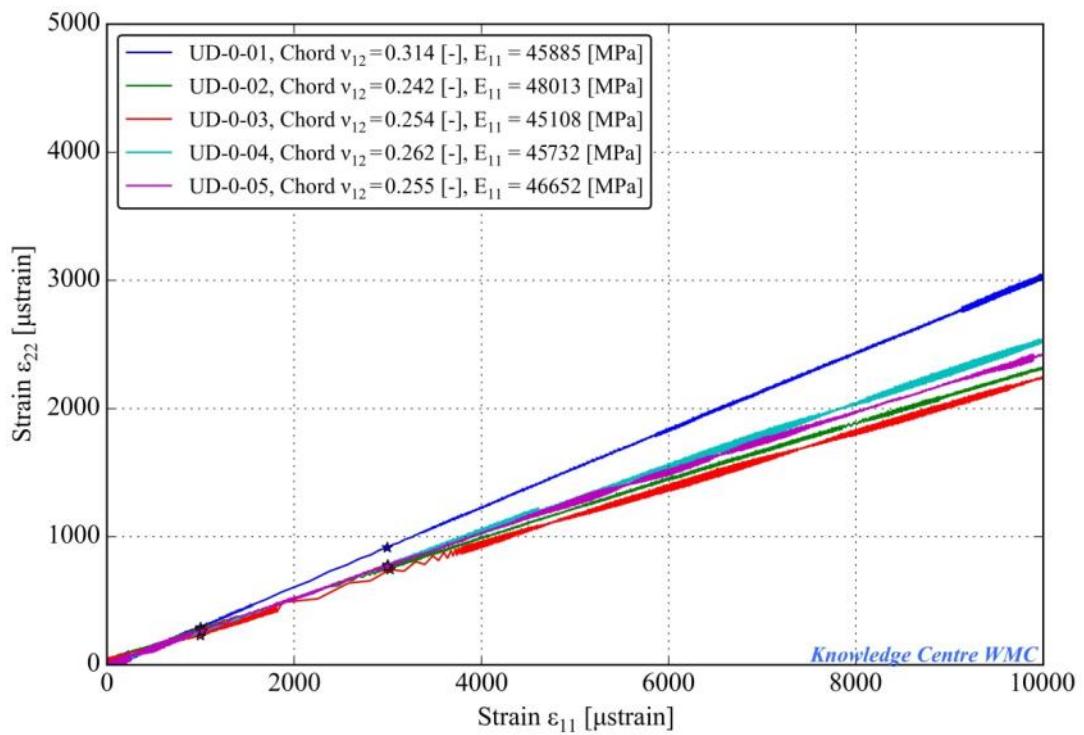


Figure 66: Strain 1 versus strain 2, side 1

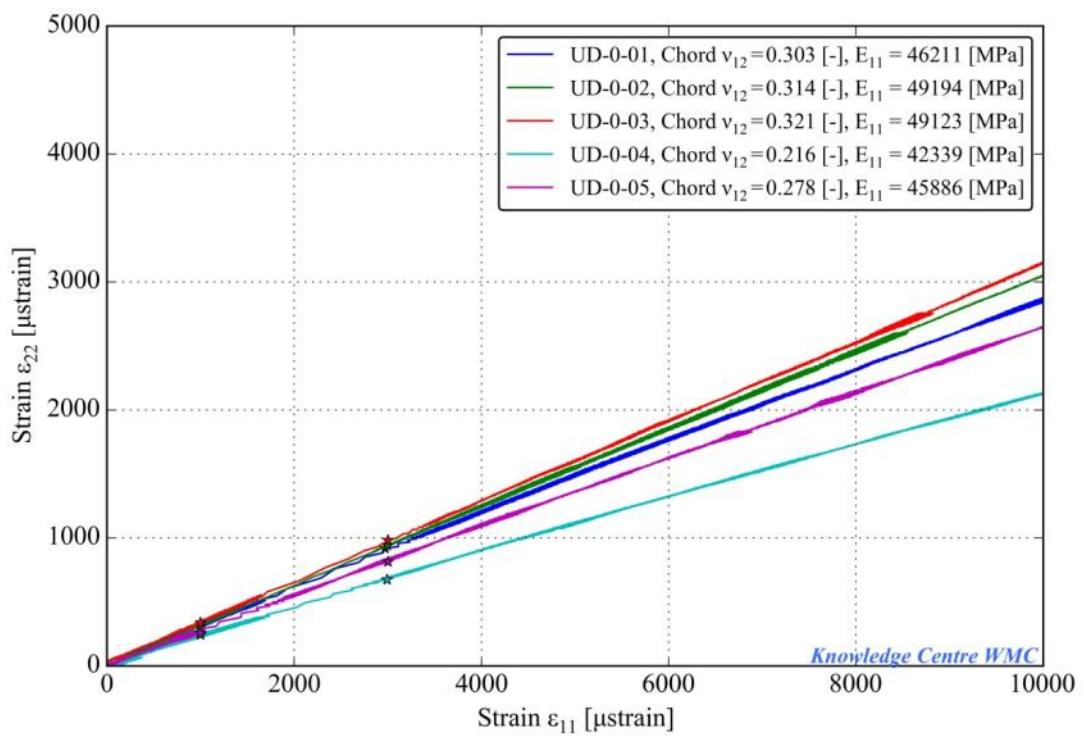


Figure 67: Strain 1 versus strain 2, side 2

4.8 UD-0-I-STT tension test. Benchmark test. Manufactured at IWES.

| Test specifications | |
|------------------------------------|--|
| Test standard: | ASTM D3039 |
| Fibre direction w.r.t. loading: | UD 0 degrees main direction |
| Test machine: | MTS 100 kN |
| Grip pressure settings: | 100bar |
| Special fixture: | Test machine grips |
| Strain sensors: | Back to back 2mm cross strain gauges |
| Test speed: | 2 mm/min |
| Test conditions: | Ambient temperature ($23\pm2^\circ\text{C}$) |
| Test date & operator: | 15-08-2017, FL, FK |

| Material specifications | |
|--|--|
| UD 1800 gsm, FV HM 3B W2020 | |
| MOMENTIVE EPIKOTE MGS RIMR 135 / 035c (Ratio 100:30) | |
| MOMENTIVE EPIKURE MGS RIMH 137 | |
| Manufactured at IWES Fraunhofer | |

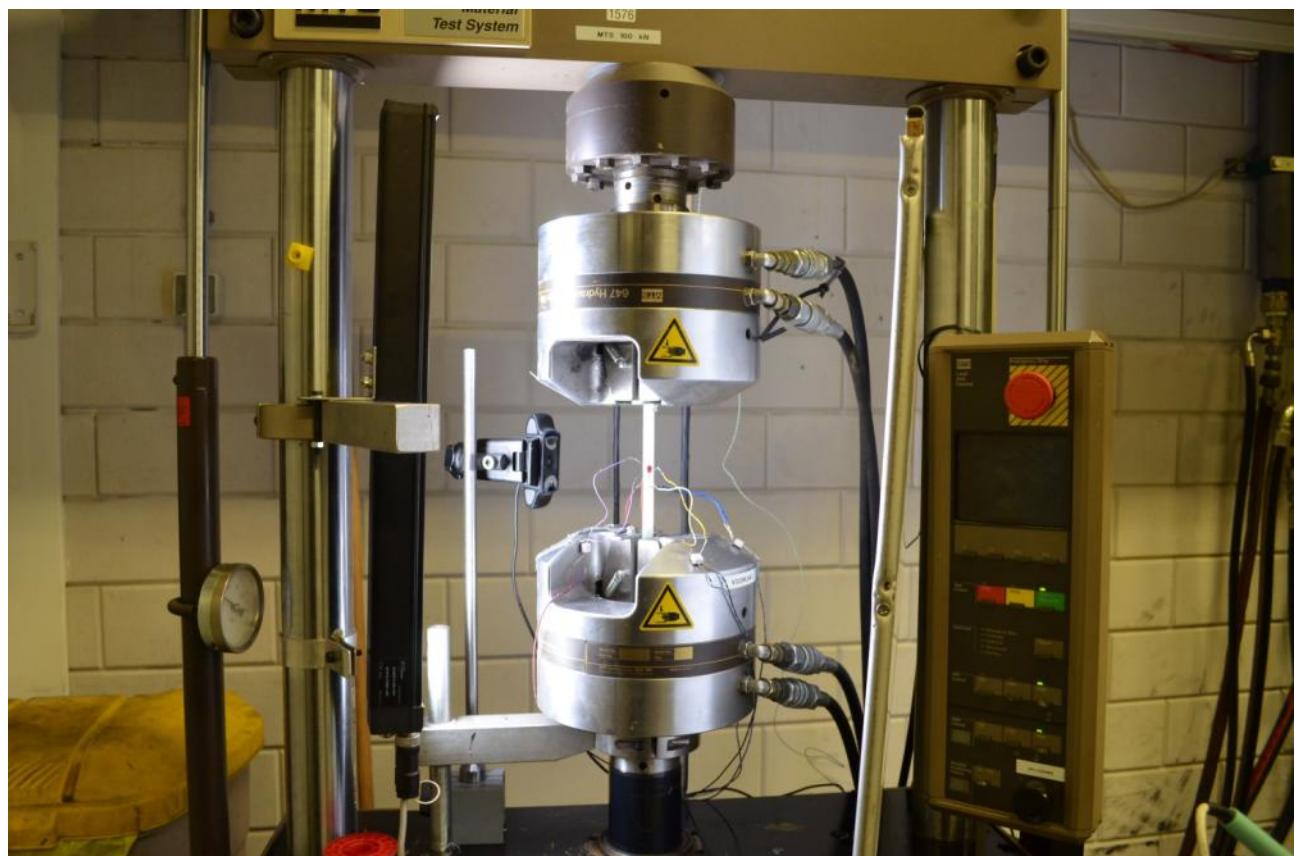


Figure 68: Test setup front

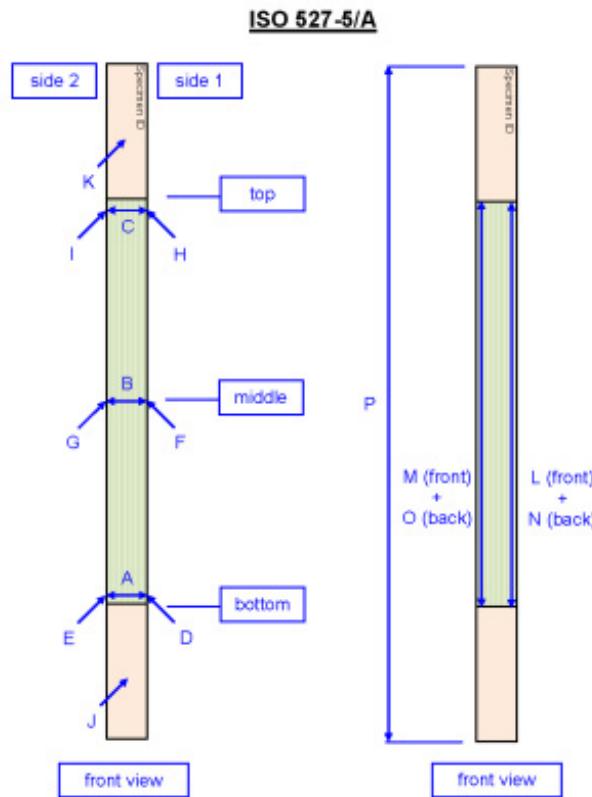


Figure 69: Coupon geometry diagram

| Id | Width | | | Thickness | | | Length | | Area |
|------------|--------|--------|-------|-----------|--------|-------|--------|--------|-------|
| | bottom | middle | top | bottom | middle | top | gauge | total | |
| | [mm] | [mm] | [mm] | [mm] | [mm] | [mm] | [mm] | [mm] | |
| UD-0-I-01 | 14.97 | 15.07 | 15.08 | 2.40 | 2.40 | 2.45 | 129.47 | 253.0 | 36.1 |
| UD-0-I-02 | 15.03 | 15.08 | 14.95 | 2.45 | 2.41 | 2.43 | 129.06 | 253.0 | 36.3 |
| UD-0-I-03 | 14.94 | 14.89 | 15.00 | 2.42 | 2.49 | 2.49 | 129.30 | 253.0 | 37.1 |
| UD-0-I-04 | 14.96 | 14.99 | 14.96 | 2.47 | 2.46 | 2.47 | 129.18 | 253.0 | 36.8 |
| UD-0-I-05 | 14.93 | 14.99 | 15.00 | 2.47 | 2.46 | 2.46 | 129.71 | 253.0 | 36.8 |
| UD-0-I-06 | 14.92 | 14.96 | 15.08 | 2.41 | 2.44 | 2.46 | 129.77 | 253.0 | 36.5 |
| UD-0-I-07 | 14.98 | 15.00 | 14.96 | 2.43 | 2.48 | 2.50 | 130.08 | 253.0 | 37.1 |
| | | | | | | | | | |
| Average | 14.96 | 15.00 | 15.00 | 2.44 | 2.45 | 2.46 | 129.51 | 253.00 | 36.67 |
| Deviation | 0.25 | 0.43 | 0.37 | 1.18 | 1.42 | 1.02 | 0.28 | 0.00 | 1.07 |
| Tolerances | ±0.08 | ±0.11 | ±0.08 | ±0.60 | ±0.61 | ±0.58 | ±20.94 | ±3.00 | ±8.91 |
| | | | | | | | | | |
| Nominal | 15 | 15 | 15 | 3 | 3 | 3 | 150 | 250 | 45 |

Table 30: Coupons dimensions

Where amb: ambient, E: elastic modulus, max: ultimate, F: force, δ : displacement, v: Poisson coefficient, T: temperature, amb: ambient

| ID | F_{\max} | δ_{\max} | σ_{\max} | $E_{\text{side}1}$ | $E_{\text{side}2}$ | $v_{\text{side}1}$ | $v_{\text{side}2}$ | T_{amb} | $\epsilon_{\max,1}$ | $\epsilon_{\max,2}$ |
|-----------|------------|-----------------|-----------------|--------------------|--------------------|--------------------|--------------------|------------------|---------------------|---------------------|
| | [kN] | [mm] | [Mpa] | [GPa] | [GPa] | [-] | [-] | [°C] | [micStrain] | [micStrain] |
| UD-0-I-01 | 40.7 | 5.04 | 1128.4 | 50.6 | 47.2 | 0.285 | 0.261 | 21.9 | | 29532 |
| UD-0-I-02 | 46.8 | 5.61 | 1263.1 | 48.3 | | 0.215 | 0.565 | 22.0 | 29031 | |
| UD-0-I-03 | 45.5 | 5.44 | 1254.1 | 46.6 | 49.6 | 0.281 | 0.294 | 22.0 | 28546 | 28203 |
| UD-0-I-04 | 43.8 | 5.18 | 1189.8 | 48.6 | 47.9 | 0.306 | 0.231 | 22.2 | 26843 | |
| UD-0-I-05 | 43.8 | 5.15 | 1200.4 | 47.9 | 47.6 | 0.302 | 0.264 | 22.0 | 27249 | 27472 |
| UD-0-I-06 | 44.8 | 5.30 | 1217.0 | 47.8 | 46.1 | 0.319 | 0.290 | 22.1 | 28022 | 28598 |
| UD-0-I-07 | 45.4 | 5.34 | 1222.6 | 45.1 | 45.7 | 0.327 | 0.287 | 22.1 | 28781 | 28627 |
| | | | | | | | | | | |
| Mean | 44.4 | 5.3 | 1210.8 | 47.8 | 47.4 | 0.291 | 0.313 | 22.0 | 28078 | 28487 |
| Std | 1.93 | 0.19 | 44.94 | 1.71 | 1.38 | 0.04 | 0.11 | 0.10 | 876.2 | 747.2 |
| COV | 4% | 4% | 4% | 4% | 3% | 13% | 36% | 0% | 3% | 3% |

Table 31: Test summary

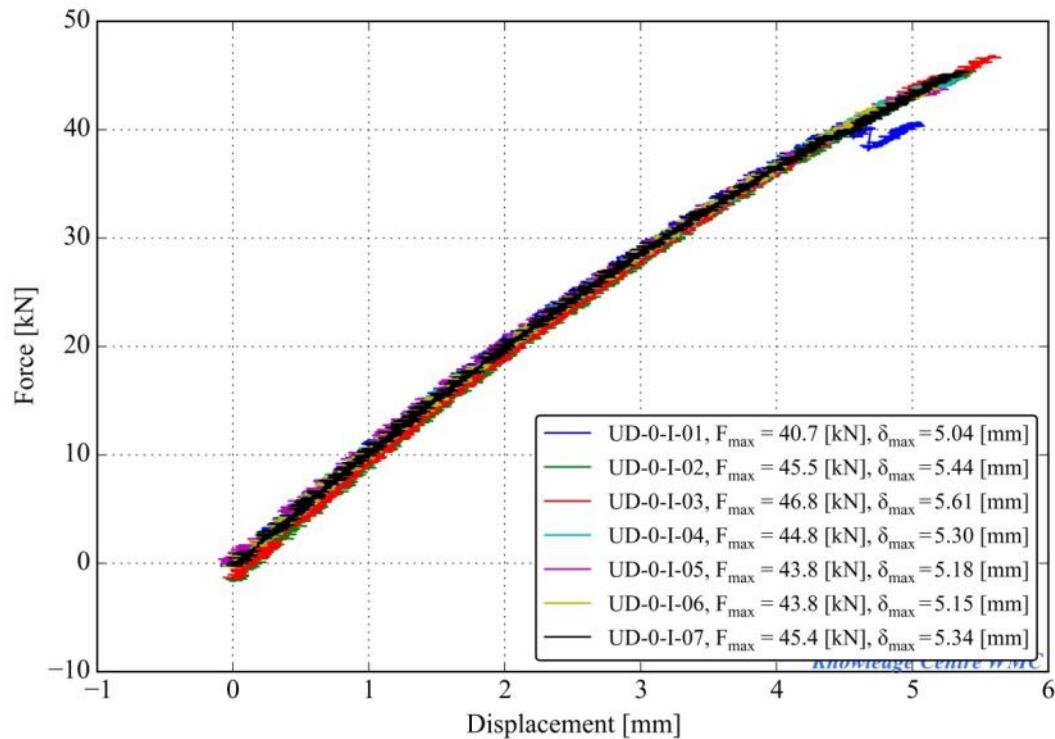


Figure 70: Force versus displacement

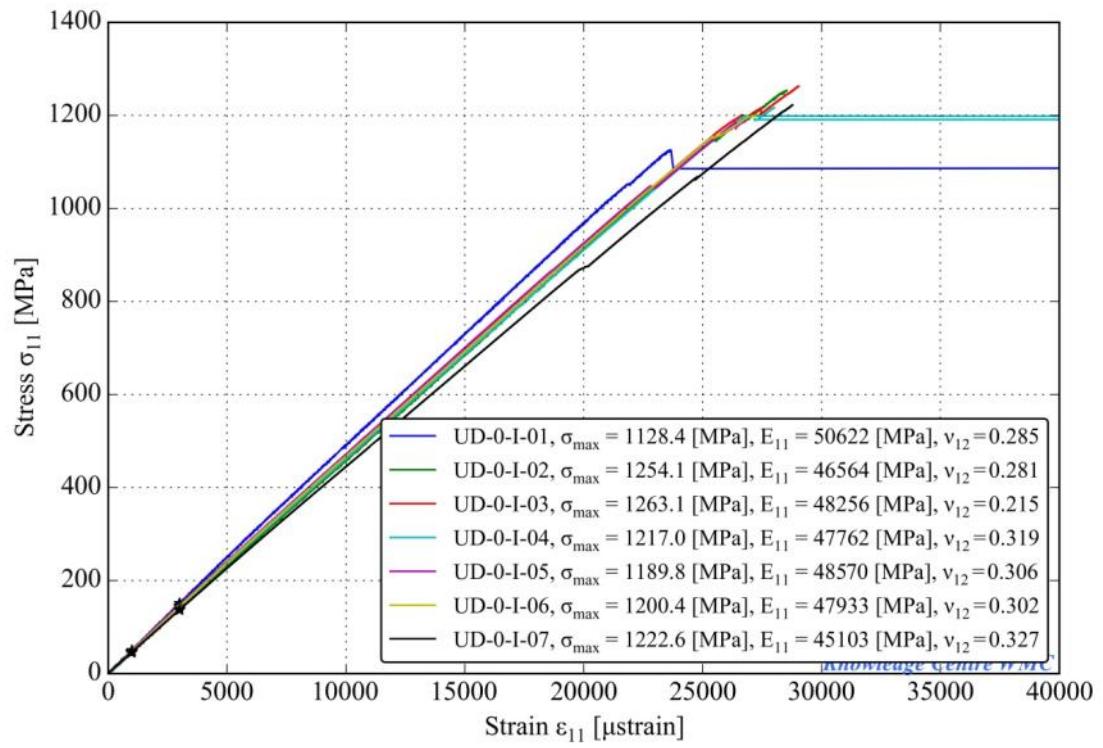


Figure 71: Stress versus strain

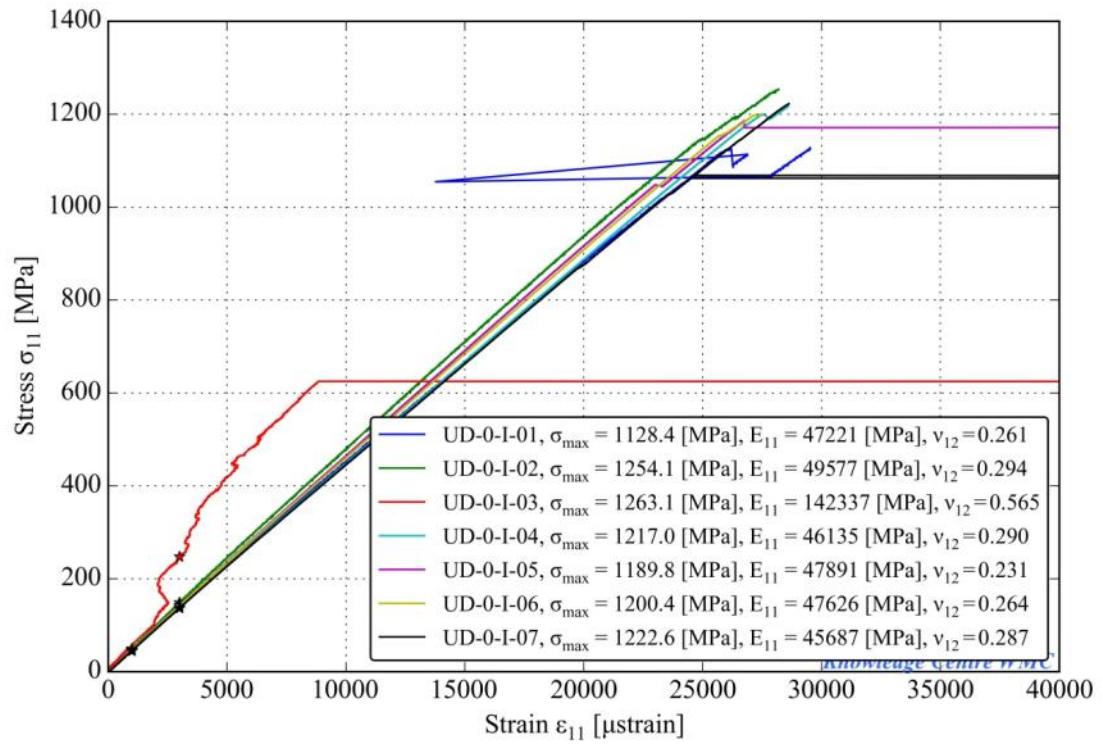


Figure 72: Stress versus strain side 2

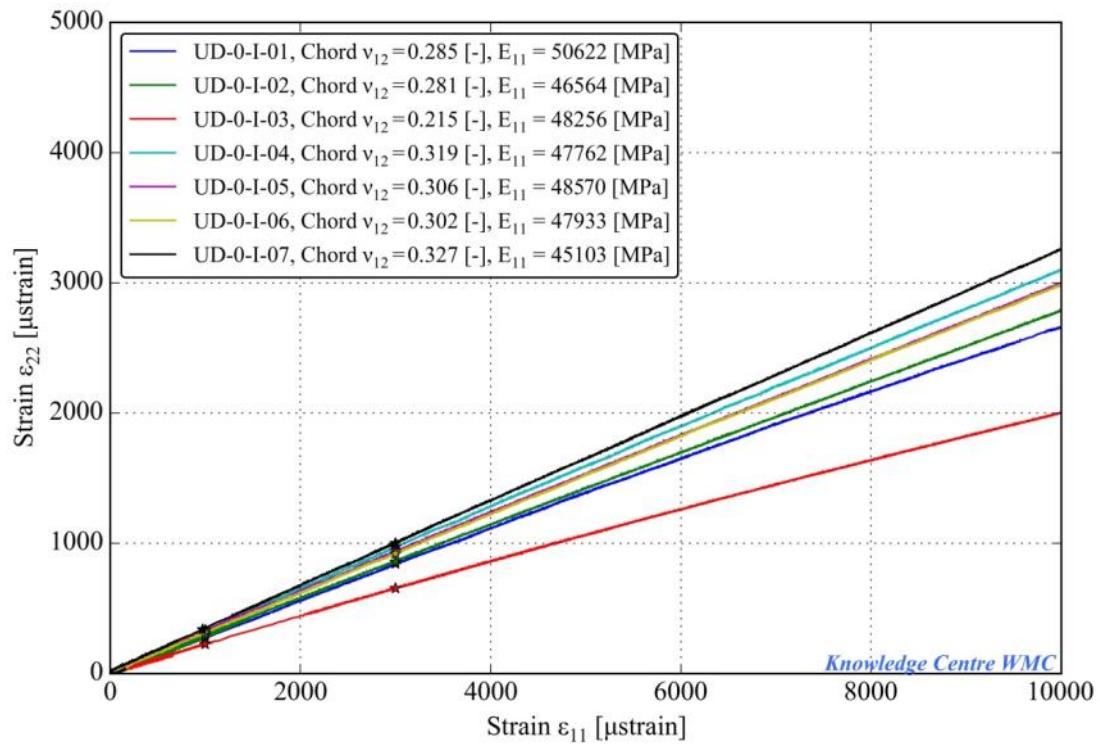


Figure 73: Strain 1 versus strain 2, side 1

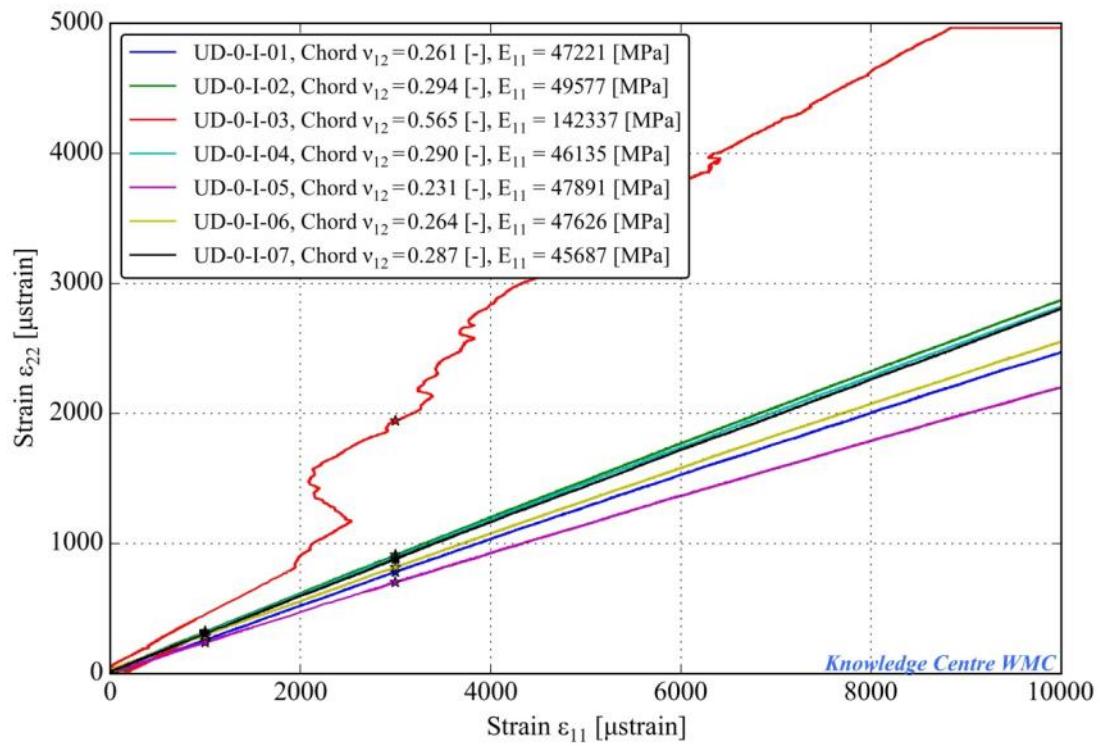


Figure 74: Strain 1 versus strain 2, side 2

5. UD static tension test benchmark

5.1 Introduction

An inter-laboratory benchmarking test was performed in the context of the joint-project: Multi-axial fatigue model verification. This is serving towards gaining confidence in the delivered experimental results, while enhancing the comparison of the theoretical models to the recorded data.

The materials description, the manufacturing process of the laminate, the stacking sequence, the laminate post tempering treatment, the coupon geometry and the test standard that was implemented together with the test boundary conditions are listed in detail.

5.2 Material

The materials that were used for the manufacturing are in Table 32.

| Material | Description |
|--------------|---------------------------------------|
| UD Fabric | UD 1800 gsm, FV HM 3B W2020 |
| Resin | MOMENTIVE EPIKOTE MGS RIMR 135 / 035c |
| Curing Agent | MOMENTIVE EPIKURE MGS RIMH 137 |

Table 32. Materials

5.3 Manufacturing process and lay-up

Each partner manufactured its own laminates with one sided mould and Vacuum Assisted Resin Transfer Moulding. For the infusion the following steps were implemented, see Table 33.

| Step | Temperature / time | Pressure |
|---------------------|---------------------------------------|----------|
| Infusion | 40 °C | -0,9 Bar |
| Maintenance | 5 min 40 °C | -0,9 Bar |
| Heating Maintenance | 0,5 °C/min till 50 °C 300 min 50 °C | -0,9 Bar |
| Heating Maintenance | 0,5 °C/min till 60 °C 300 min a 60 °C | -0,9 Bar |
| Heating Maintenance | 0,5 °C/min till 70 °C 300 min a 70 °C | -0,9 Bar |
| Cooling | 1 °C/min till room temperature | -0,9 Bar |

Table 33. Curing cycle

The manufactured laminate had a [UD]s symmetric stacking sequence, with the backing plies towards the intern of the coupon and the UDO° fibres at the outermost surfaces. IWES manufactured an extra UD series for all partners.

5.4 Coupon geometry and tabs

The coupon geometry will be the same as described in ASTM D3039/D3039M-14 for a UDO° test specimen.

| Dimension | Value |
|---------------------|-------|
| Width [mm] | 15 |
| Overall length [mm] | 250 |
| Tabs length [mm]* | 60 |
| Tabs thickness [mm] | 1,5 |
| Tabs end angle [°] | 90 |

Table 34. Curing cycle

* In the standard is required 56mm

The tabs were manufactured from a Biax [45/-45/45] laminate.

5.5 Instrumentation, coupon tests and reporting

Two series of tests were conducted. Each partner manufactured its own specimens and then tested them accordingly, while IWES manufactured and distributed specimens to each partner. In the legends of the following Figures the testing institute is always referenced as first and as second the institute that manufactured the coupons. The specimens were instrumented back to back with rosettes (axial and transverse strain gauges). Each partner used different strain gauges. All test related details including the strain gauge grid, the load cell accuracy level etc. are summarized in the Appendix, Table 38 and Table 39.

The tests were performed according to the ASTM D3039/D3039M [6] in universal coupon machines which were calibrated.

The tests were in general in a good agreement to each other with some limited exceptions. To enhance the comparison between the Laboratory results the experimental values were validated against theoretical values, calculated based on the rule of mixtures [7]. The calculations were based on the assumptions that the UD laminate consists of 95% UDO and 5% UD90 due to the backing ply. The stiches of the UD fabric were disregarded. The resin density was considered 1,2gr/cm³ and the fibre density 2,6gr/ cm³. The UD90 laminate was assumed to have 14000MPa modulus of elasticity and the glass fibres had a Young Modulus of 82000MPa.

The comparison to theory both for Young modulus and major Poisson ratio are shown in the following Figures. Only one test series is variating in comparison to the rest. This deviation is probably due to the coupon geometry measurement accuracy but it has to be further investigated.

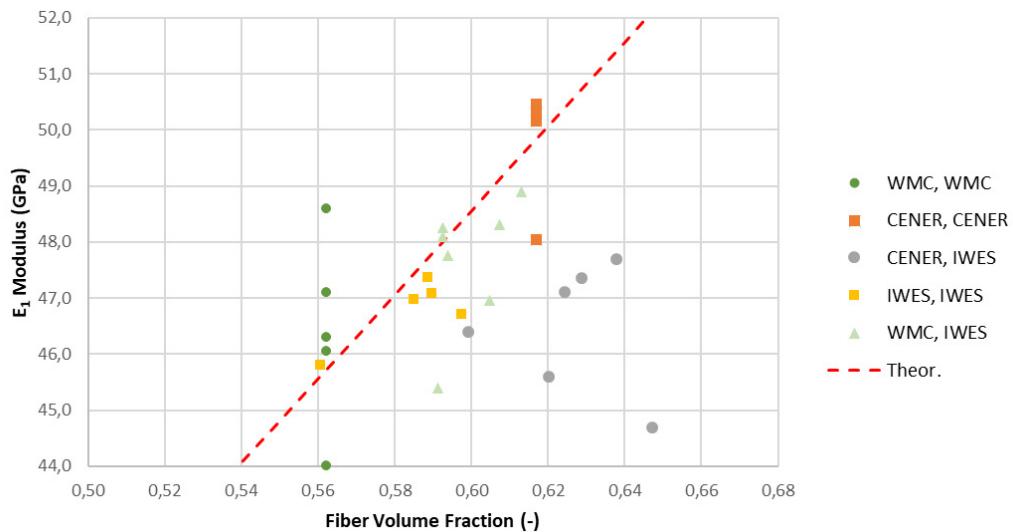


Figure 75 E-Modulus variation with composite Fibre Volume Fraction

The very low coefficient of variation (CoV) of the E-Modulus (<5%), see Figure 76 advocates repeatability of the tests and the instrumentation.

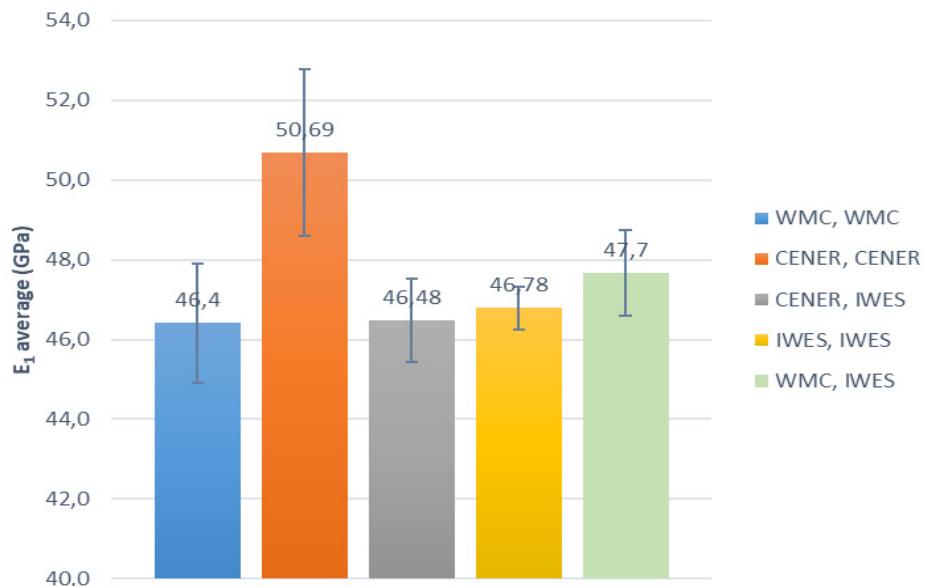


Figure 76 E₁ modulus average (values has not been corrected with the fibre volume content)

The major Poisson ratio is also in a good agreement with the theoretical prediction, see Figure 77, following the reduction trend with increasing FVF.

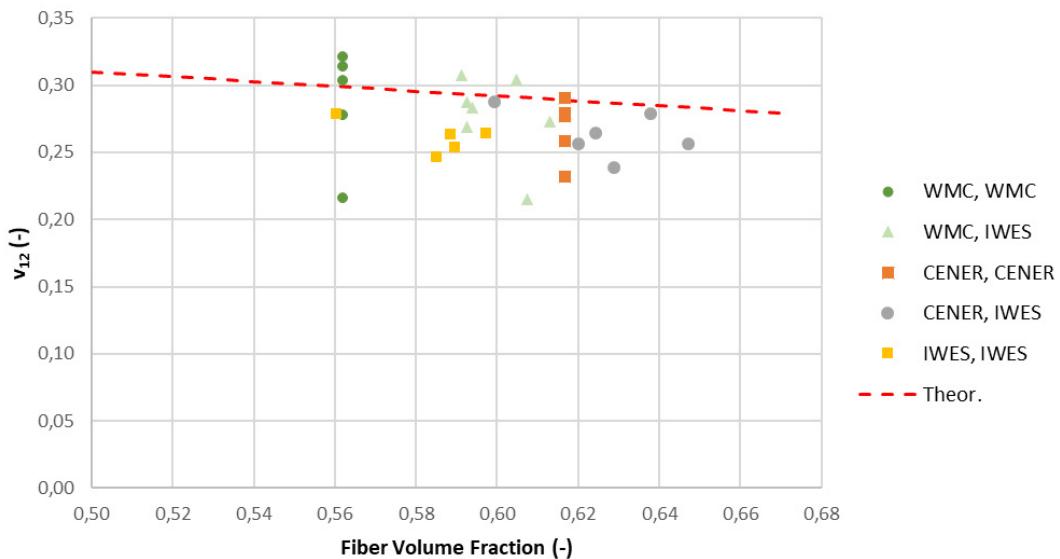


Figure 77 Major Poisson variation with composite Fibre Volume Fraction

The relative high Coefficient of Variation (CoV) of the Poisson ratio especially when separately both side records are considered is something that has to be further investigated, see Appendix and Figure 101, Figure 102. In the average values however this variation is substantially reduced.

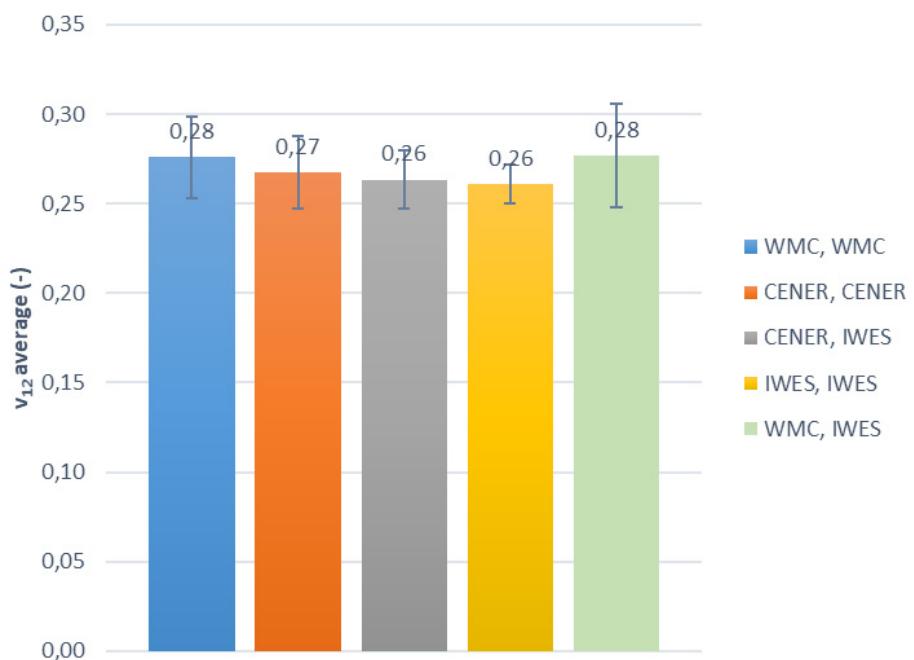


Figure 78 Poisson ratio v₁₂ average (values has not been corrected with the fibre volume content)

In the case of the coupons strength (X_T) the scatter was relative low between the labs. The results though were not clearly consistence in a physically based sense, since the strength should increase with increasing Fibre Volume Fraction, see Figure 79.

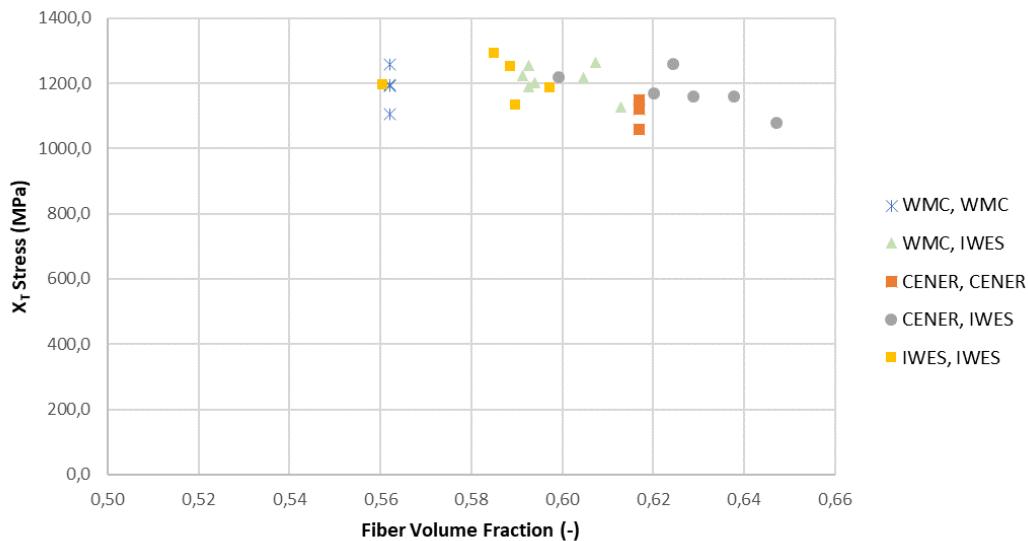


Figure 79 Correlation of Fibre Volume Fraction with strength

Based on the E-modulus performance, a 4% increase of strength was expected between 59% and 62% Fibre Volume Fraction. This is however covered from the test results variation.

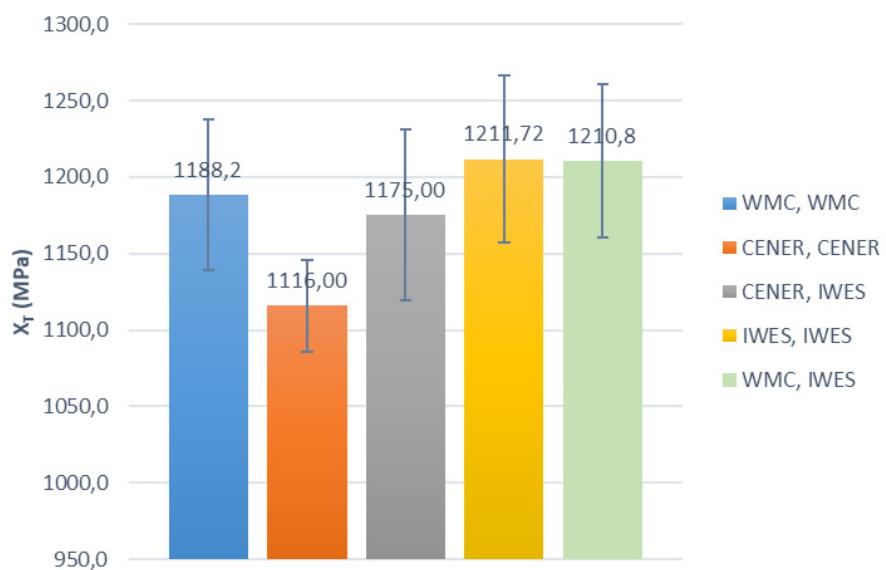


Figure 80 Static tensile strength (values has not been corrected with the fibre volume content)

6. Conclusions

Overall, the project has proceeded without incidences. However, the scope of some of the parts within WP2 has changed slightly:

- The tubular coupons in multi-axial have been substituted by Multiaxial dog-bone coupons.
- The plane multiaxial laminate coupons have been finally loaded on axis, 10° off-axis and 60° off-axis.

The joint experiments provided the necessary data to evaluate the developed fatigue calculation methodology. The validation of the developed fatigue calculation methodology was performed in the framework of IRPWIND project [7]. Promising results have been achieved in the comparison between simulations and test results. This correlation work needs to be completed for all the tests performed within this project.

With regard to the benchmarking, the tests showed a good agreement in between labs.

7. References

- [1] D.J. Lekou, T.T. Assimakopoulou and T.P. Philippidis, Estimation of the uncertainty in measurement of composite material mechanical properties during static tests, strain, 47, 2011, pp.430-438.
- [2] R. Nijssen. OptiDAT-database reference document-OB_TC_R018 rev. 005, 2006, [www.wmc.eu/optidat_files/Optidat reference document.pdf](http://www.wmc.eu/optidat_files/Optidat%20reference%20document.pdf).
- [3] Fraisse A, Povl B. Compression fatigue of Wind Turbine Blade composites materials and damage mechanisms. In: ICCM21, editor. 21st Int. Conf. Compos. Mater., Xi'an, China: 2017.
- [4] J. Estarriaga. Considerations previous to testing (summary). IRPWIND 2nd call Joint Experiments: Multi-axial fatigue model verification. 2017
- [5] ASTM D6641/D6641M-16^{e1}, Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials Using a Combined Loading Compression (CLC) Test Fixture¹
- [6] ASTM D3039/D3039M-14, Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials
- [7] Helmut Schürmann, Konstruieren mit Faser-Kunststoff-Verbunden, Springer-Verlag Berlin Heidelberg 2005, 2007, ISBN 978-3-540-72189-5
- [8] IRPWIND project. D71.3 Report on validation and improvement of blade design tools. 2017

8. Appendix

8.1 CENER tests

8.1.1 WP1- Fatigue. UD_0°_R=0.1



Figure 81: UD_0°_R=0.1.Front



Figure 82: UD_0°_R=0.1.Side

8.1.2 WP2- Fatigue. DVal1_0°_R=-1



Figure 83: DVal1_0°_R=-1.Front

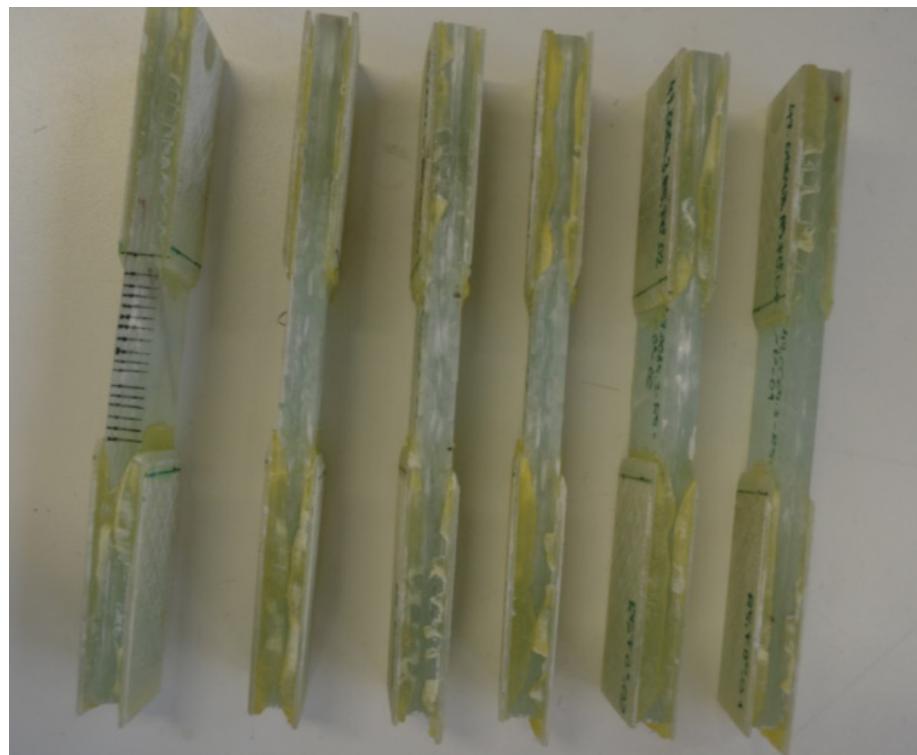


Figure 84: DVal1_0°_R=-1.Side

8.1.3 WP2- Fatigue. DVal1_10°_R=-1



Figure 85: DVal1_10°_R=-1.Front

8.1.4 WP2- Fatigue. DVal1_60°_R=-2



Figure 86: DVal1_60°_R=-2.Front

8.1.5 WP2- Static. Benchmarking tests. Coupons manufactured by IWES

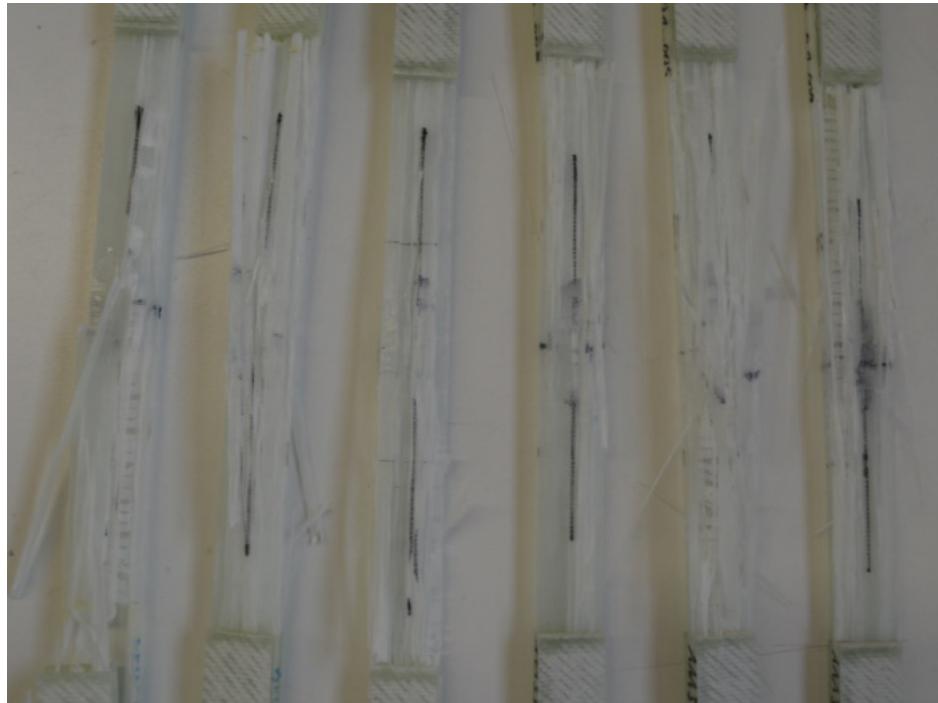


Figure 87: Benchmarking IWES coupons. Front.

8.1.6 WP2- Static. Benchmarking tests. Coupons manufactured by CENER



Figure 88: Benchmarking CENER coupons. Front.

8.2 IWES tests

| | Width 1 | Width 2 | Width 3 | Thick. 1 | Thick. 2 | Thick. 3 |
|-------------------|---------|---------|---------|----------|----------|----------|
| Specimen ID | [mm] | [mm] | [mm] | [mm] | [mm] | [mm] |
| 111333_001_01_003 | 24,98 | 24,98 | 24,98 | 3,85 | 3,85 | 3,84 |
| 111333_001_01_004 | 24,98 | 24,98 | 24,98 | 3,70 | 3,75 | 3,77 |
| 111333_001_01_005 | 25,02 | 25,02 | 25,01 | 3,67 | 3,64 | 3,68 |
| 111333_001_01_006 | 24,98 | 24,98 | 24,97 | 3,79 | 3,74 | 3,73 |
| 111333_001_01_007 | 24,97 | 24,97 | 24,96 | 3,77 | 3,75 | 3,76 |
| 111333_001_01_008 | 25,06 | 25,06 | 25,08 | 3,76 | 3,75 | 3,72 |
| 111333_001_01_009 | 24,99 | 24,99 | 24,99 | 3,73 | 3,75 | 3,78 |
| 111333_001_01_010 | 24,97 | 24,98 | 24,97 | 3,75 | 3,73 | 3,74 |
| 111333_001_01_011 | 24,98 | 24,98 | 24,98 | 3,89 | 3,70 | 3,70 |
| 111333_001_01_012 | 25,06 | 25,05 | 25,05 | 3,86 | 3,82 | 3,70 |
| 111333_001_01_013 | 24,99 | 24,99 | 24,98 | 3,76 | 3,77 | 3,87 |
| 111333_001_01_014 | 25,00 | 25,00 | 25,00 | 3,83 | 3,77 | 3,75 |

Table 35 Specimen UDO geometry fatigue R=10

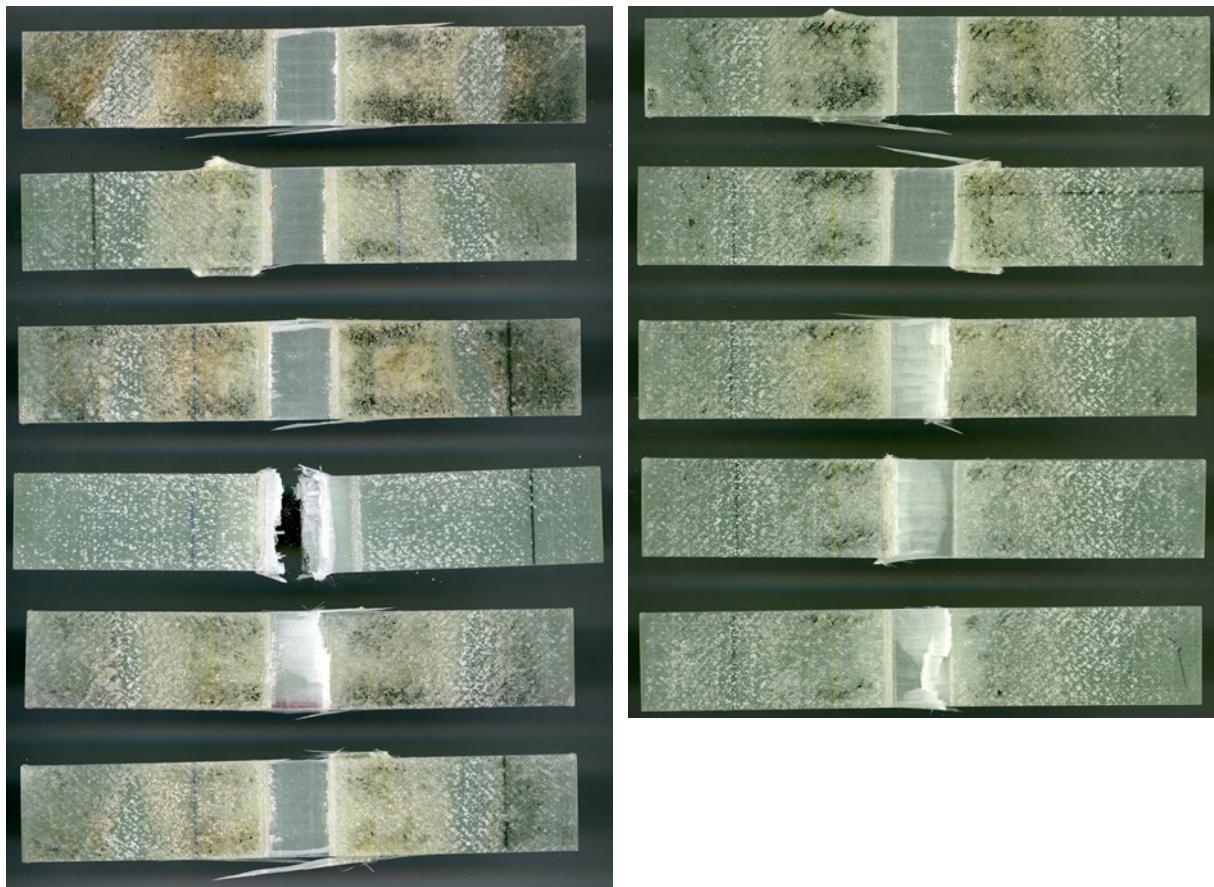


Figure 89 Front side UDO failure mode fatigue R=10

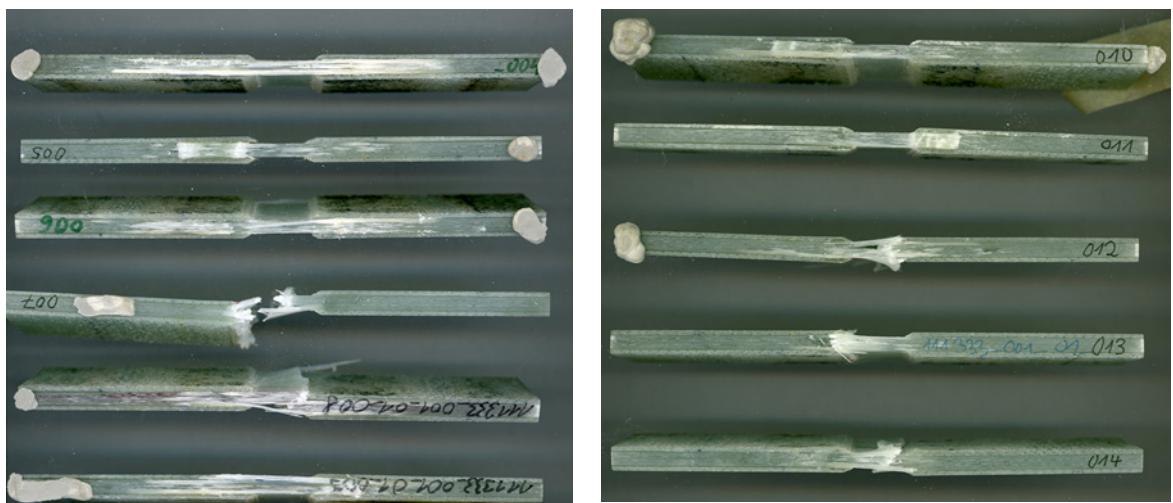


Figure 90 Side 1 view UDO failure mode fatigue R=10

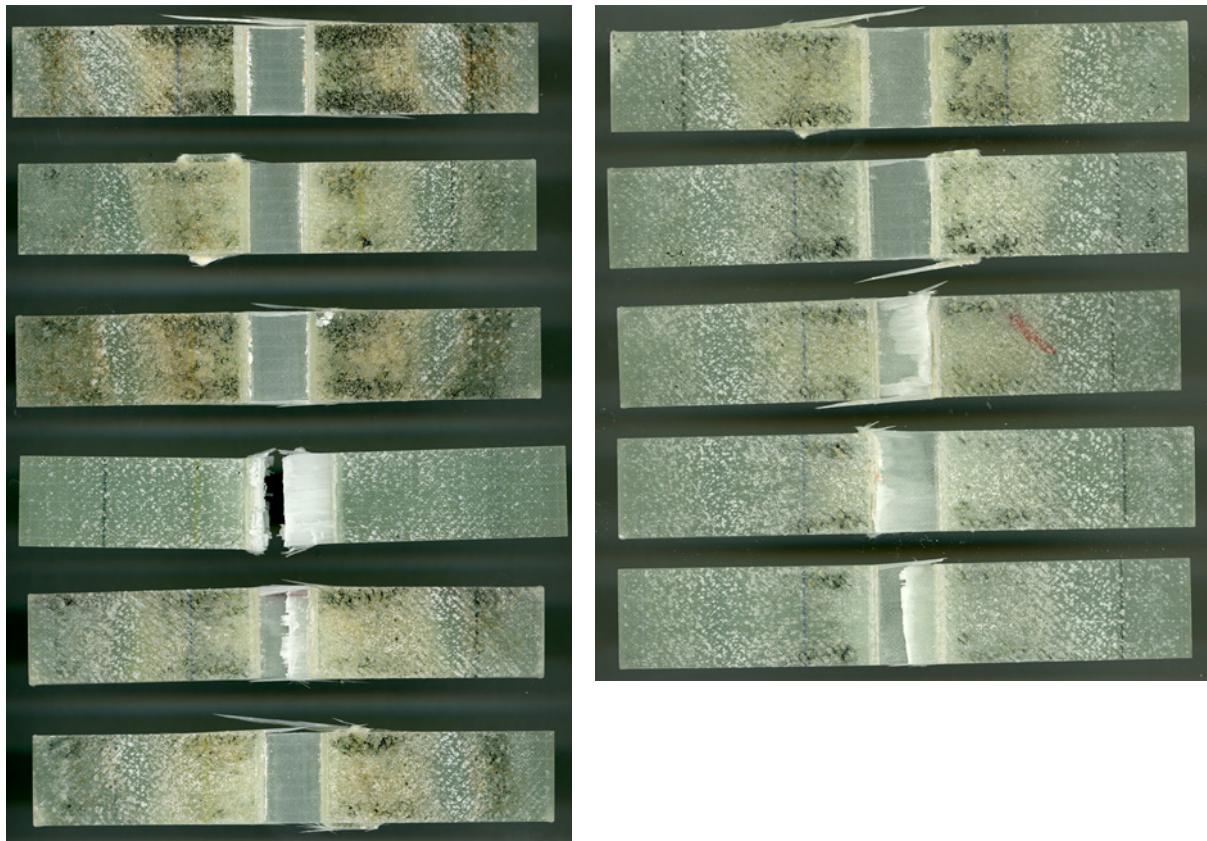


Figure 91 Back view UDO failure mode fatigue R=10

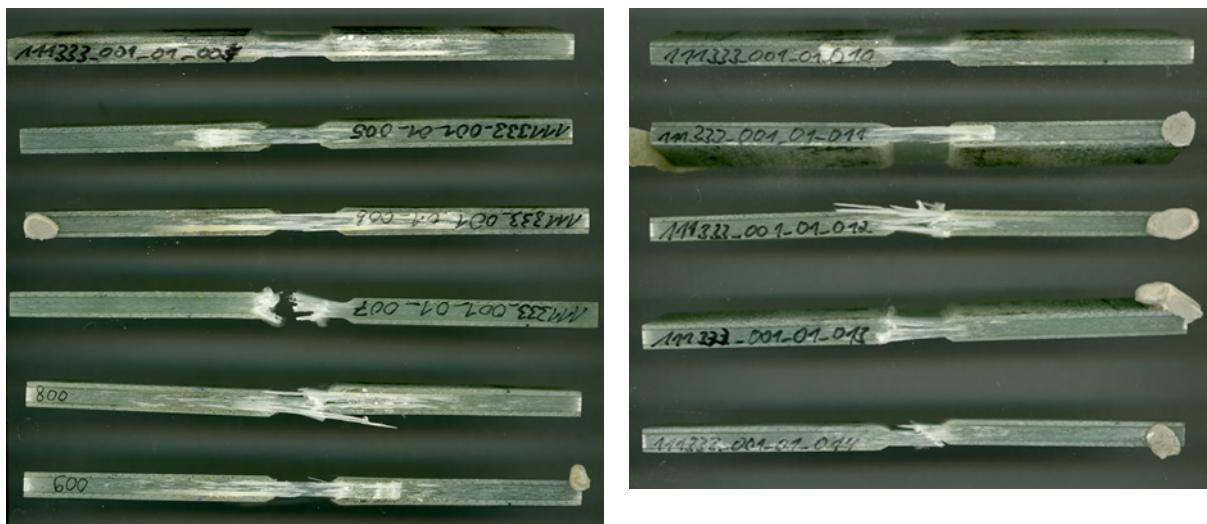


Figure 92 Side 2 view UDO failure mode fatigue R=10

| | Width 1 | Width 2 | Width 3 | Thick. 1 | Thick. 2 | Thick. 3 |
|-------------------|---------|---------|---------|----------|----------|----------|
| Specimen ID | [mm] | [mm] | [mm] | [mm] | [mm] | [mm] |
| 111333_002_01_004 | 14,96 | 14,96 | 14,96 | 3,69 | 3,70 | 3,69 |
| 111333_002_01_006 | 14,96 | 14,96 | 14,96 | 3,76 | 3,75 | 3,74 |
| 111333_002_01_007 | 14,94 | 14,95 | 14,95 | 3,72 | 3,73 | 3,69 |
| 111333_002_01_010 | 14,98 | 14,98 | 14,98 | 3,74 | 3,75 | 3,71 |
| 111333_002_01_011 | 14,97 | 14,97 | 14,97 | 3,83 | 3,77 | 3,76 |
| 111333_002_01_012 | 14,97 | 14,97 | 14,97 | 3,74 | 3,77 | 3,74 |
| 111333_002_01_013 | 14,97 | 14,97 | 14,97 | 3,71 | 3,71 | 3,73 |
| 111333_002_01_015 | 14,92 | 14,92 | 14,91 | 3,80 | 3,79 | 3,78 |
| 111333_002_01_001 | 14,98 | 14,98 | 14,99 | 3,69 | 3,68 | 3,69 |
| 111333_002_01_002 | 14,96 | 14,97 | 14,96 | 3,70 | 3,72 | 3,74 |

Table 36 Specimen UD5 geometry fatigue R=0.1

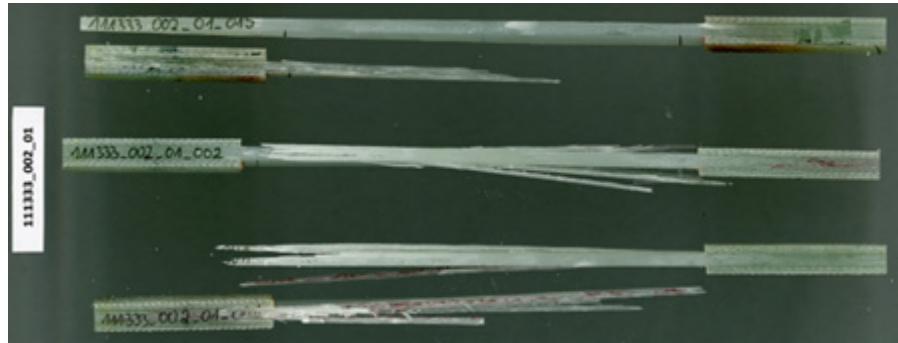
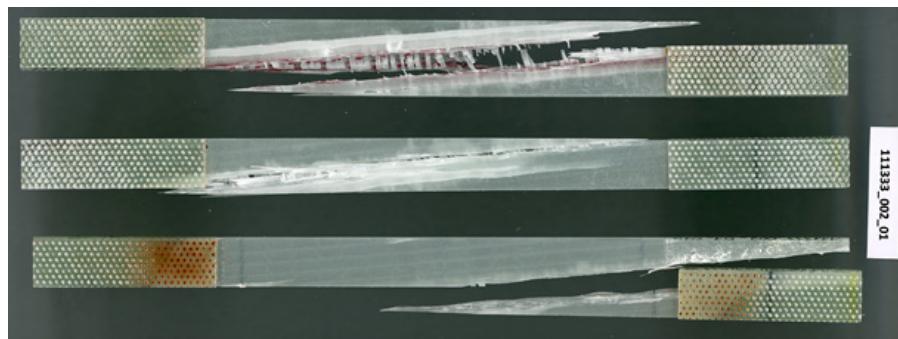


Figure 93 UD5° failure mode static test

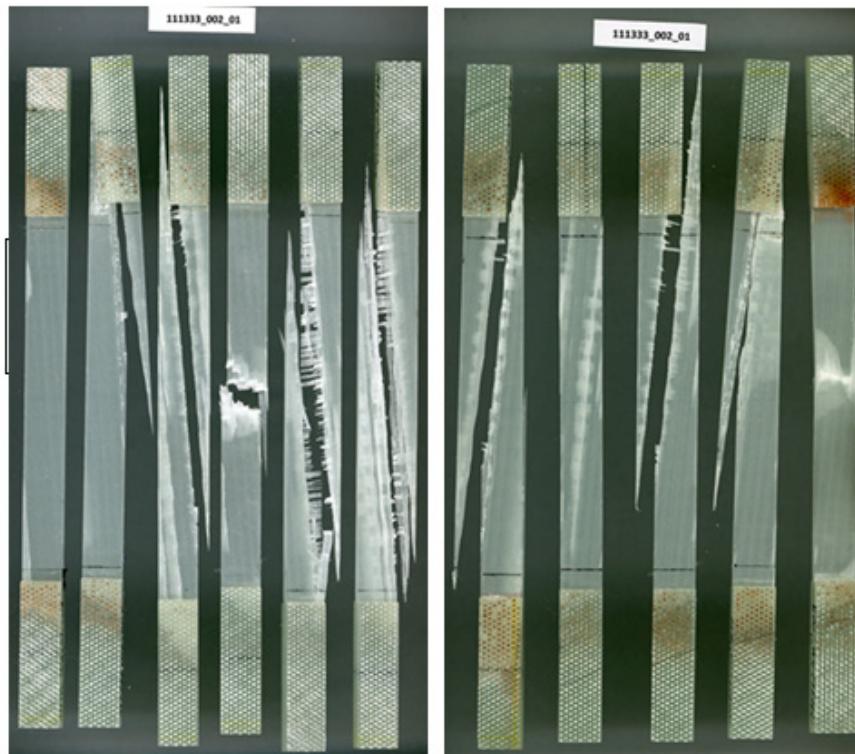


Figure 94 Front side UD5° failure mode fatigue test R=0.1

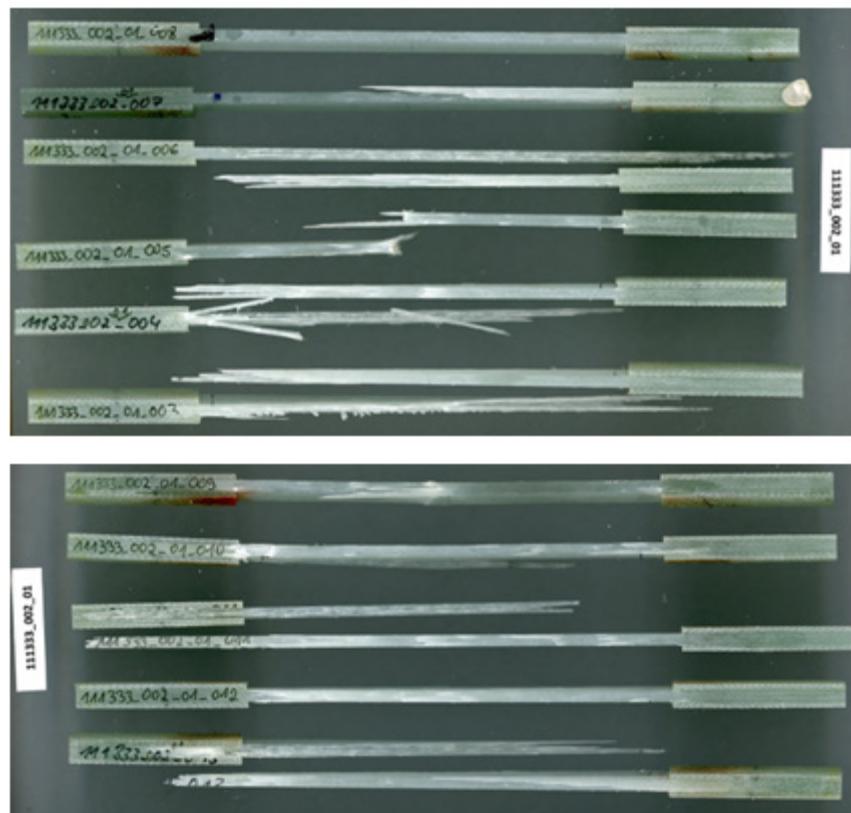


Figure 95 Front side UD5° failure mode fatigue test R=0.1

| | Width 1 | Width 2 | Width 3 | Thick. 1 | Thick. 2 | Thick. 3 |
|-------------------|---------|---------|---------|----------|----------|----------|
| Specimen ID | [mm] | [mm] | [mm] | [mm] | [mm] | [mm] |
| 111333_003_01_004 | 14,96 | 14,95 | 14,95 | 3,82 | 3,88 | 3,85 |
| 111333_003_01_005 | 15,02 | 15,02 | 15,01 | 3,82 | 3,81 | 3,83 |
| 111333_003_01_007 | 14,96 | 14,99 | 14,95 | 3,78 | 3,87 | 3,76 |
| 111333_003_01_008 | 14,95 | 14,95 | 14,94 | 3,81 | 3,80 | 3,83 |
| 111333_003_01_009 | 14,95 | 14,96 | 14,95 | 3,77 | 3,81 | 3,86 |
| 111333_003_01_010 | 14,97 | 14,97 | 14,96 | 3,78 | 3,80 | 3,80 |
| 111333_003_01_001 | 15,01 | 15,01 | 15,02 | 3,74 | 3,78 | 3,72 |
| 111333_003_01_002 | 14,96 | 14,96 | 14,96 | 3,69 | 3,73 | 3,72 |

Table 37 Specimen UD10 geometry fatigue R=0.1

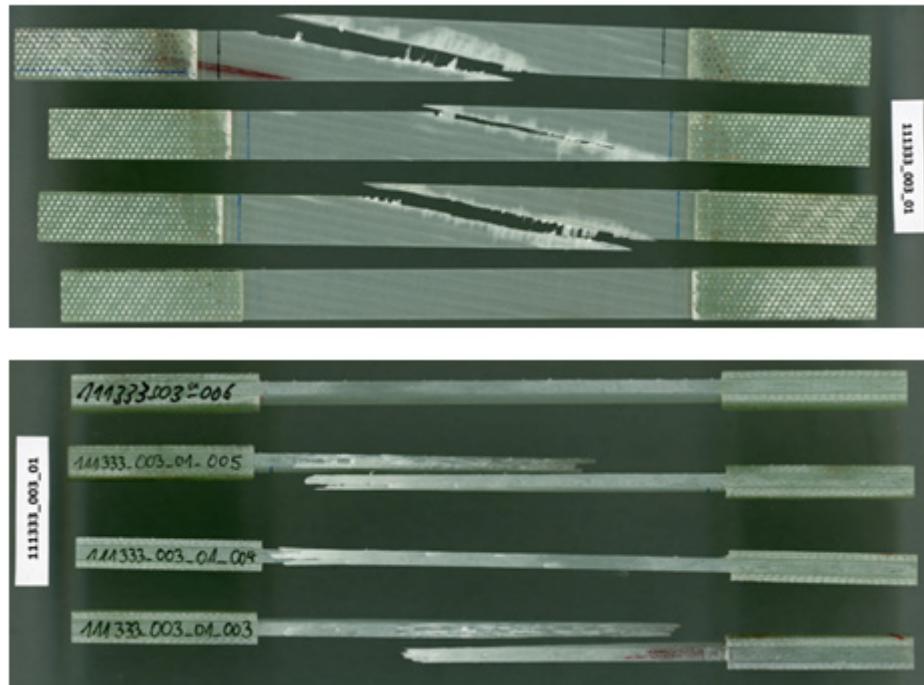


Figure 96 UD10° failure mode static test

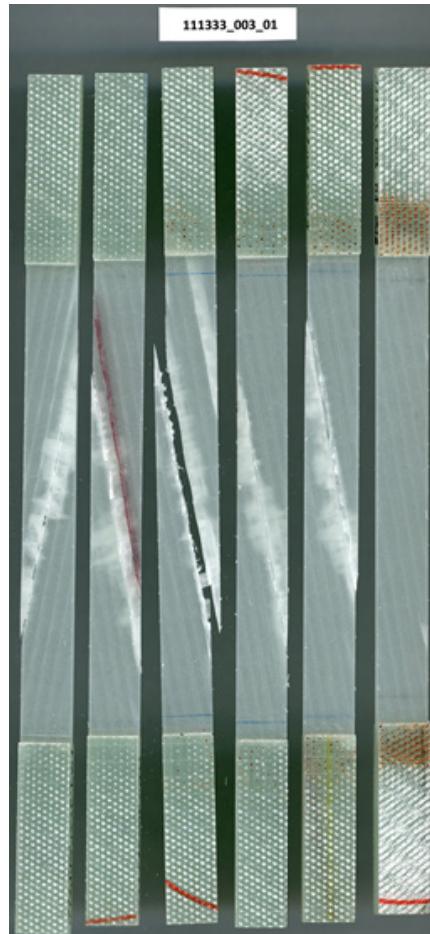


Figure 97 Front side UD10° failure mode fatigue test R=0.1

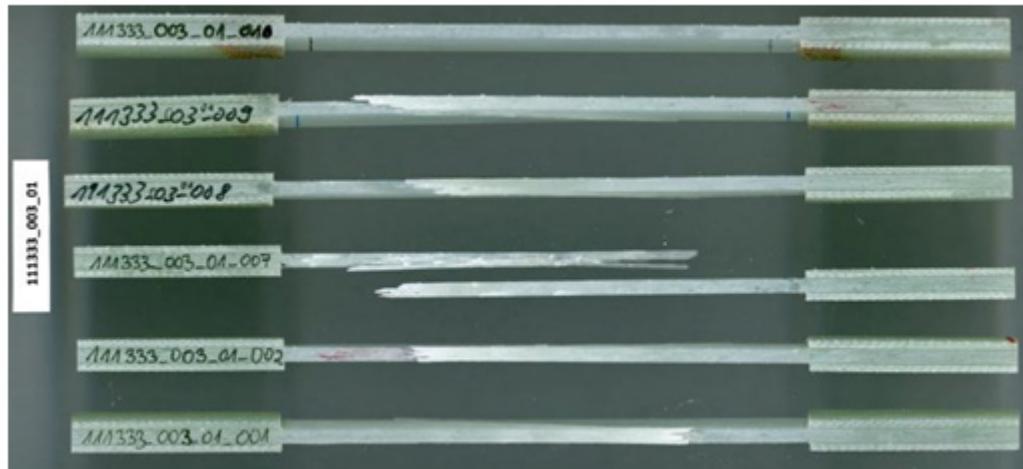


Figure 98 Side view UD10° failure mode fatigue test R=0.1

| Tested | Manufactured | Coupons | width top | | width middle | | width bottom | width average | thick. top | thick. middle | thick. bottom | thickness average |
|--------|--------------|-------------|--------------|--------------|--------------|--------------|--------------|---------------|------------|---------------|---------------|-------------------|
| | | | mm | mm | mm | mm | | | | | | |
| WMC | WMC | UD-0-01 | 14,91 | 14,92 | 14,91 | 14,91 | 2,56 | 2,64 | 2,64 | 2,61 | | |
| WMC | WMC | UD-0-02 | 14,89 | 14,87 | 14,86 | 14,87 | 2,61 | 2,61 | 2,56 | 2,59 | | |
| WMC | WMC | UD-0-03 | 14,9 | 14,89 | 14,94 | 14,91 | 2,5 | 2,52 | 2,61 | 2,54 | | |
| WMC | WMC | UD-0-04 | 14,85 | 14,84 | 14,87 | 14,85 | 2,56 | 2,58 | 2,57 | 2,57 | | |
| WMC | WMC | UD-0-05 | 14,88 | 14,88 | 14,88 | 14,88 | 2,54 | 2,57 | 2,58 | 2,56 | | |
| | | Mean | 14,89 | 14,88 | 14,89 | 14,89 | 2,55 | 2,58 | 2,59 | 2,58 | | |
| | | Std | 0,02 | 0,03 | 0,03 | 0,02 | 0,04 | 0,04 | 0,03 | 0,03 | 0,02 | |
| | | COV | 0,14 | 0,18 | 0,20 | 0,15 | 1,39 | 1,56 | 1,13 | 0,94 | | |
| | | | | | | | | | | | | |
| WMC | IWES | UD-0-I-01 | 14,97 | 15,07 | 15,08 | 15,04 | 2,40 | 2,40 | 2,45 | 2,42 | | |
| WMC | IWES | UD-0-I-02 | 15,03 | 15,08 | 14,95 | 15,02 | 2,45 | 2,41 | 2,43 | 2,43 | | |
| WMC | IWES | UD-0-I-03 | 14,94 | 14,89 | 15 | 14,94 | 2,42 | 2,49 | 2,49 | 2,47 | | |
| WMC | IWES | UD-0-I-04 | 14,96 | 14,99 | 14,96 | 14,97 | 2,47 | 2,46 | 2,47 | 2,47 | | |
| WMC | IWES | UD-0-I-05 | 14,93 | 14,99 | 15 | 14,97 | 2,47 | 2,46 | 2,46 | 2,46 | | |
| WMC | IWES | UD-0-I-06 | 14,92 | 14,96 | 15,08 | 14,99 | 2,41 | 2,44 | 2,46 | 2,44 | | |
| WMC | IWES | UD-0-I-07 | 14,98 | 15 | 14,96 | 14,98 | 2,43 | 2,48 | 2,50 | 2,47 | | |
| | | Mean | 14,96 | 15,00 | 15,00 | 14,99 | 2,44 | 2,45 | 2,47 | 2,45 | | |
| | | Std | 0,03 | 0,06 | 0,05 | 0,03 | 0,03 | 0,03 | 0,02 | 0,02 | 0,02 | |
| | | COV | 0,23 | 0,40 | 0,34 | 0,20 | 1,07 | 1,28 | 0,89 | 0,82 | | |
| | | | | | | | | | | | | |
| CENER | CENER | 1 | N.a | N.a | N.a | 15,30 | N.a | N.a | N.a | N.a | 2,35 | |
| CENER | CENER | 2 | N.a | N.a | N.a | 15,30 | N.a | N.a | N.a | N.a | 2,35 | |
| CENER | CENER | 3 | N.a | N.a | N.a | 15,70 | N.a | N.a | N.a | N.a | 2,28 | |
| CENER | CENER | 4 | N.a | N.a | N.a | 15,60 | N.a | N.a | N.a | N.a | 2,32 | |
| CENER | CENER | 5 | N.a | N.a | N.a | 15,90 | N.a | N.a | N.a | N.a | 2,31 | |
| | | Mean | - | - | - | 15,56 | N.a | N.a | N.a | N.a | 2,32 | |
| | | Std | - | - | - | 0,23 | N.a | N.a | N.a | N.a | 0,03 | |
| | | COV | - | - | - | 1,50 | N.a | N.a | N.a | N.a | 1,14 | |
| | | | | | | | | | | | | |
| CENER | IWES | 1 | N.a | N.a | N.a | 14,90 | N.a | N.a | N.a | N.a | 2,45 | |
| CENER | IWES | 2 | N.a | N.a | N.a | 15,80 | N.a | N.a | N.a | N.a | 2,40 | |
| CENER | IWES | 3 | N.a | N.a | N.a | 15,80 | N.a | N.a | N.a | N.a | 2,34 | |
| CENER | IWES | 4 | N.a | N.a | N.a | 14,80 | N.a | N.a | N.a | N.a | 2,38 | |
| CENER | IWES | 5 | N.a | N.a | N.a | 14,90 | N.a | N.a | N.a | N.a | 2,39 | |
| CENER | IWES | 6 | N.a | N.a | N.a | 14,90 | N.a | N.a | N.a | N.a | 2,36 | |
| | | Mean | - | - | - | 15,18 | N.a | N.a | N.a | N.a | 2,39 | |
| | | Std | - | - | - | 0,44 | N.a | N.a | N.a | N.a | 0,03 | |
| | | COV | - | - | - | 2,88 | N.a | N.a | N.a | N.a | 1,44 | |
| | | | | | | | | | | | | |
| IWES | IWES | 1 | 14,942 | 14,934 | 14,94 | 14,94 | 2,50 | 2,45 | 2,48 | 2,47 | | |
| IWES | IWES | 2 | 14,94 | 14,937 | 14,941 | 14,94 | 2,59 | 2,48 | 2,59 | 2,55 | | |
| IWES | IWES | 3 | 14,954 | 14,946 | 14,949 | 14,95 | 2,45 | 2,46 | 2,46 | 2,45 | | |
| IWES | IWES | 4 | 14,947 | 14,95 | 14,958 | 14,95 | 2,49 | 2,47 | 2,50 | 2,49 | | |
| IWES | IWES | 5 | 14,947 | 14,951 | 14,958 | 14,95 | 2,52 | 2,48 | 2,43 | 2,48 | | |
| | | Mean | 14,95 | 14,94 | 14,95 | 14,95 | 2,51 | 2,47 | 2,49 | 2,49 | | |
| | | Std | 0,00 | 0,01 | 0,01 | 0,00 | 0,05 | 0,01 | 0,05 | 0,03 | 0,03 | |
| | | COV | 0,03 | 0,05 | 0,05 | 0,03 | 1,83 | 0,53 | 2,12 | 1,35 | | |

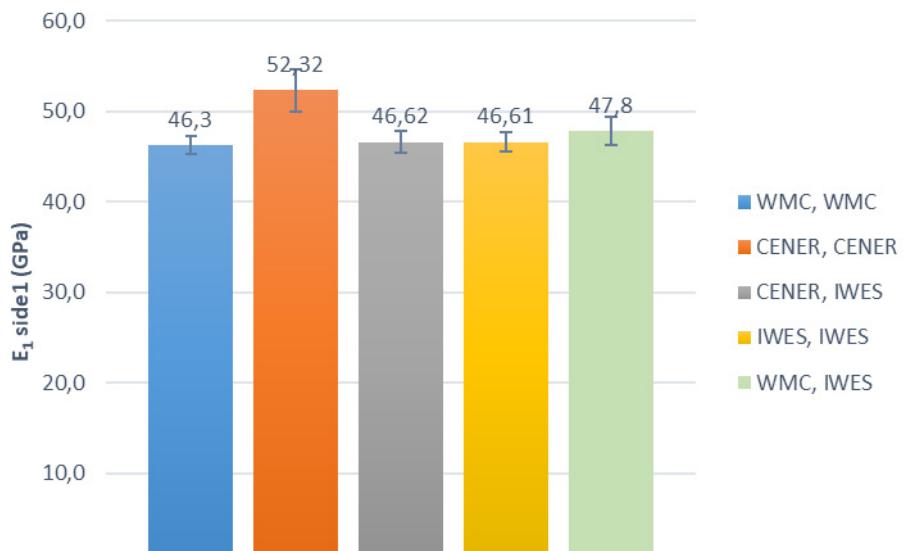
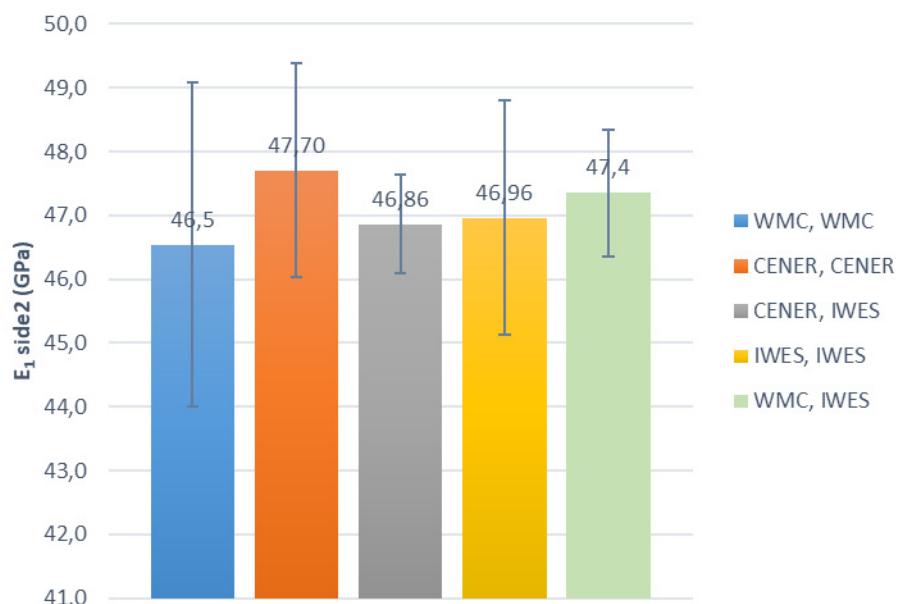
Table 38 Benchmark Coupons Geometry

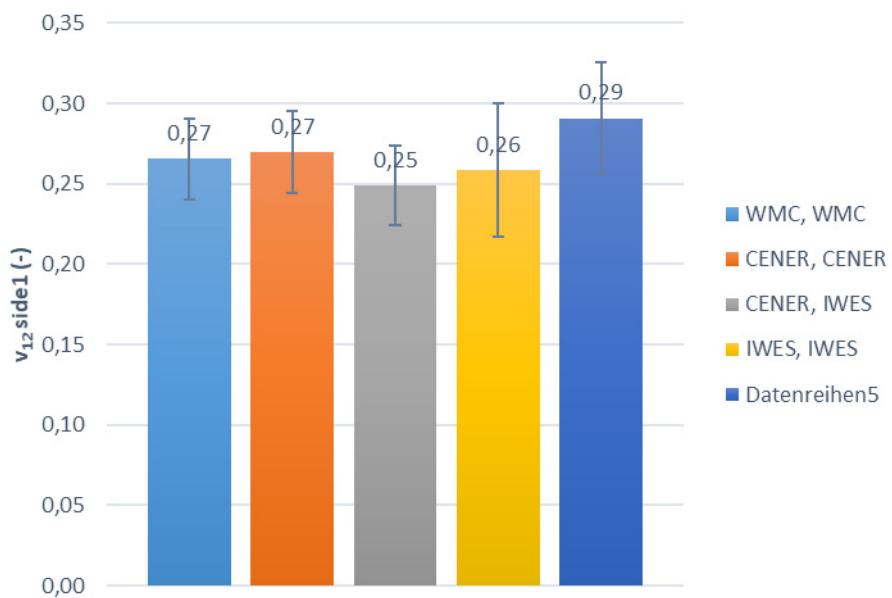
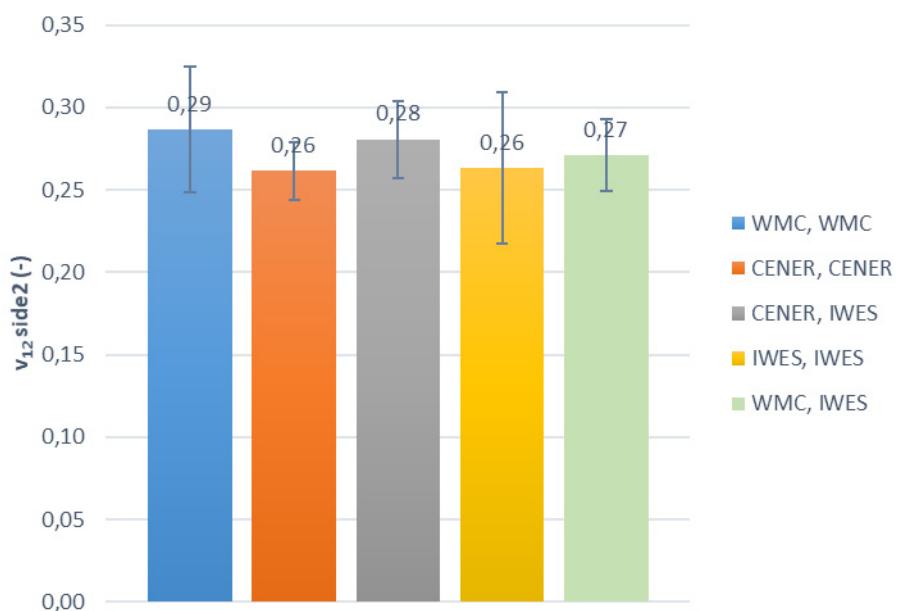
| Tested | Manufactured | Coupons | Fiber Mass Fraction | Fiber Volume Fraction | Strain gauge grid | Load cell class |
|---------------|---------------------|----------------|----------------------------|------------------------------|--------------------------|------------------------|
| | | | % | - | mm | |
| WMC | WMC | UD-0-01 | 73,3 | 0,56 | 2 | 0,5 |
| WMC | WMC | UD-0-02 | 73,3 | 0,56 | 2 | 0,5 |
| WMC | WMC | UD-0-03 | 73,3 | 0,56 | 2 | 0,5 |
| WMC | WMC | UD-0-04 | 73,3 | 0,56 | 2 | 0,5 |
| WMC | WMC | UD-0-05 | 73,3 | 0,56 | 2 | 0,5 |
| | | Mean | 73,30 | 0,56 | - | - |
| | | Std | 0,00 | 0,00 | - | - |
| | | COV | 0,00 | 0,00 | - | - |
| | | | | | | |
| WMC | IWES | UD-0-I-01 | 76,67 | 0,61 | 2 | 0,5 |
| WMC | IWES | UD-0-I-02 | 76,25 | 0,61 | 2 | 0,5 |
| WMC | IWES | UD-0-I-03 | 75,12 | 0,59 | 2 | 0,5 |
| WMC | IWES | UD-0-I-04 | 75,12 | 0,59 | 2 | 0,5 |
| WMC | IWES | UD-0-I-05 | 75,22 | 0,59 | 2 | 0,5 |
| WMC | IWES | UD-0-I-06 | 76,04 | 0,60 | 2 | 0,5 |
| WMC | IWES | UD-0-I-07 | 75,02 | 0,59 | 2 | 0,5 |
| | | Mean | 75,63 | 0,60 | - | - |
| | | Std | 0,62 | 0,01 | - | - |
| | | COV | 0,82 | 1,36 | - | - |
| | | | | | | |
| CENER | CENER | 1 | 76,96 | 0,62 | 3 | 0,5 |
| CENER | CENER | 2 | 76,96 | 0,62 | 3 | 0,5 |
| CENER | CENER | 3 | 76,96 | 0,62 | 3 | 0,5 |
| CENER | CENER | 4 | 76,96 | 0,62 | 3 | 0,5 |
| CENER | CENER | 5 | 76,96 | 0,62 | 3 | 0,5 |
| | | Mean | 76,96 | 0,62 | - | - |
| | | Std | 0,00 | 0,00 | - | - |
| | | COV | 0,00 | 0,00 | - | - |
| | | | | | | |
| CENER | IWES | 1 | 75,63 | 0,60 | 3 | 0,5 |
| CENER | IWES | 2 | 77,20 | 0,62 | 3 | 0,5 |
| CENER | IWES | 3 | 79,18 | 0,65 | 3 | 0,5 |
| CENER | IWES | 4 | 77,85 | 0,63 | 3 | 0,5 |
| CENER | IWES | 5 | 77,53 | 0,62 | 3 | 0,5 |
| CENER | IWES | 6 | 78,51 | 0,64 | 3 | 0,5 |
| | | Mean | 77,65 | 0,63 | - | - |
| | | Std | 1,11 | 0,01 | - | - |
| | | COV | 1,43 | 2,39 | - | - |
| | | | | | | |
| IWES | IWES | 1 | 74,89 | 0,59 | 5 | 0,5 |
| IWES | IWES | 2 | 72,58 | 0,56 | 5 | 0,5 |
| IWES | IWES | 3 | 75,48 | 0,60 | 5 | 0,5 |
| IWES | IWES | 4 | 74,53 | 0,59 | 5 | 0,5 |
| IWES | IWES | 5 | 74,80 | 0,59 | 5 | 0,5 |
| | | Mean | 74,46 | 0,58 | - | - |
| | | Std | 0,99 | 0,01 | - | - |
| | | COV | 1,33 | 2,15 | - | - |

Table 39 Benchmark Coupons Manufacturing & experimental set up

| Tested | Manufactured | Coupons | Fmax | δ_{max} | σ_{max} | Eside1 | Eside2 | E-Average | vside1 | vside2 | vaver. | $\epsilon_{max1\ strength}$ | $\epsilon_{max2\ strength}$ | $\epsilon_{average\ strength}$ | $\epsilon_{max1\ bruch}$ | $\epsilon_{max2\ bruch}$ | Test temp. | |
|--------|--------------|-------------|--------|----------------|----------------|--------|--------|-----------|--------|--------|--------|-----------------------------|-----------------------------|--------------------------------|--------------------------|--------------------------|------------|----|
| | | | kN | mm | MPa | GPa | GPa | GPa | - | - | - | μm/m | μm/m | μm/m | μm/m | μm/m | °C | |
| WMC | WMC | UD-0-01 | 47,0 | 5,5 | 1193,9 | 45,9 | 46,2 | 46,1 | 0,31 | 0,30 | 0,31 | 28664 | 29059 | 28862 | N.a | N.a | 25,0 | |
| WMC | WMC | UD-0-02 | 46,2 | 5,3 | 1190,9 | 48,0 | 49,2 | 48,6 | 0,24 | 0,31 | 0,28 | 27053 | 26300 | 26677 | N.a | N.a | 24,9 | |
| WMC | WMC | UD-0-03 | 47,2 | 5,7 | 1258,9 | 45,1 | 49,1 | 47,1 | 0,25 | 0,32 | 0,29 | 30969 | 27996 | 29483 | N.a | N.a | 24,7 | |
| WMC | WMC | UD-0-04 | 45,6 | 5,5 | 1193,6 | 45,7 | 42,3 | 44,0 | 0,26 | 0,22 | 0,24 | 28250 | 29654 | 28952 | N.a | N.a | 24,5 | |
| WMC | WMC | UD-0-05 | 42,1 | 5,0 | 1103,6 | 46,7 | 45,9 | 46,3 | 0,26 | 0,28 | 0,27 | 26282 | 27409 | 26846 | N.a | N.a | 24,5 | |
| | | Mean | 45,6 | 5,4 | 1188,2 | 46,3 | 46,5 | 46,4 | 0,27 | 0,29 | 0,28 | 28244 | 28084 | 28164 | - | - | - | |
| | | Std | 1,9 | 0,2 | 49,4 | 1,0 | 2,5 | 1,5 | 0,0 | 0,0 | 0,02 | 1604 | 1188 | 1166 | - | - | - | |
| | | COV | 4,06 | 4,11 | 4,16 | 2,16 | 5,45 | 3,23 | 9,47 | 13,31 | 8,35 | 5,68 | 4,23 | 4,14 | - | - | - | |
| | | | | | | | | | | | | | | | | | | |
| WMC | IWES | UD-0-I-01 | 40,7 | 43195 | 1128,4 | 50,6 | 47,2 | 48,9 | 0,285 | 0,261 | 0,273 | | 29532 | 29532 | N.a | N.a | 21,9 | |
| WMC | IWES | UD-0-I-02 | 46,8 | 22402 | 1263,1 | 48,3 | | 48,3 | 0,215 | | 0,215 | | 29031 | | 29031 | N.a | N.a | 22 |
| WMC | IWES | UD-0-I-03 | 45,5 | 16193 | 1254,1 | 46,6 | 49,6 | 48,1 | 0,281 | 0,294 | 0,2875 | 28546 | 28203 | 28375 | N.a | N.a | 22,2 | |
| WMC | IWES | UD-0-I-04 | 43,8 | 43221 | 1189,8 | 48,6 | 47,9 | 48,25 | 0,306 | 0,231 | 0,2685 | 26843 | | 26843 | N.a | N.a | 22 | |
| WMC | IWES | UD-0-I-05 | 43,8 | 42125 | 1200,4 | 47,9 | 47,6 | 47,75 | 0,302 | 0,264 | 0,283 | 27249 | 27472 | 27361 | N.a | N.a | 22,1 | |
| WMC | IWES | UD-0-I-06 | 44,8 | 11079 | 1217 | 47,8 | 46,1 | 46,95 | 0,319 | 0,29 | 0,3045 | 28022 | 28598 | 28310 | N.a | N.a | 22,1 | |
| WMC | IWES | UD-0-I-07 | 45,4 | 12540 | 1222,6 | 45,1 | 45,7 | 45,4 | 0,327 | 0,287 | 0,307 | 28781 | 28627 | 28704 | N.a | N.a | 22,1 | |
| | | Mean | 44,4 | 27250,7 | 1210,8 | 47,8 | 47,4 | 47,7 | 0,29 | 0,27 | 0,28 | 28078,7 | 28486,4 | 28104 | - | - | - | |
| | | Std | 1,8 | 13909,0 | 41,6 | 1,6 | 1,3 | 1,1 | 0,03 | 0,02 | 0,03 | 799,7 | 668,6 | 699,5 | - | - | - | |
| | | COV | 4,04 | 51,04 | 3,44 | 3,30 | 2,69 | 2,26 | 11,87 | 8,10 | 10,34 | 2,85 | 2,35 | 2,49 | - | - | - | |
| | | | | | | | | | | | | | | | | | | |
| CENER | CENER | 1 | 40,7 | 4,95 | 1130 | 48,7 | 47,4 | 48,05 | 0,23 | 0,24 | 0,23 | 25457 | 20413 | 22935 | N.a | N.a | 21,5 | |
| CENER | CENER | 2 | 40,5 | 4,91 | 1120 | 51,1 | 49,8 | 50,45 | 0,27 | 0,28 | 0,28 | 24290 | 22511 | 23401 | N.a | N.a | 21,5 | |
| CENER | CENER | 3 | 37,8 | 4,68 | 1060 | 52,2 | 48,4 | 50,3 | 0,26 | 0,26 | 0,26 | 23631 | | 23631 | N.a | N.a | 21,5 | |
| CENER | CENER | 4 | 41,4 | 5 | 1150 | 54,5 | - | 54,5 | 0,28 | - | 0,28 | 21971 | | 21971 | N.a | N.a | 21,5 | |
| CENER | CENER | 5 | 41,1 | 4,84 | 1120 | 55,1 | 45,2 | 50,15 | 0,31 | 0,27 | 0,29 | 21792 | 24717 | 23255 | N.a | N.a | 21,5 | |
| | | Mean | 40,30 | 4,88 | 1116,00 | 52,32 | 47,70 | 50,69 | 0,27 | 0,26 | 0,27 | 23428 | 22547 | 23038 | - | - | - | |
| | | Std | 1,29 | 0,11 | 30,07 | 2,33 | 1,68 | 2,10 | 0,03 | 0,02 | 0,02 | 1393 | 1757 | 579 | - | - | - | |
| | | COV | 3,20 | 2,28 | 2,69 | 4,45 | 3,51 | 4,14 | 9,44 | 6,68 | 7,65 | 5,95 | 7,79 | 2,52 | - | - | - | |
| | | | | | | | | | | | | | | | | | | |
| CENER | IWES | 1 | 44,3 | 4,84 | 1220 | 45,6 | 47,2 | 46,4 | 0,29 | 0,29 | 0,29 | 27428 | 27461 | 27445 | 28256 | 28601 | 21,5 | |
| CENER | IWES | 2 | 44,4 | 4,92 | 1170 | - | 45,6 | 45,6 | - | 0,26 | 0,26 | - | 28144 | 28144 | - | 30863 | 21,5 | |
| CENER | IWES | 3 | 39,9 | 4,55 | 1080 | 44,7 | - | 44,7 | 0,26 | - | 0,26 | 26450 | 27869 | 27160 | 27449 | 29120 | 21,5 | |
| CENER | IWES | 4 | 41,2 | 4,46 | 1160 | 47,4 | 47,3 | 47,35 | 0,21 | 0,27 | 0,24 | 27083 | 26017 | 26550 | 27366 | 26261 | 21,5 | |
| CENER | IWES | 5 | 44,6 | 4,91 | 1260 | 47,8 | 46,4 | 47,1 | 0,26 | 0,27 | 0,26 | 29226 | 27600 | 28413 | - | 28563 | 21,5 | |
| CENER | IWES | 6 | 40,8 | 4,4 | 1160 | 47,6 | 47,8 | 47,7 | 0,24 | 0,32 | 0,28 | 29226 | 27600 | 28413 | 26329 | 25934 | 21,5 | |
| | | Mean | 42,53 | 4,68 | 1175,00 | 46,62 | 46,86 | 46,48 | 0,25 | 0,28 | 0,26 | 27883 | 27449 | 27687 | 27350 | 28224 | - | |
| | | Std | 1,94 | 0,22 | 55,90 | 1,24 | 0,77 | 1,05 | 0,02 | 0,02 | 0,02 | 1141 | 678 | 751 | 684 | 1689 | - | |
| | | COV | 4,56 | 4,61 | 4,76 | 2,66 | 1,65 | 2,25 | 9,79 | 8,34 | 6,08 | 4,09 | 2,47 | 2,71 | 2,50 | 5,99 | - | |
| | | | | | | | | | | | | | | | | | | |
| IWES | IWES | 1 | 41,932 | 7,142 | 1134 | 44,8 | 49,38 | 47,08 | 0,24 | 0,27 | 0,25 | 26215 | 24778 | 25497 | 28021 | 28641 | 21,76 | |
| IWES | IWES | 2 | 45,563 | | 1194 | 47,3 | 44,26 | 45,80 | 0,28 | 0,28 | 0,28 | 28117 | 28945 | 28531 | 30496 | 31359 | 21,71 | |
| IWES | IWES | 3 | 43,559 | 8,688 | 1187 | 47,4 | 46,03 | 46,71 | 0,30 | 0,23 | 0,26 | 28420 | 29188 | 28804 | 31348 | 31999 | 21,65 | |
| IWES | IWES | 4 | 48,047 | 8,269 | 1292 | 47,4 | 46,52 | 46,98 | 0,29 | 0,21 | 0,25 | 29382 | 30159 | 29771 | 30783 | 31757 | 21,62 | |
| IWES | IWES | 5 | 46,344 | 8,086 | 1251 | 46,1 | 48,60 | 47,36 | 0,19 | 0,34 | 0,26 | - | 29600 | 29600 | - | 31565 | 21,6 | |
| | | Mean | 45,09 | 8,05 | 1211,72 | 46,61 | 46,96 | 46,78 | 0,26 | 0,26 | 0,26 | 28034 | 28534 | 28440 | 30162 | 31064 | - | |
| | | Std | 2,14 | 0,57 | 54,84 | 1,04 | 1,84 | 0,54 | 0,04 | 0,05 | 0,01 | 1149,10 | 1922,56 | 1544,07 | 1273,55 | 1229,91 | - | |
| | | COV | 4,74 | 7,03 | 4,53 | 2,23 | 3,91 | 1,15 | 16,16 | 17,45 | 4,18 | 4,10 | 6,74 | 5,43 | 4,22 | 3,96 | - | |

Table 40 Benchmark experimental results


Figure 99 E_1 modulus side1

Figure 100 E_1 modulus side2


Figure 101 Poisson ratio $v_{12\text{ side}1}$

Figure 102 Poisson ratio $v_{12\text{ side}2}$

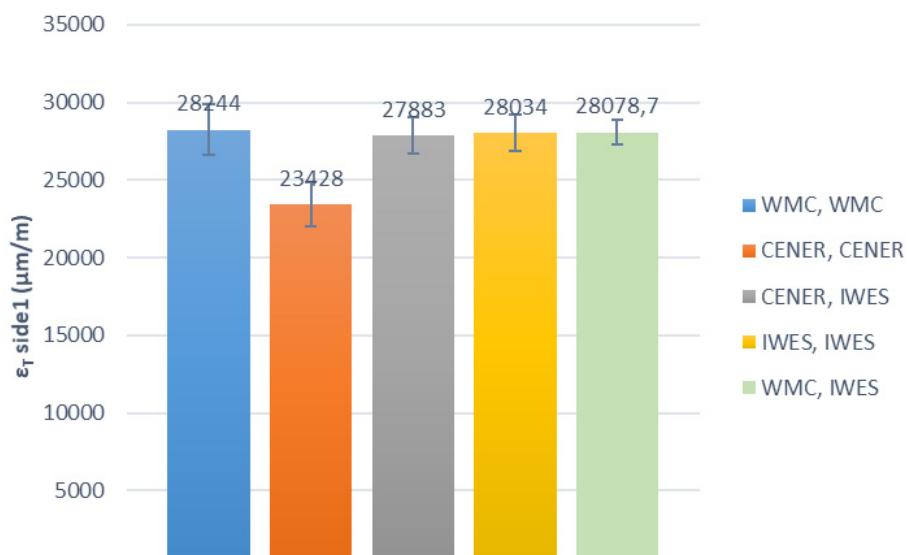


Figure 103 Strain at maximum stress side 1

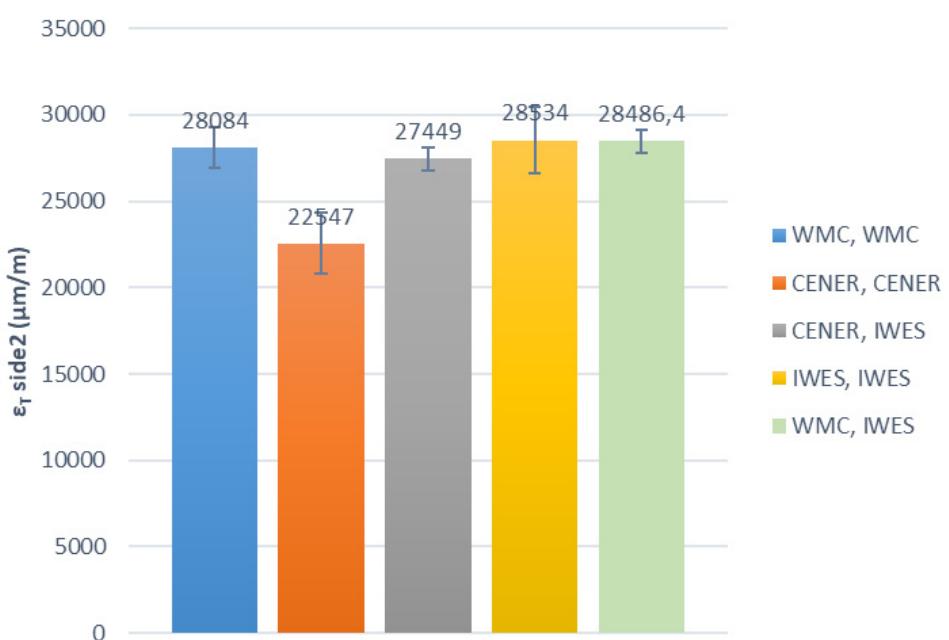


Figure 104 Strain at maximum stress side 2

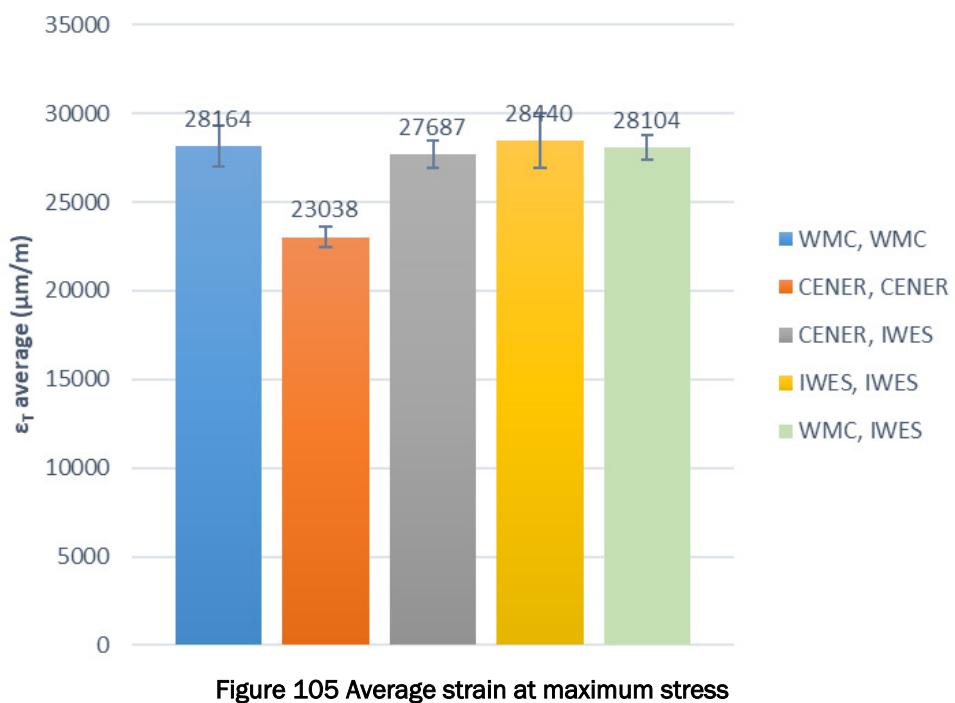


Figure 105 Average strain at maximum stress

8.3 WMC tests

8.3.1 UD-45-STT tension test



Figure 106: UD-45-16 to UD-45-20 front

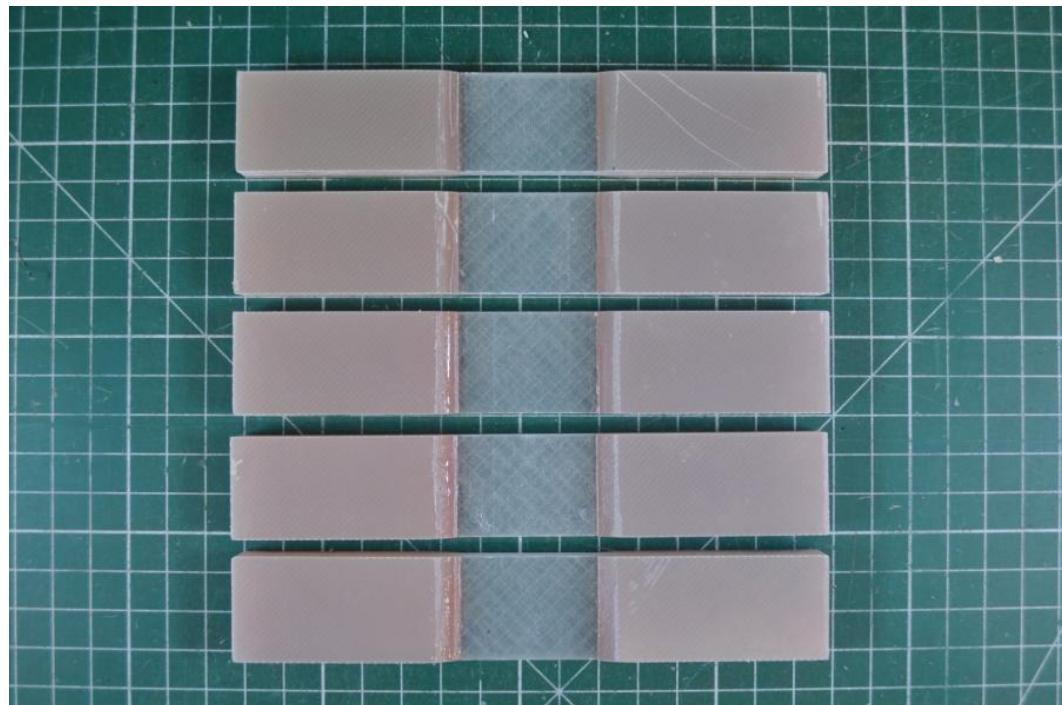


Figure 107: UD-45-16 to UD-45-20 back

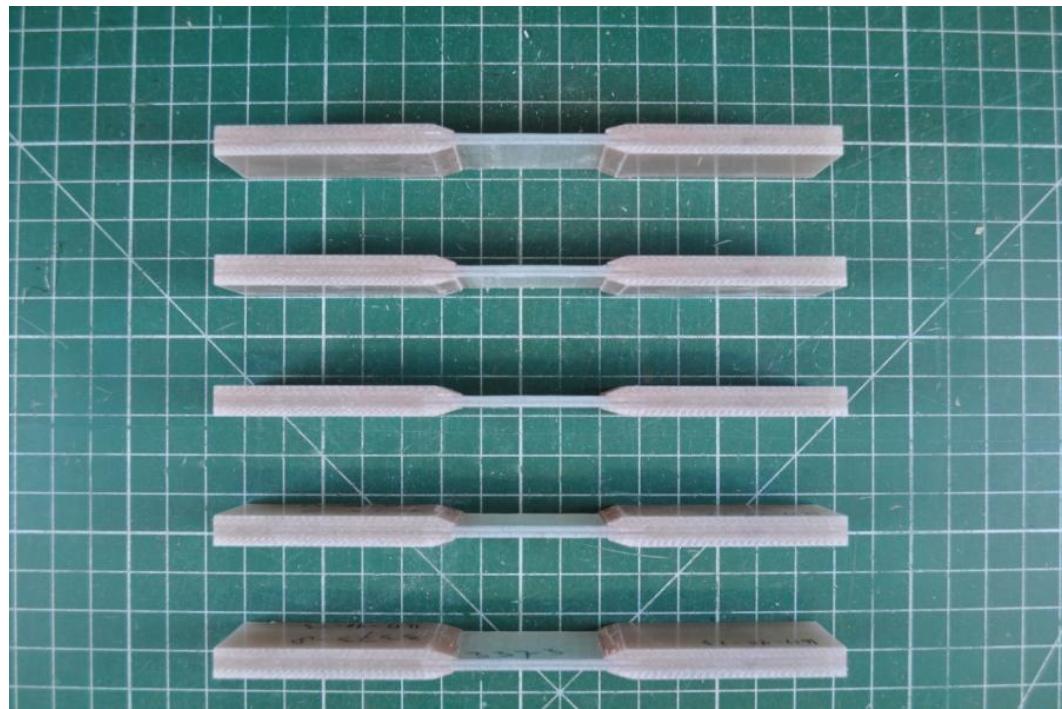


Figure 108: UD-45-16 to UD-45-20 side1

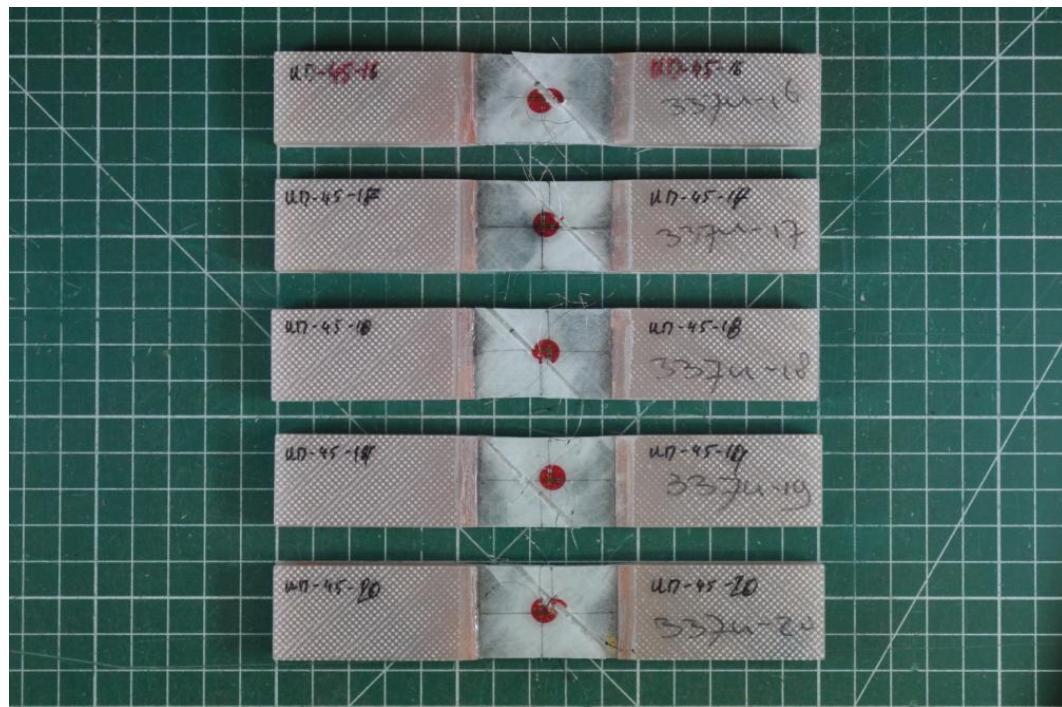


Figure 109: UD-45-16 to UD-45-20 front, after

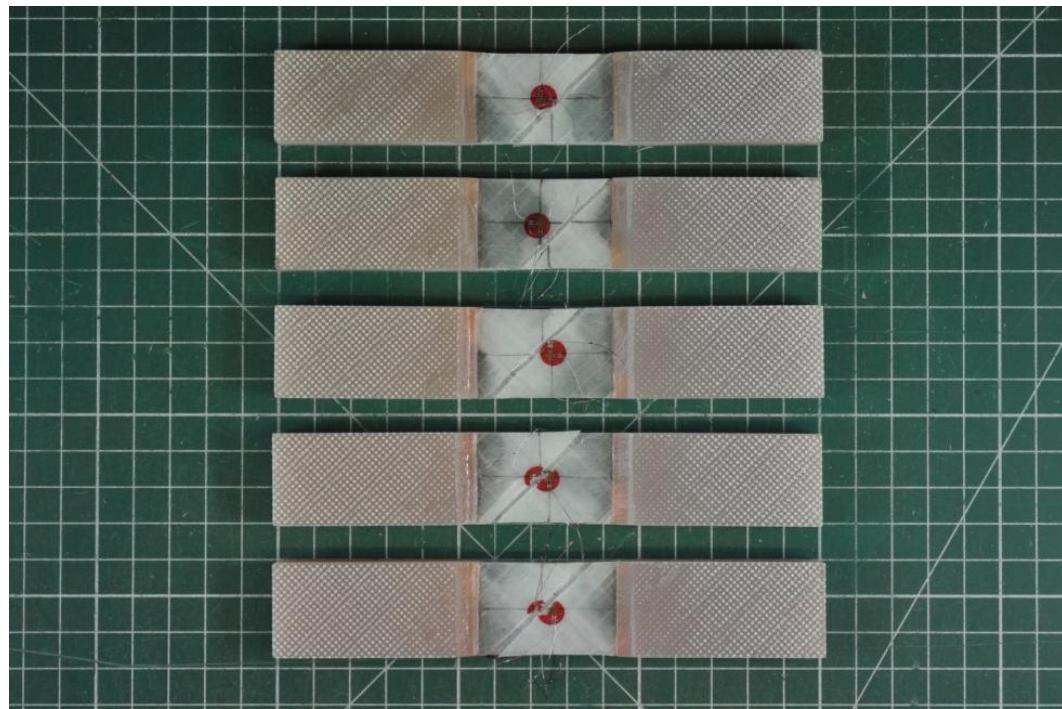


Figure 110: UD-45-16 to UD-45-20 back, after

8.3.2 UD ± 45 layup test CA R=0.1

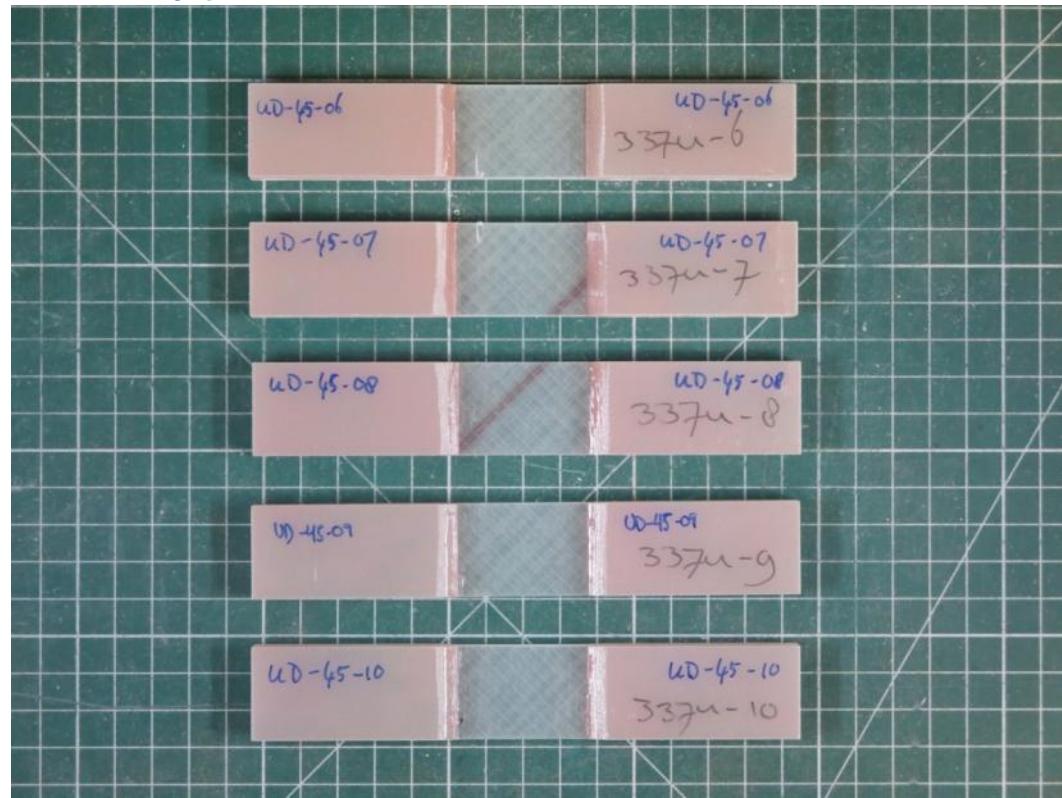


Figure 111: UD-45-06 to UD-45-10 front

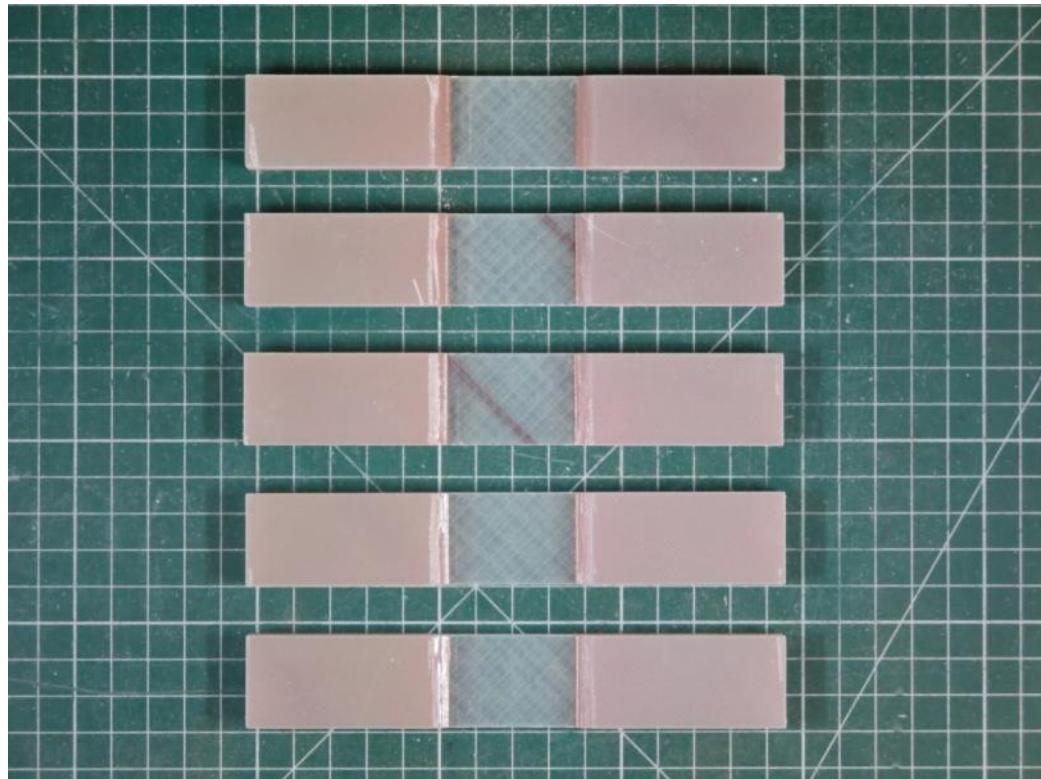


Figure 112: UD-45-06 to UD-45-10 back

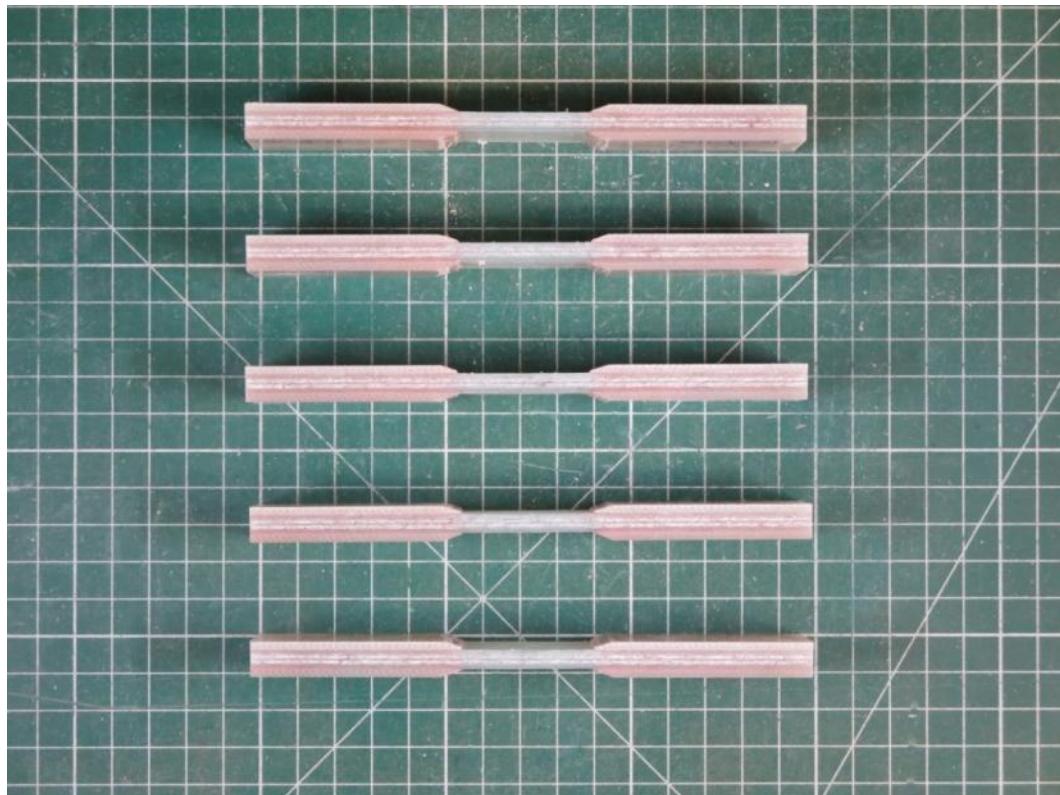


Figure 113: UD-45-06 to UD-45-10 side1

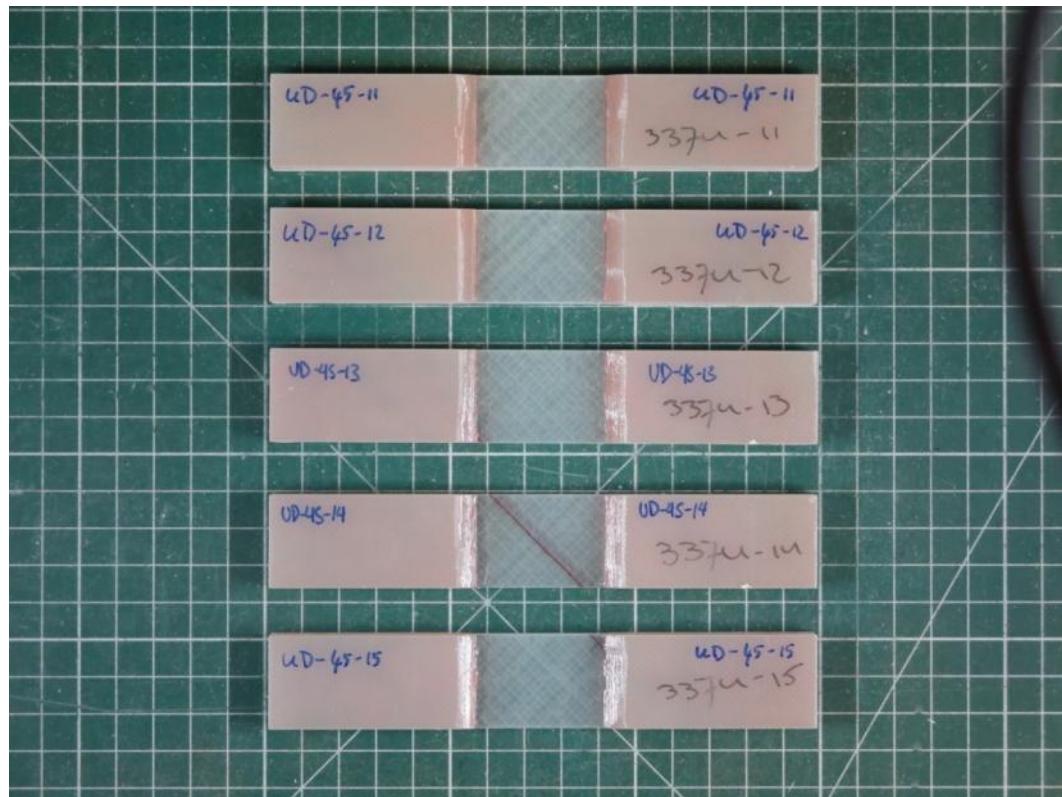


Figure 114: UD-45-11 to UD-45-15 front

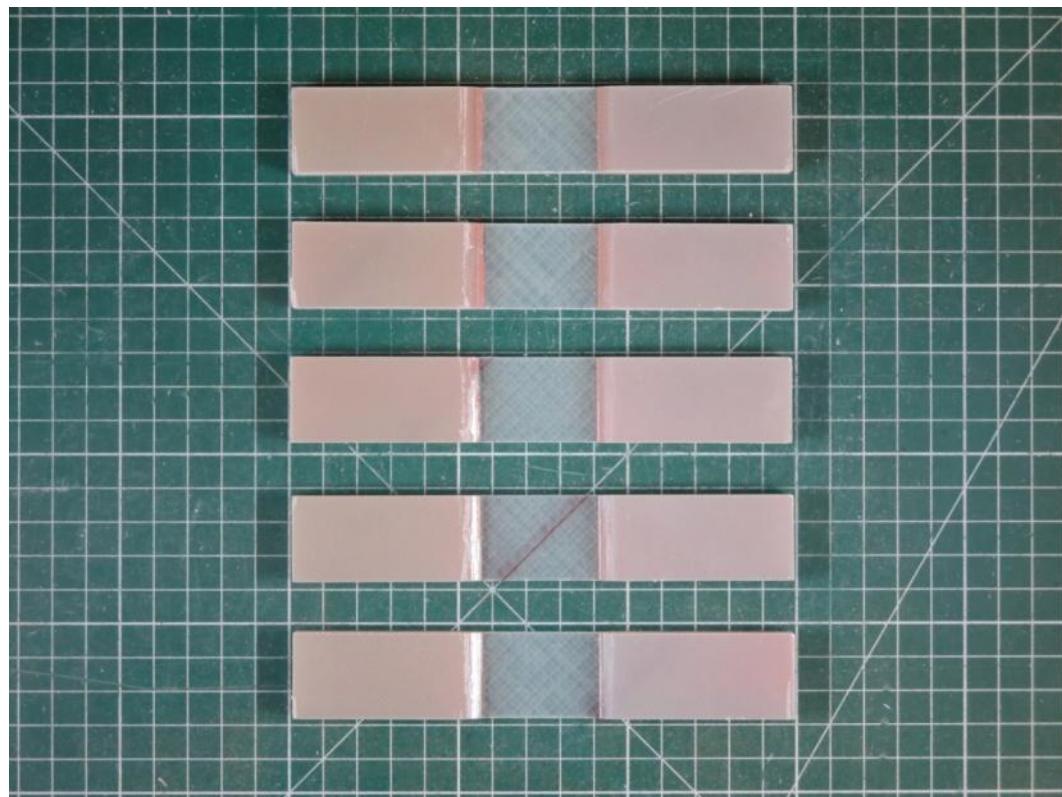


Figure 115: UD-45-11 to UD-45-15 back

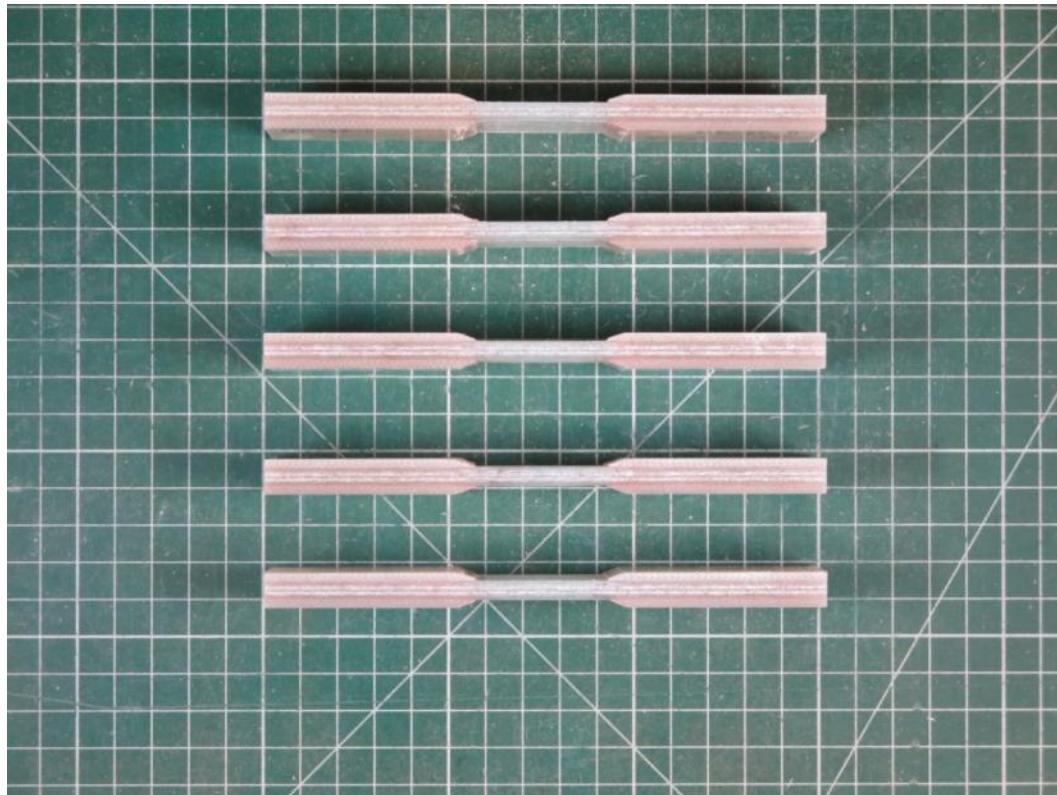


Figure 116: UD-45-11 to UD-45-15 side1

8.3.3 UD-90-STT tension test

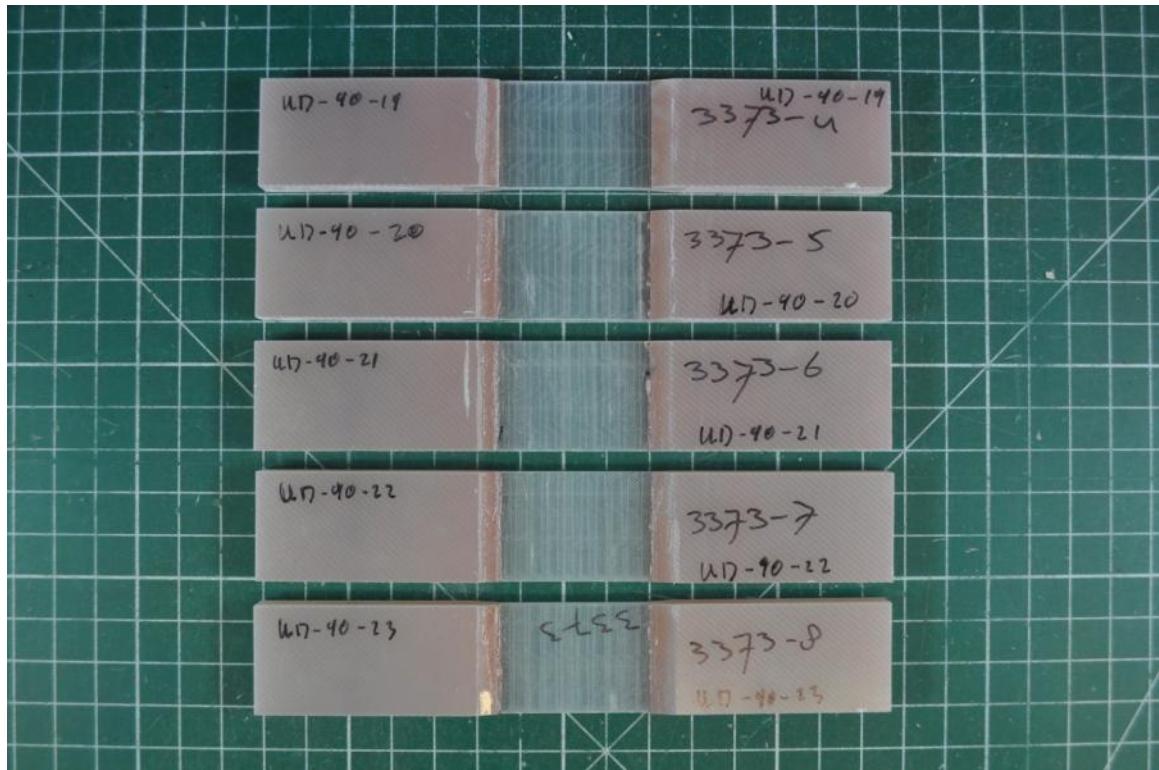


Figure 117: UD-90-19 to UD-90-23 front

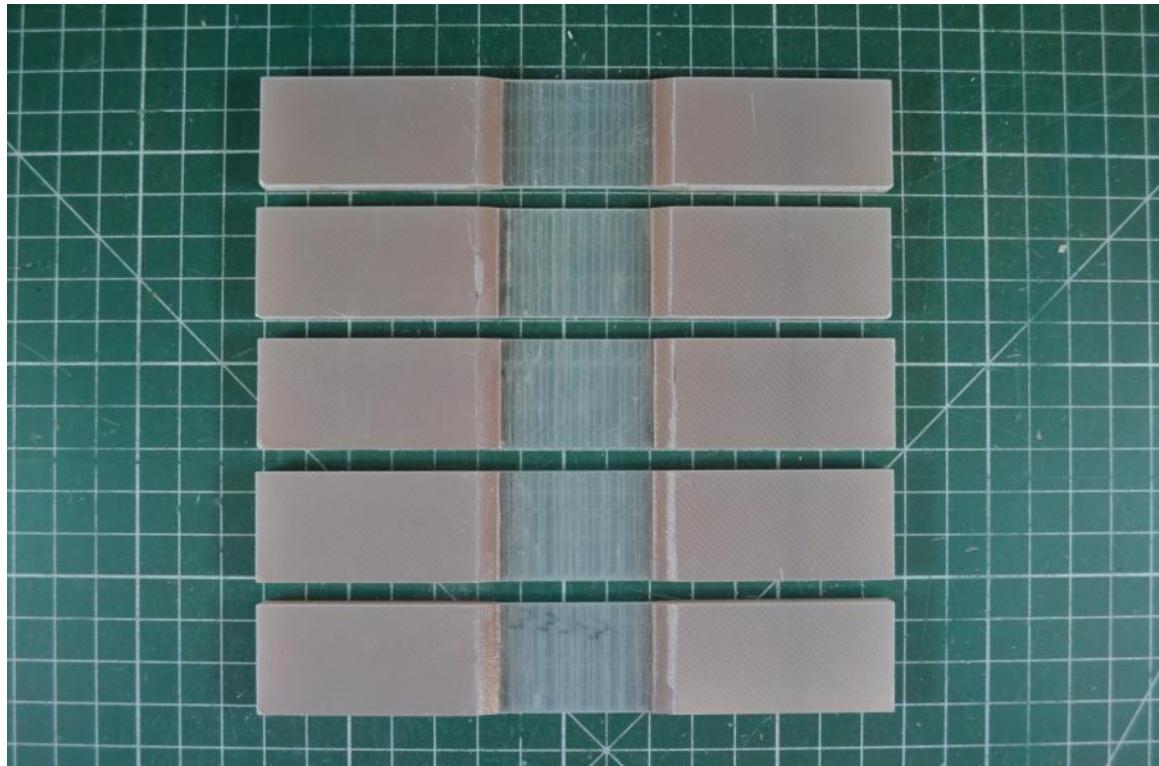


Figure 118: UD-90-19 to UD-90-23 back



Figure 119: UD-90-19 to UD-90-23 side1

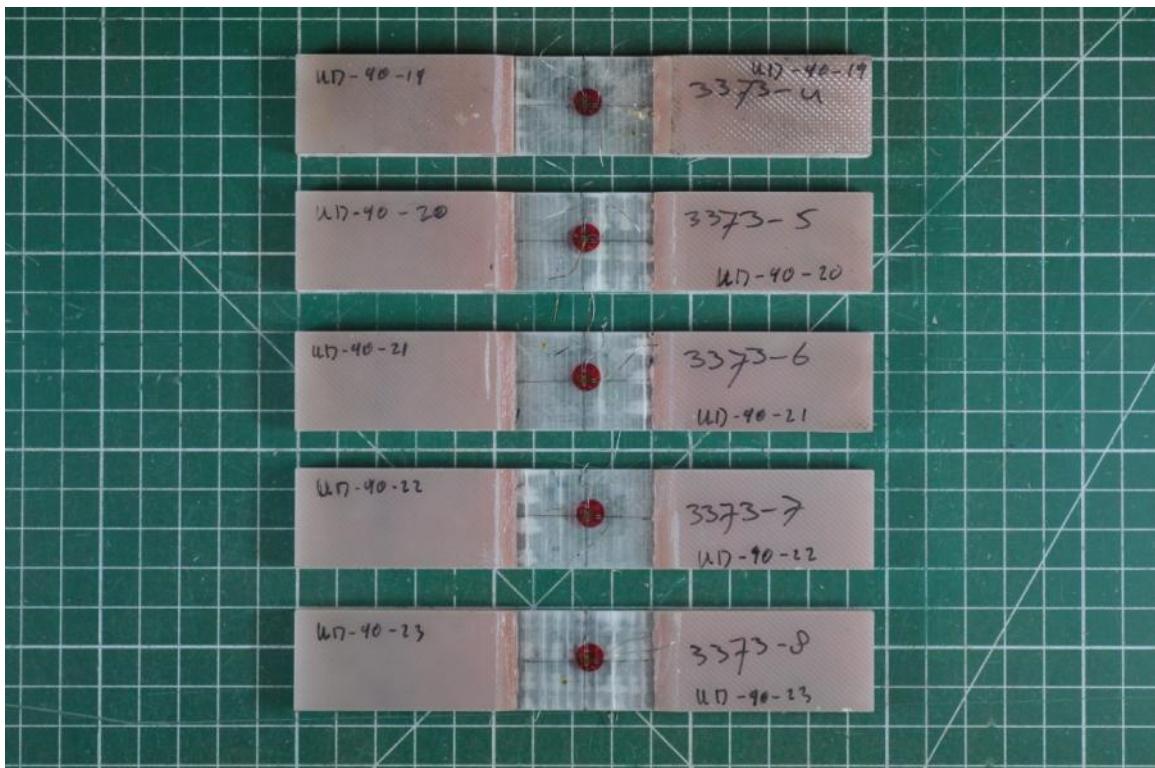


Figure 120: UD-90-19 to UD-90-23 front, after

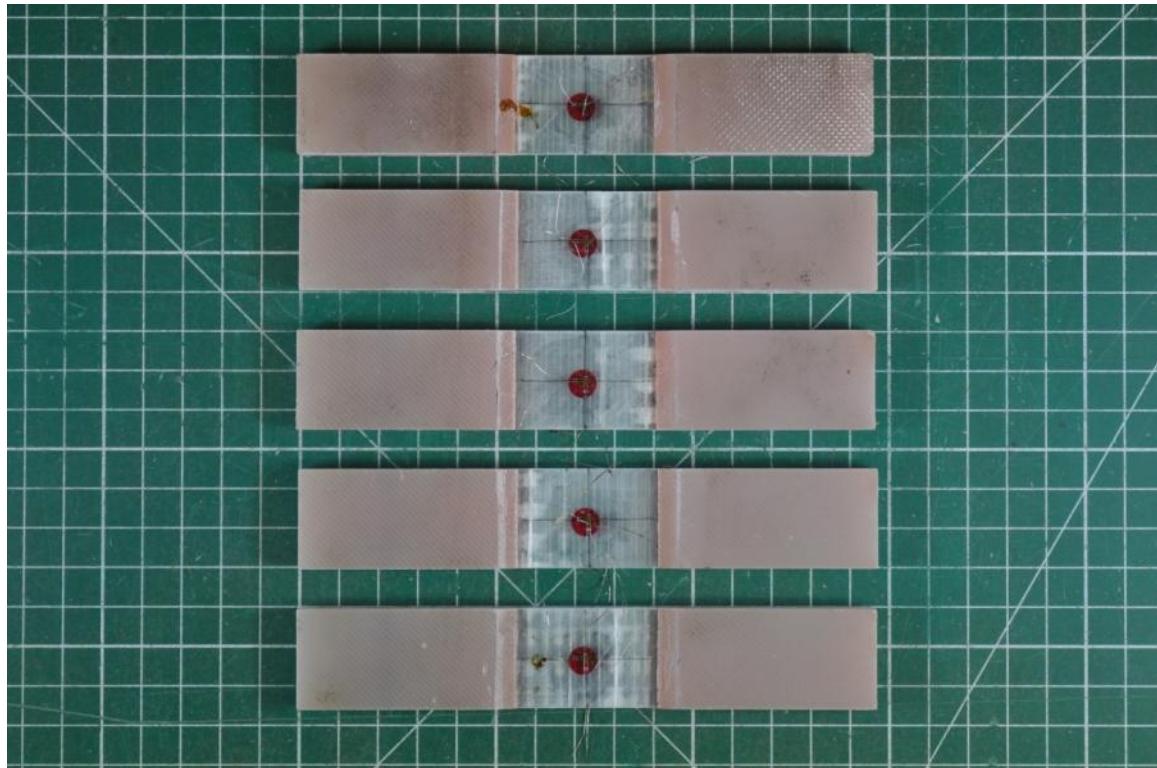


Figure 121: UD-90-19 to UD-90-23 back, after

8.3.4 UD 90 layup test CA R=0.1

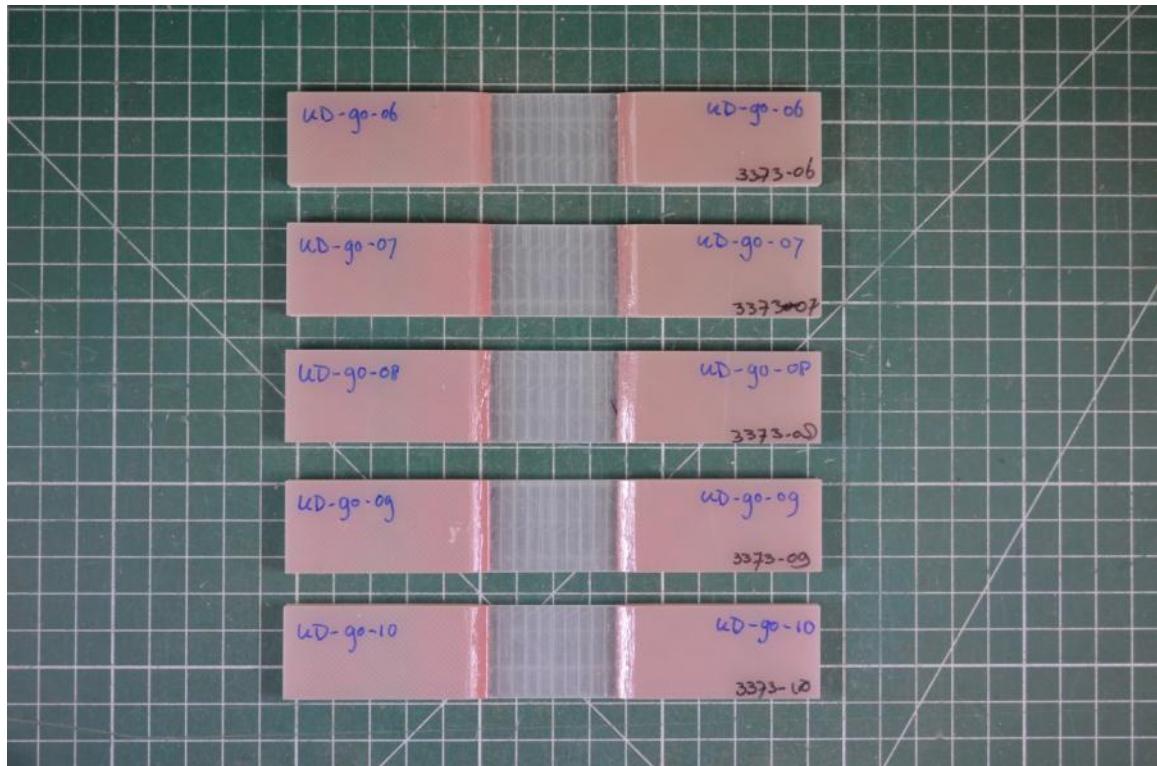


Figure 122: UD-90-06 to UD-90-10 front

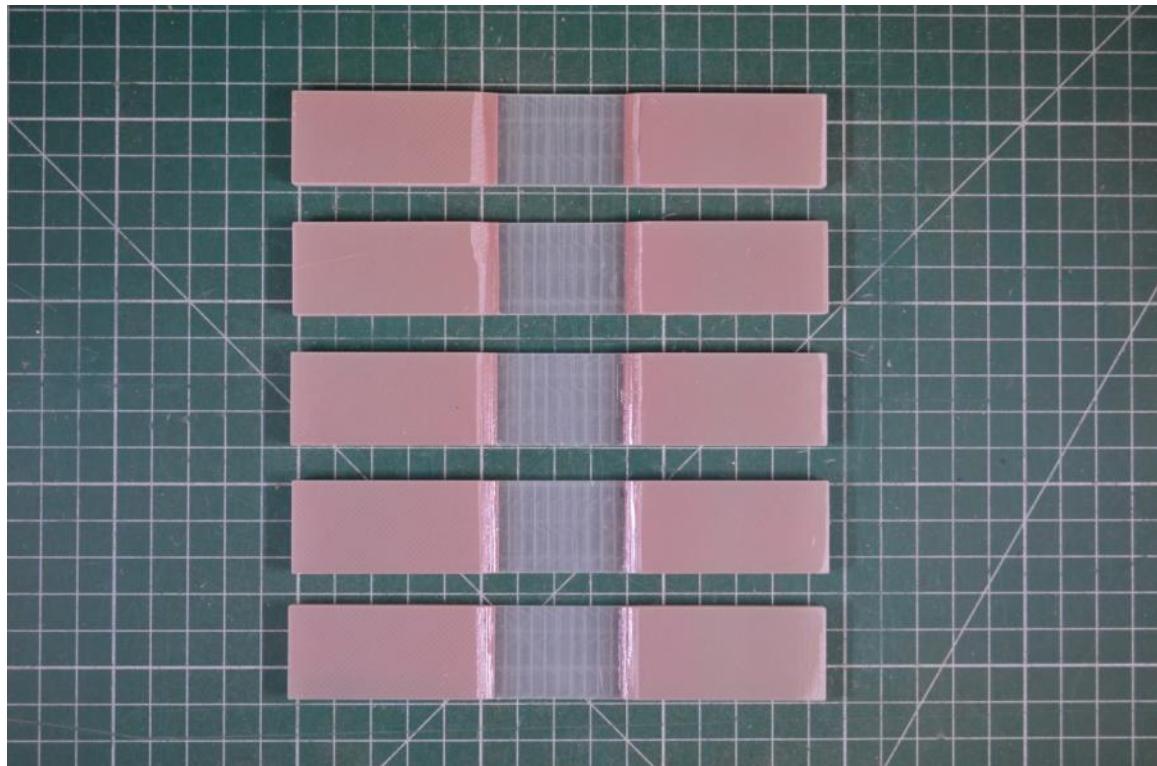


Figure 123: UD-90-06 to UD-90-10 back

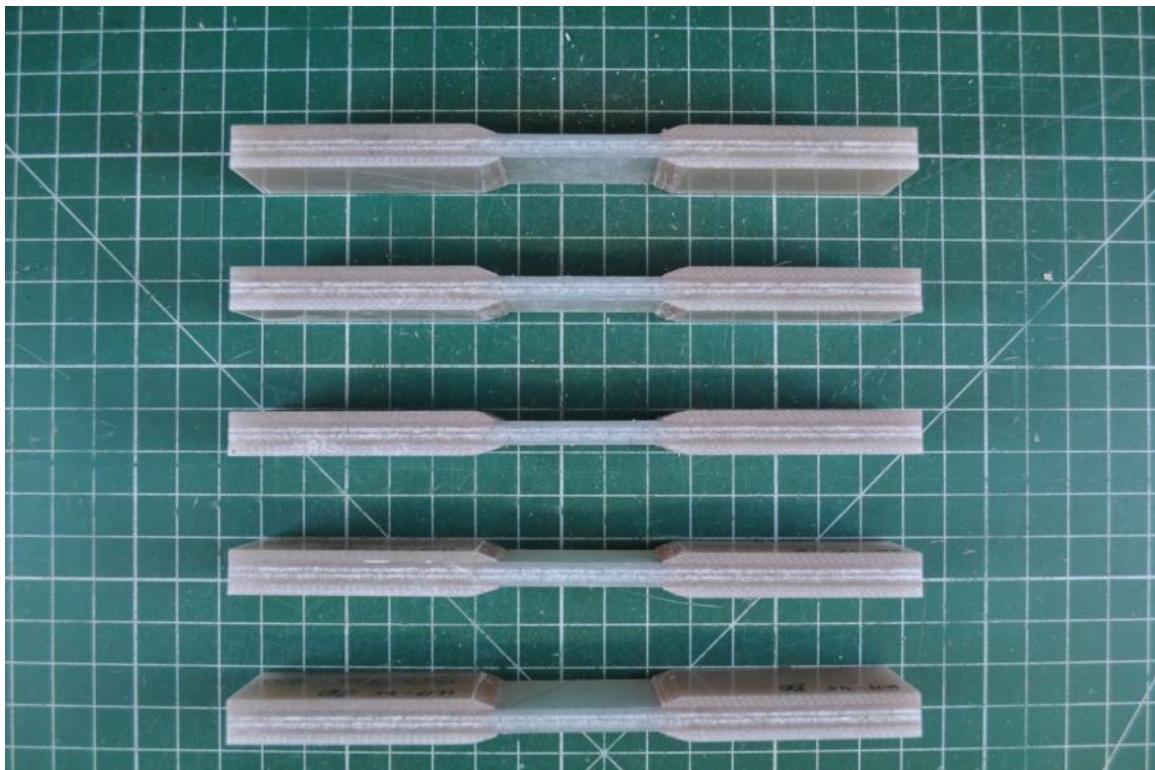


Figure 124: UD-45-06 to UD-45-10 side1

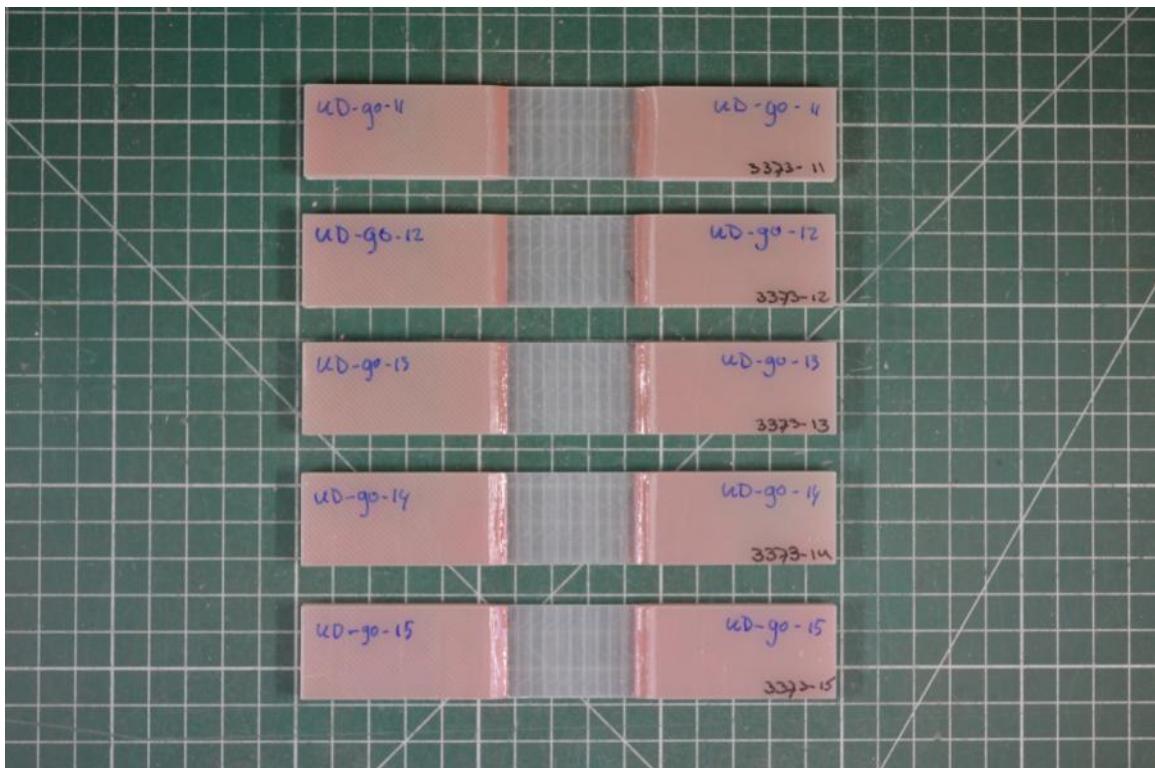


Figure 125: UD-90-11 to UD-90-15 front

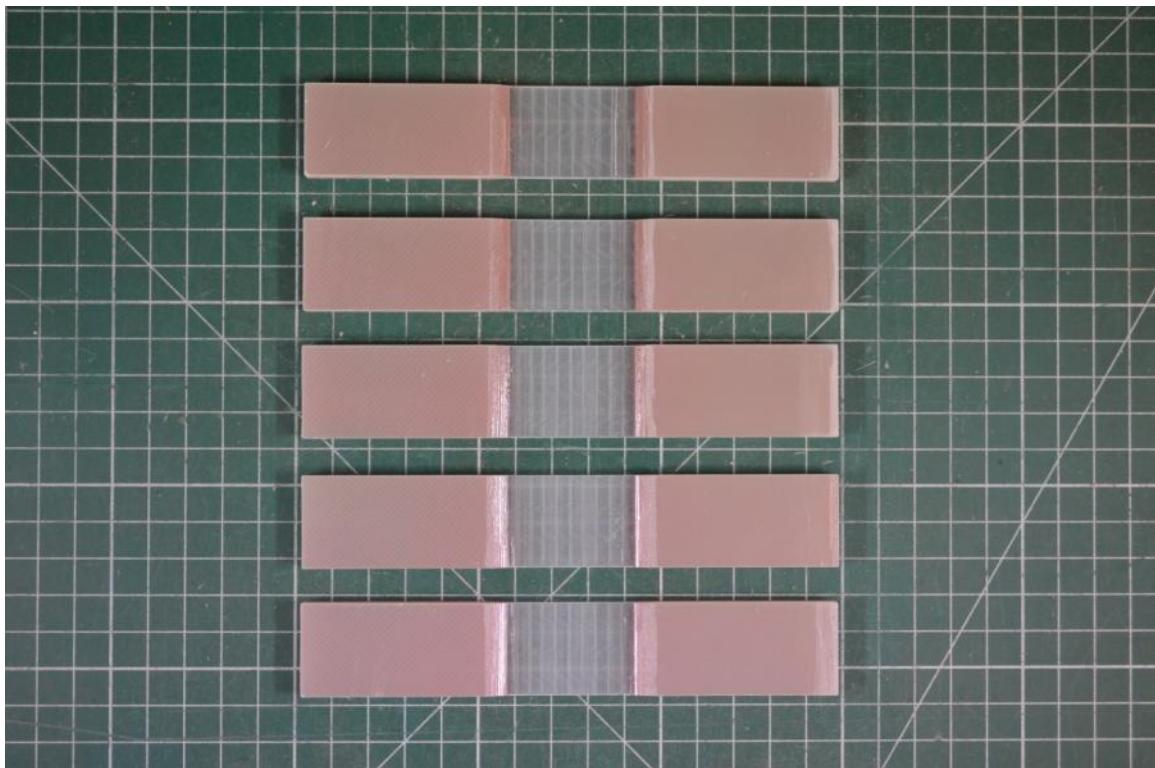


Figure 126: UD-45-11 to UD-45-15 back



Figure 127: UD-45-11 to UD-45-15 side1

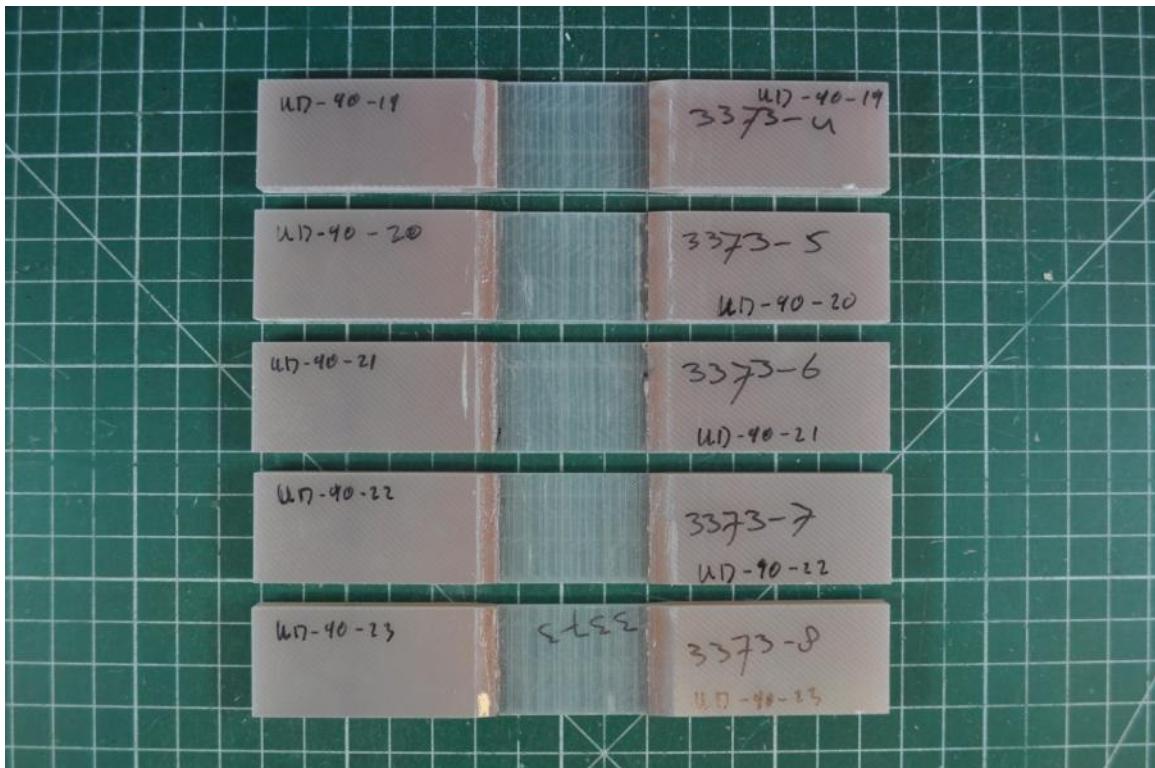


Figure 128: UD-90-19 to UD-90-23 front

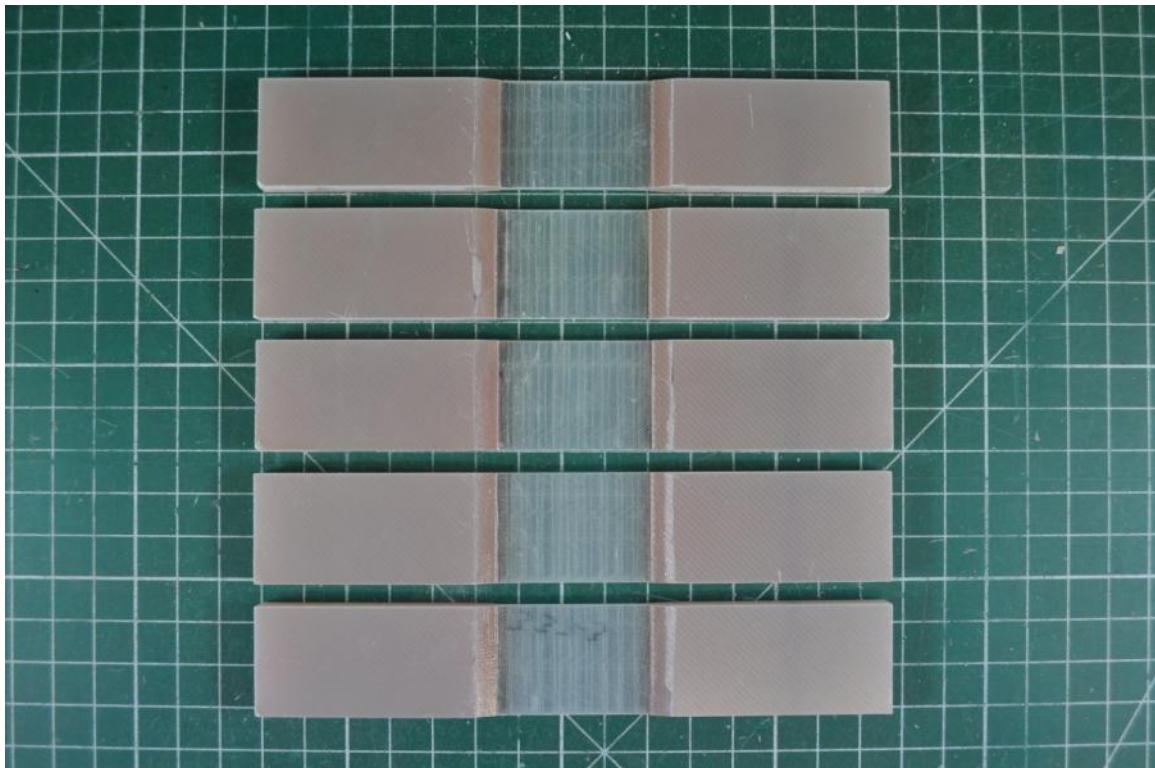


Figure 129: UD-90-19 to UD-90-23 back



Figure 130: UD-90-19 to UD-90-23 side1



Figure 131: UD-90-06 to UD-90-10 front, after

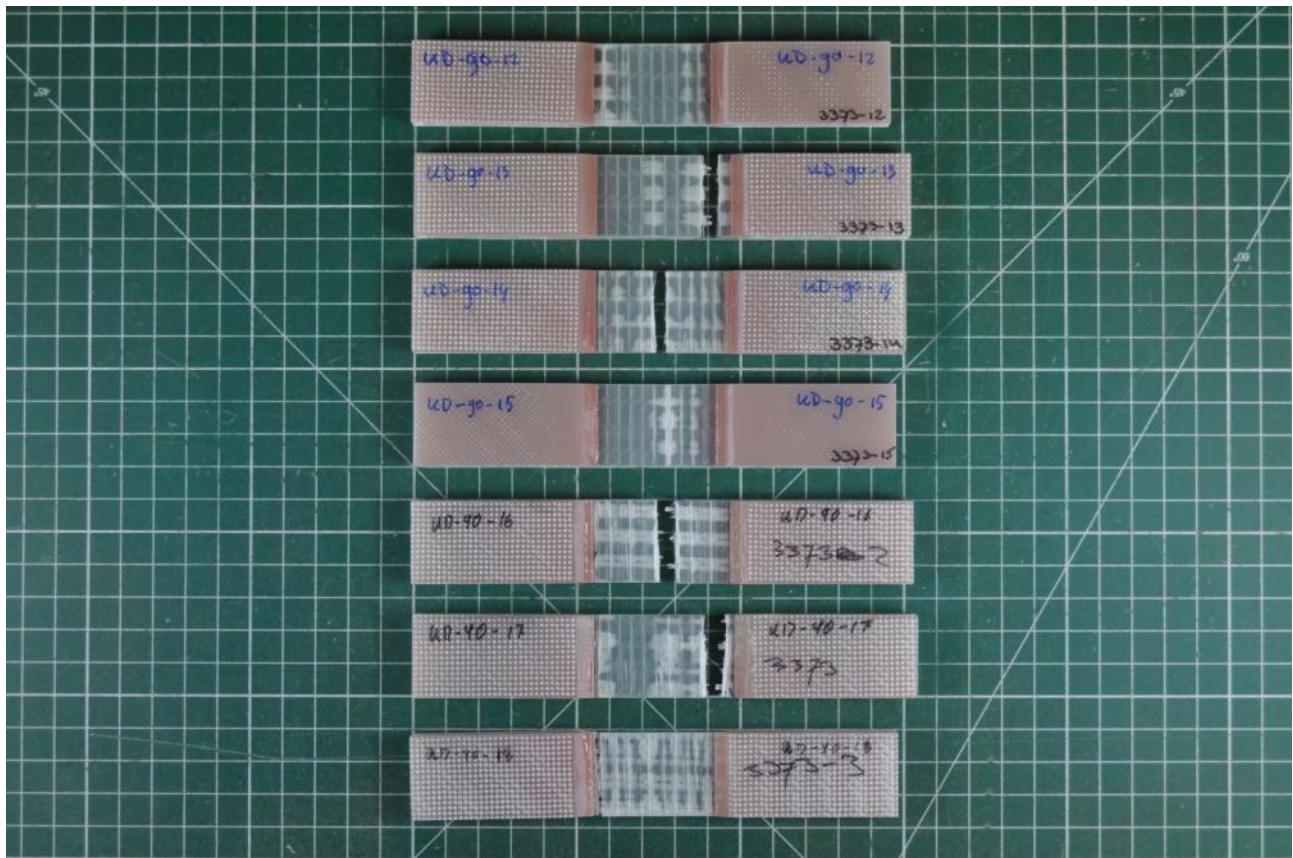


Figure 132: UD-90-12 to UD-90-18 front, after

8.3.5 MU-045-STT tension test

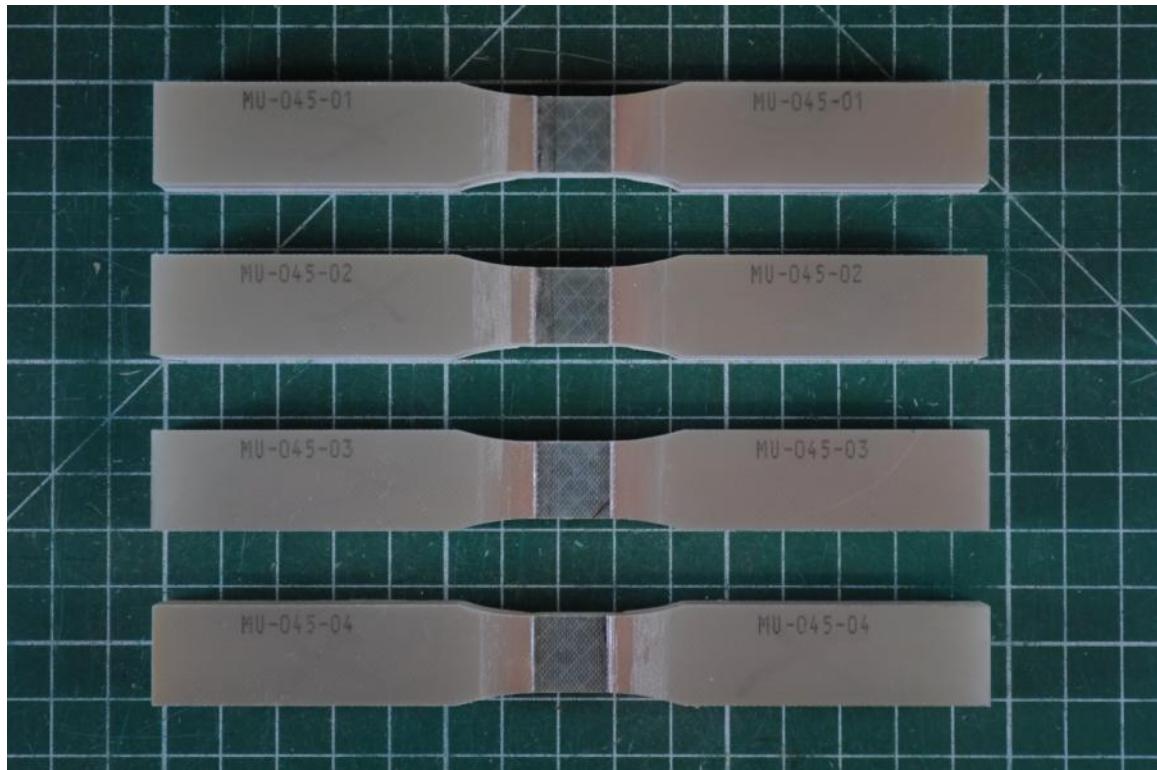


Figure 133: MU-045-01 to MU-045-04 front

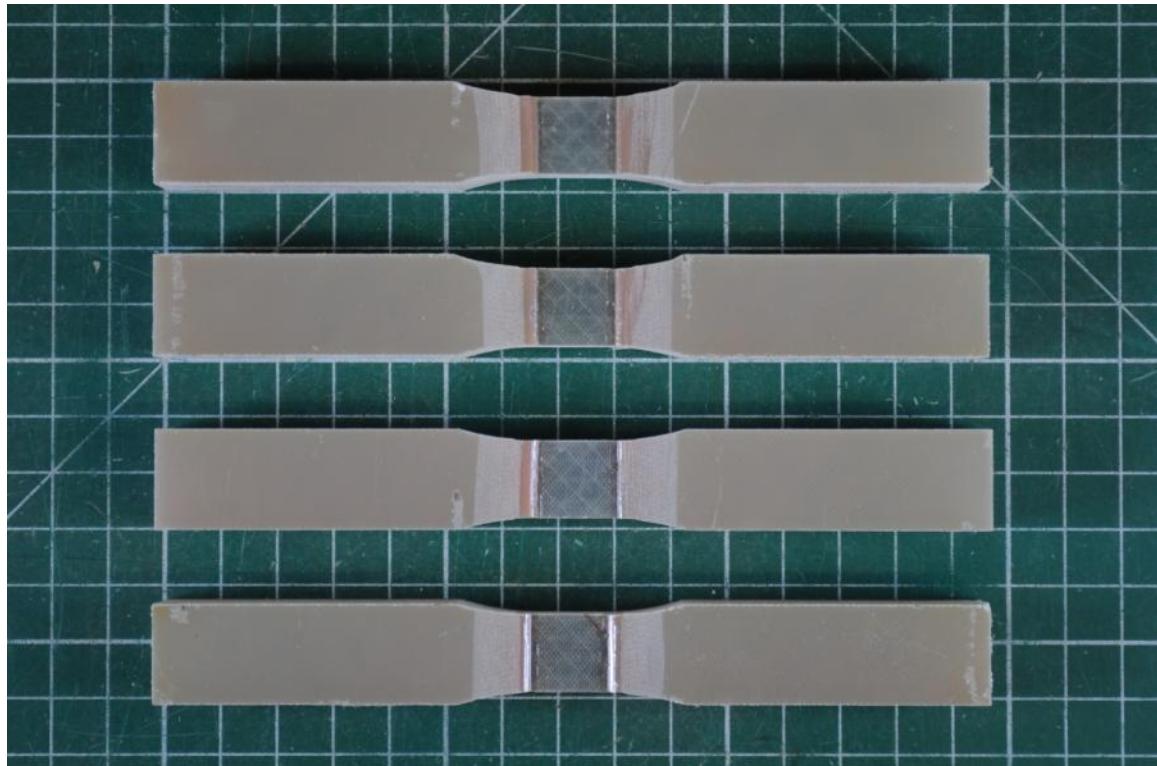


Figure 134: MU-045-01 to MU-045-04 back

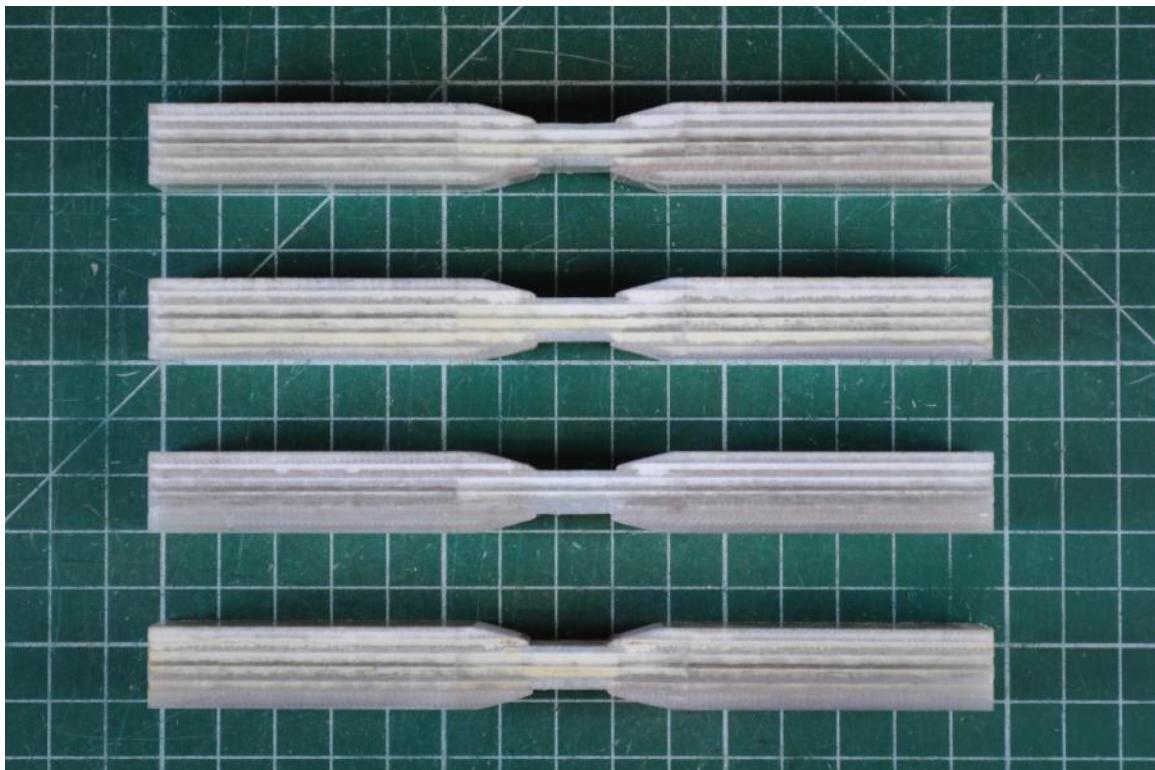


Figure 135: MU-045-01 to MU-045-04 side1

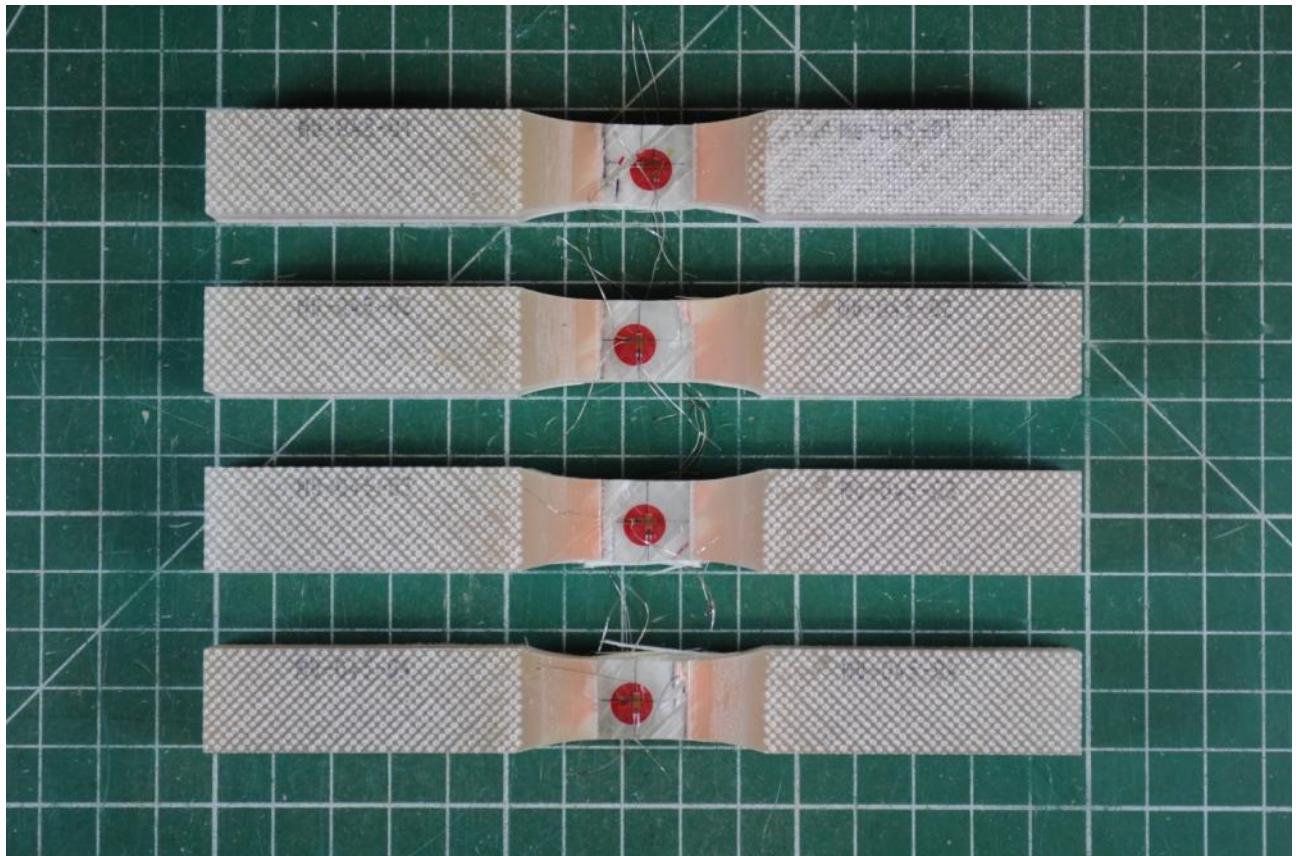


Figure 136: MU-045-01 to MU-045-04 front, after

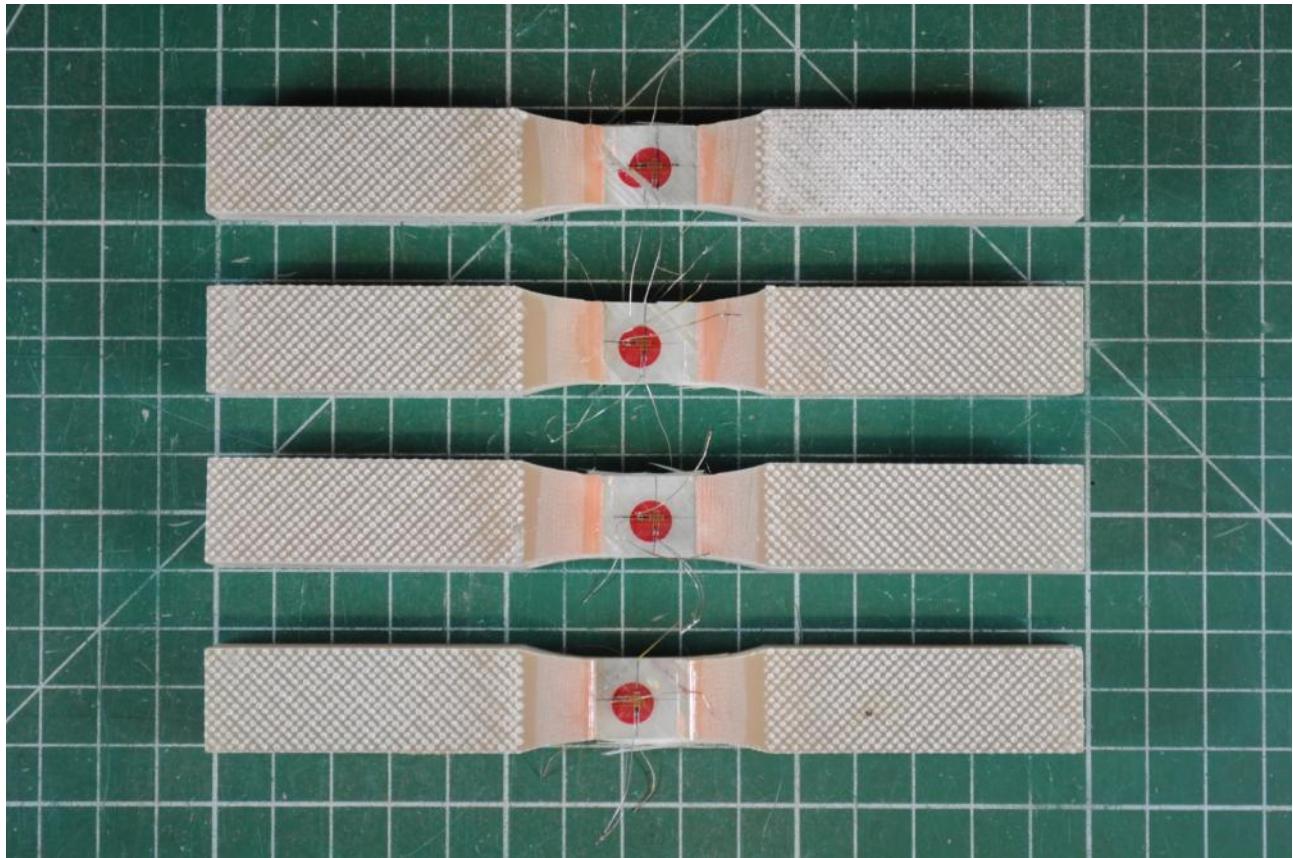


Figure 137: MU-045-01 to MU-045-04 back, after

8.3.6 UD Multiaxial layup test CA R=-1



Figure 138: MU-45-05 to MU-45-08 front

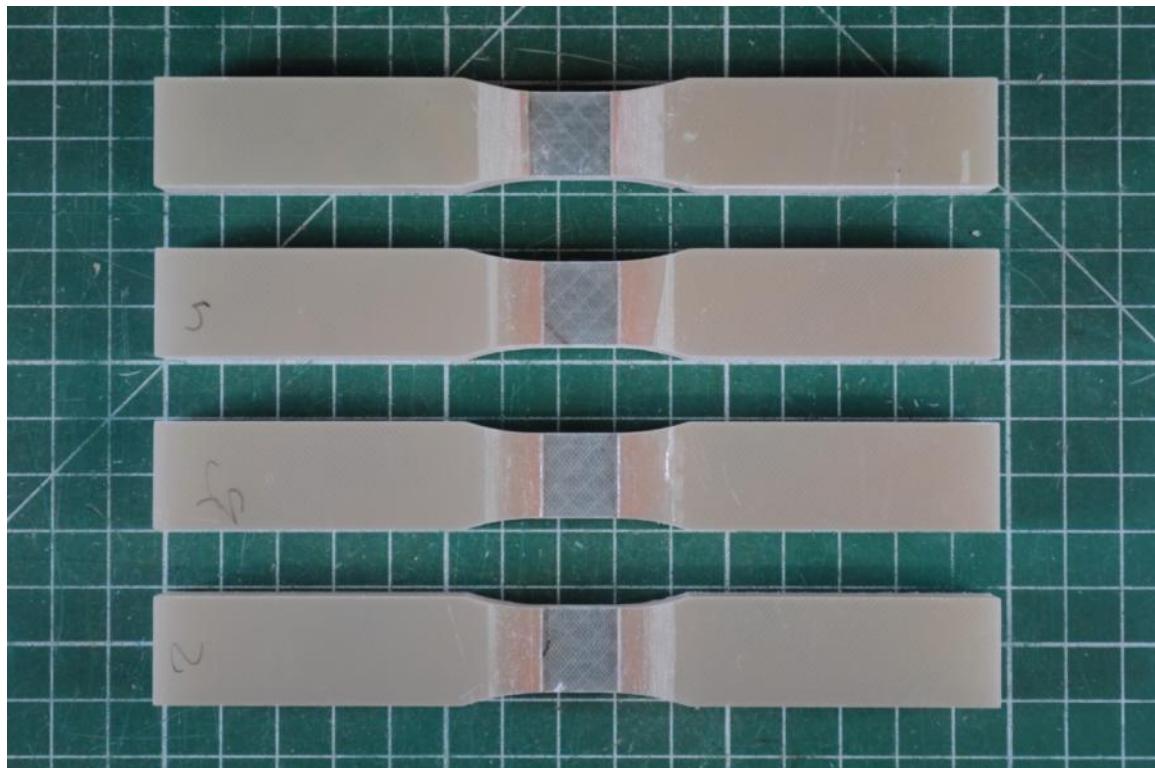


Figure 139: MU-45-05 to MU-45-08 front

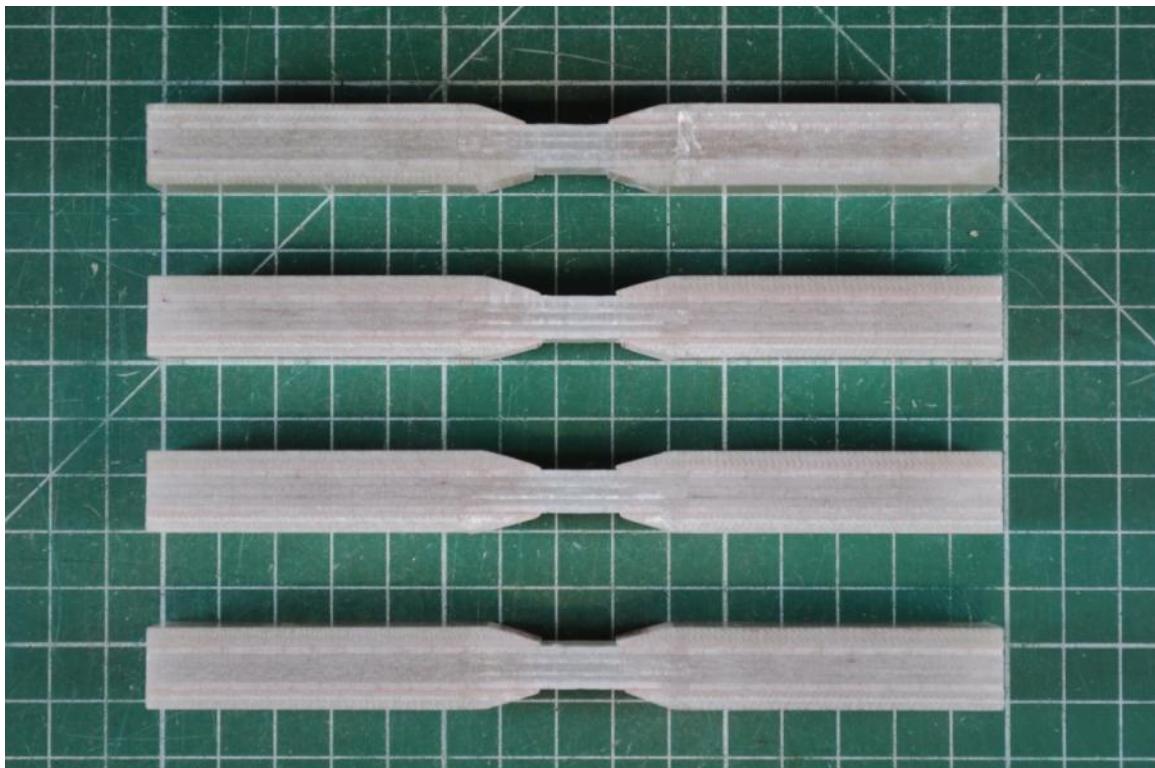


Figure 140: MU-45-05 to MU-45-08 side1



Figure 141: MU-45-09 to MU-45-10 front



Figure 142: MU-45-09 to MU-45-10 back

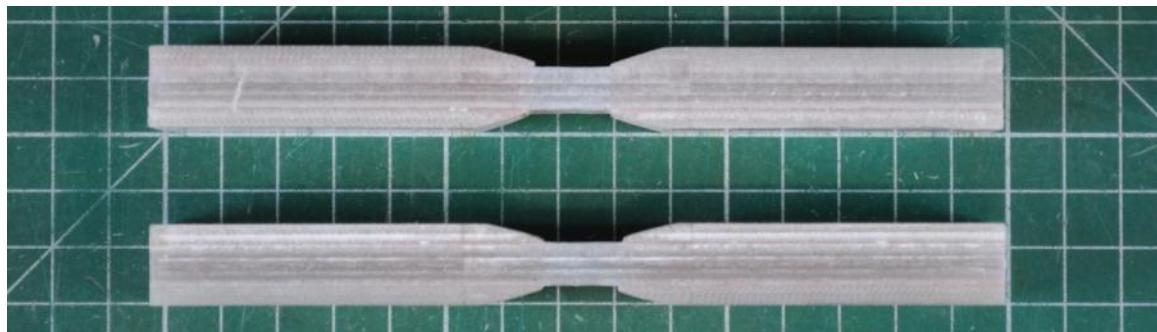


Figure 143: MU-45-09 to MU-45-10 side 1

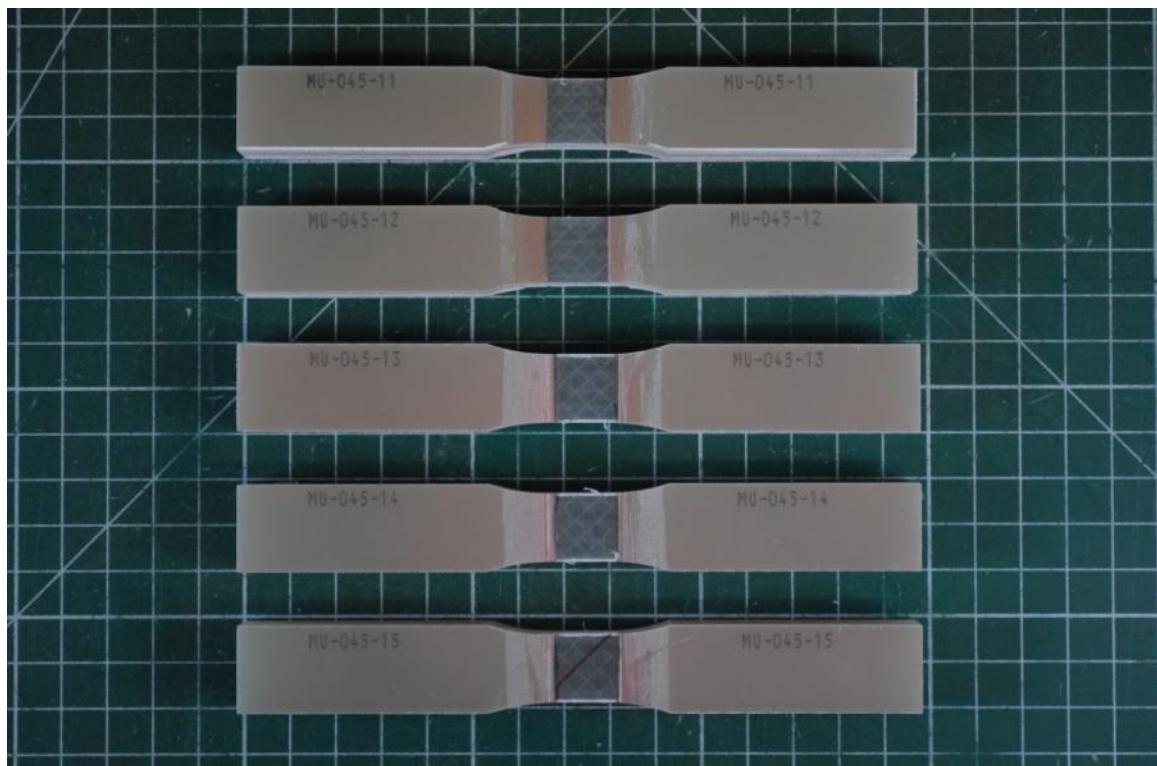


Figure 144: MU-45-11 to MU-45-15 front

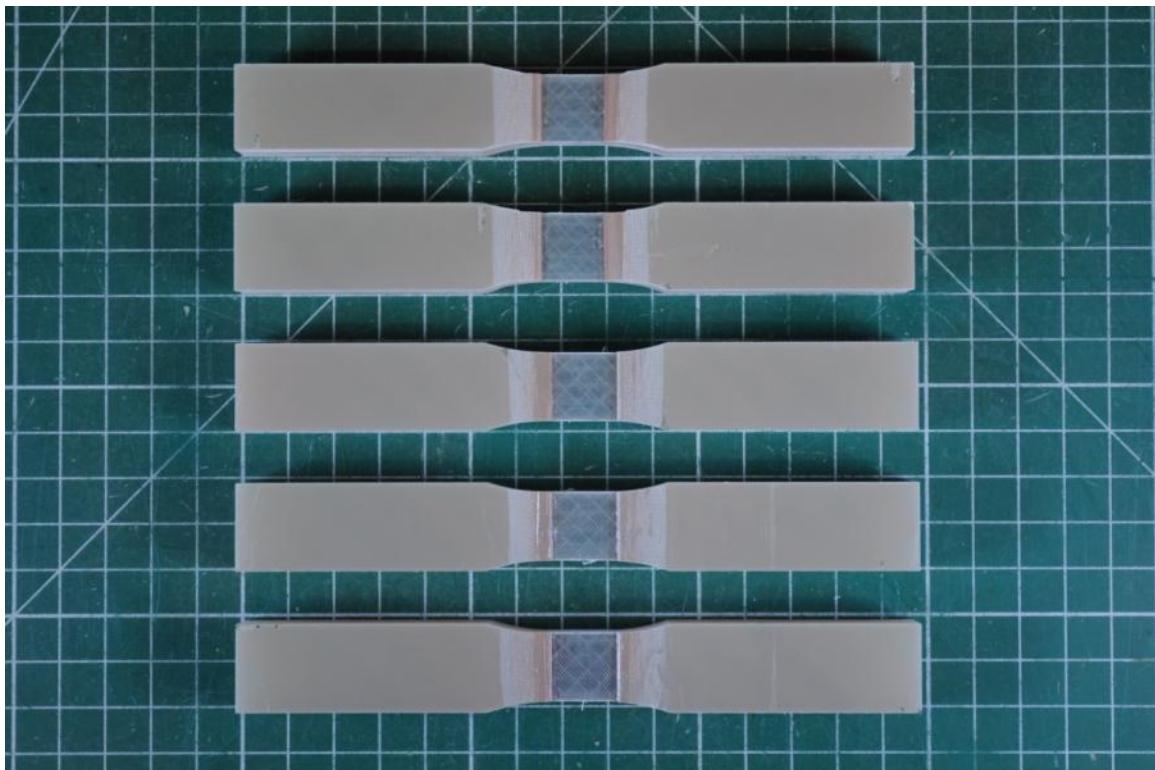


Figure 145: MU-45-11 to MU-45-15 back

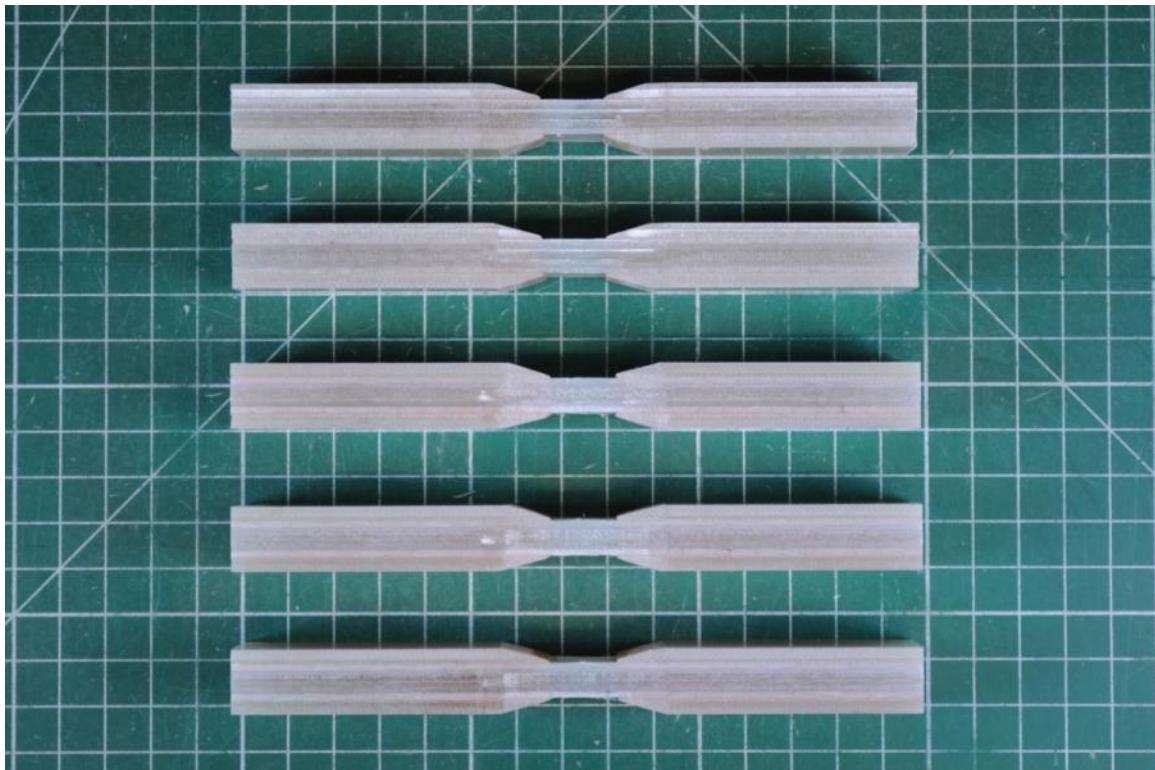


Figure 146: MU-45-11 to MU-45-15 side 1



Figure 147: MU-45-16 to MU-45-20 front

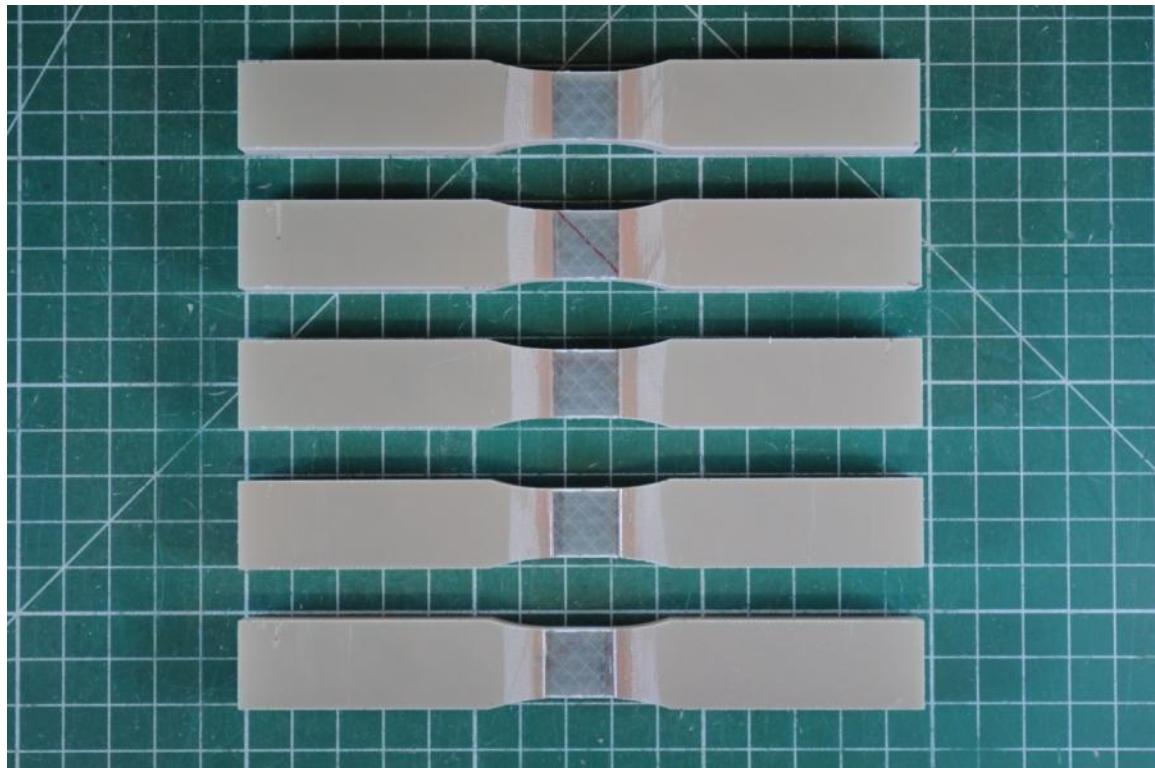


Figure 148: MU-45-16 to MU-45-20 back

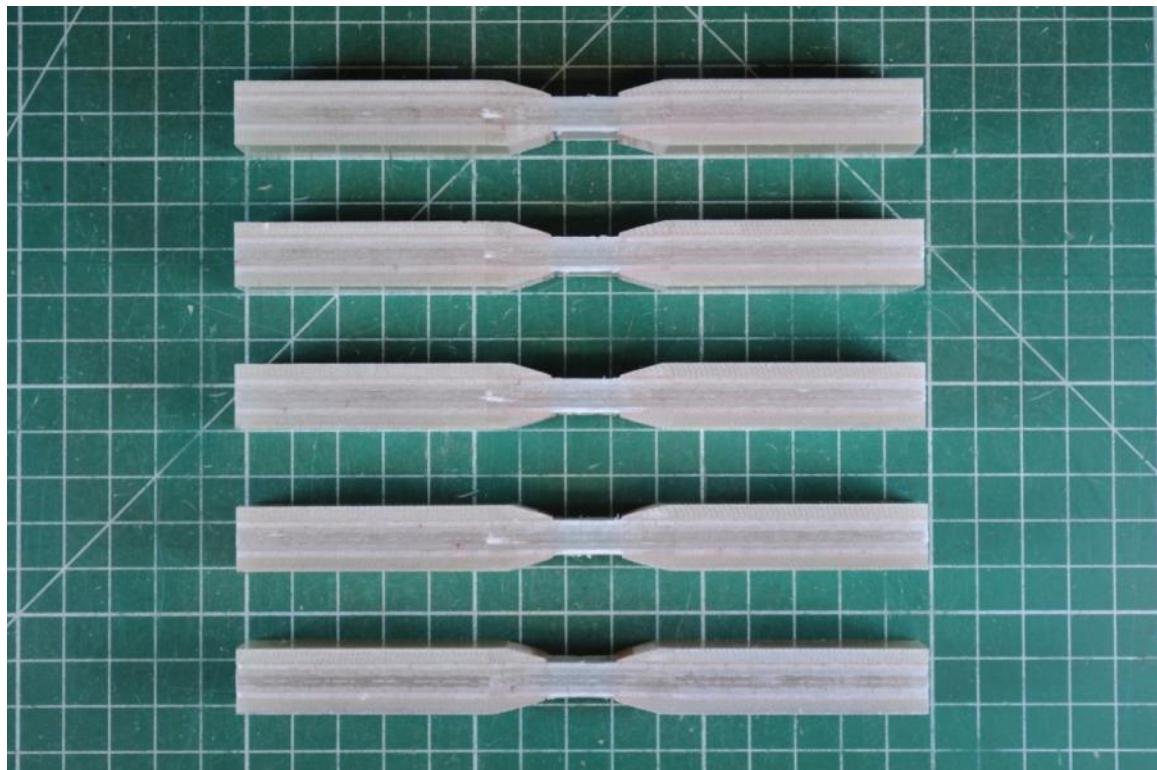


Figure 149: MU-45-16 to MU-45-20 side1

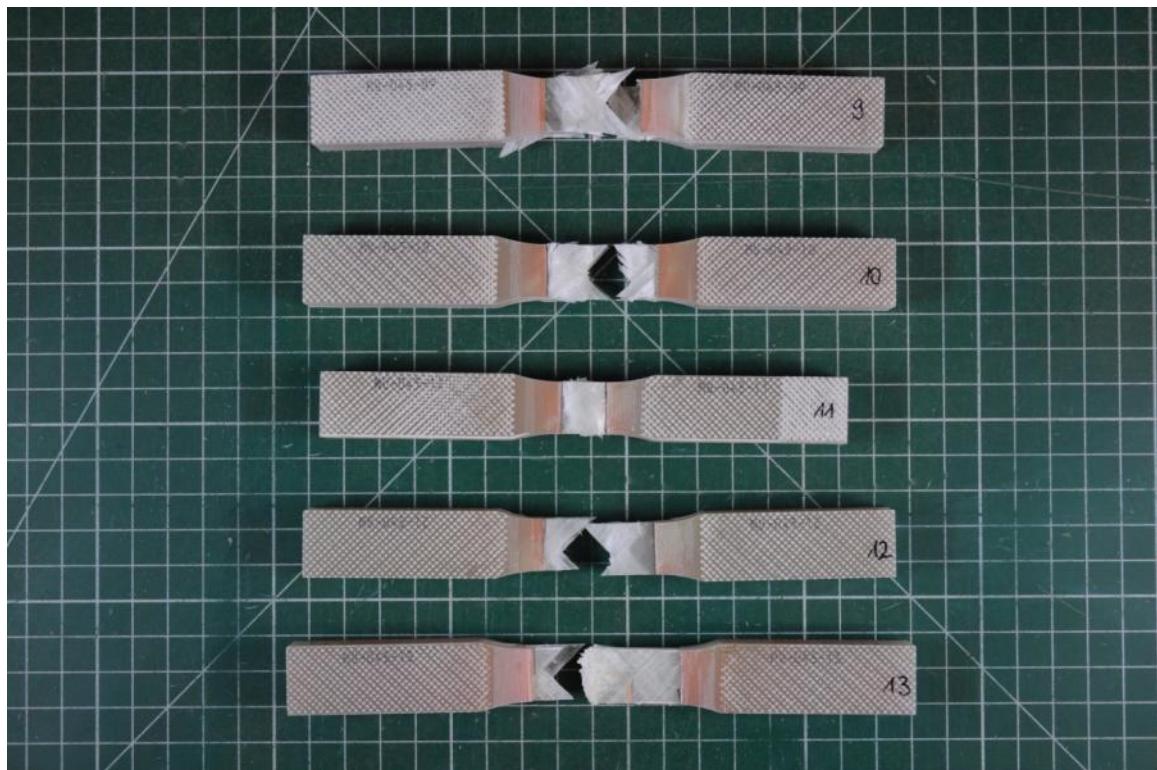


Figure 150: MU-45-09 to MU-45-13 front, after

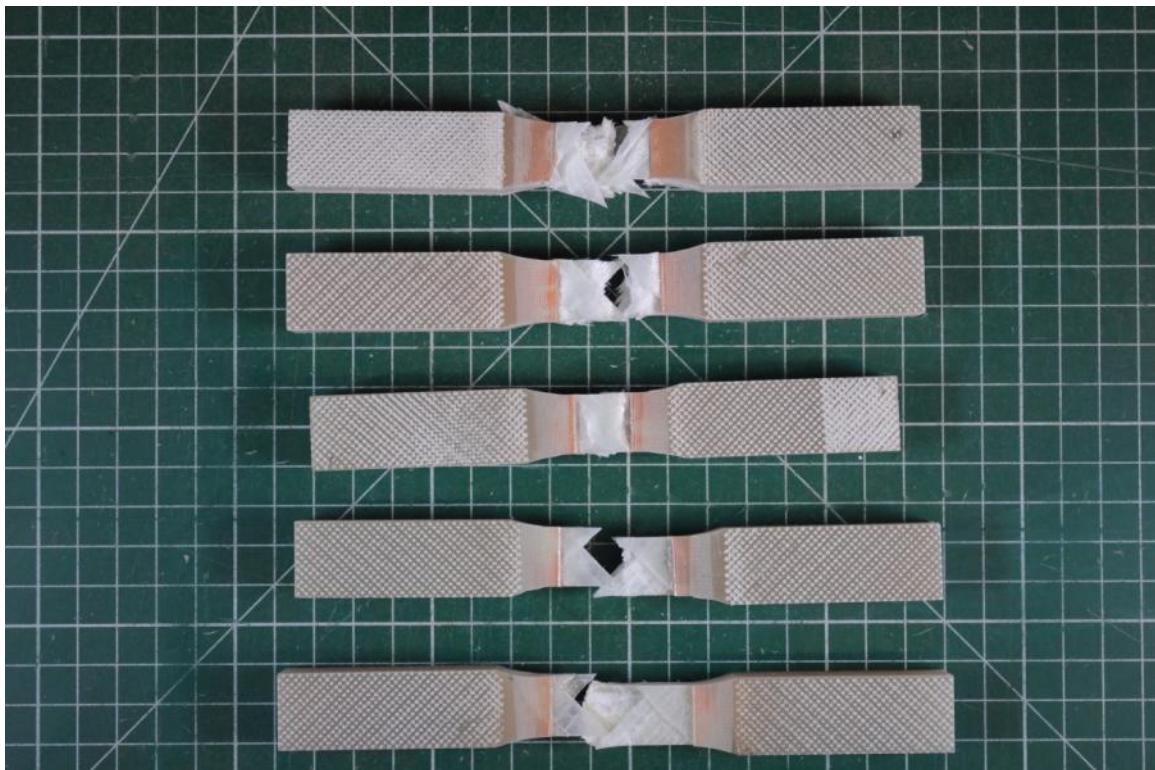


Figure 151: MU-45-09 to MU-45-13 back, after

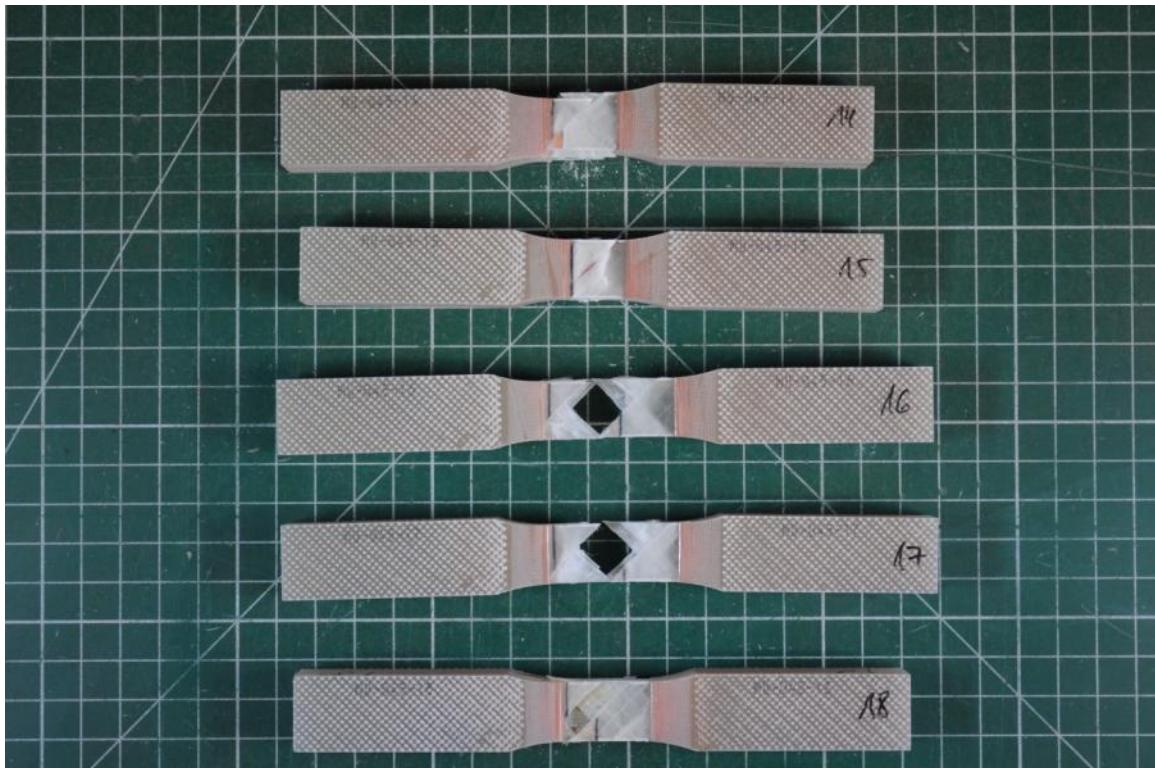


Figure 152: MU-45-14 to MU-45-18 front, after

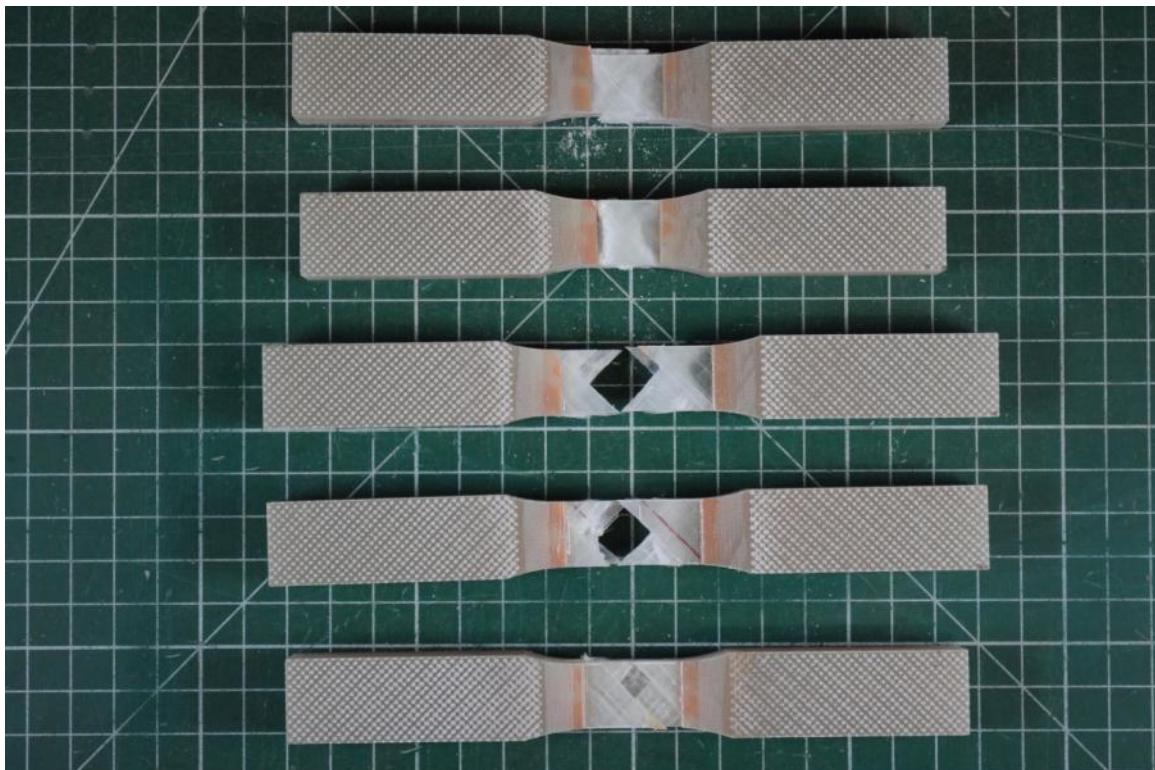


Figure 153: MU-45-14 to MU-45-18 front, after

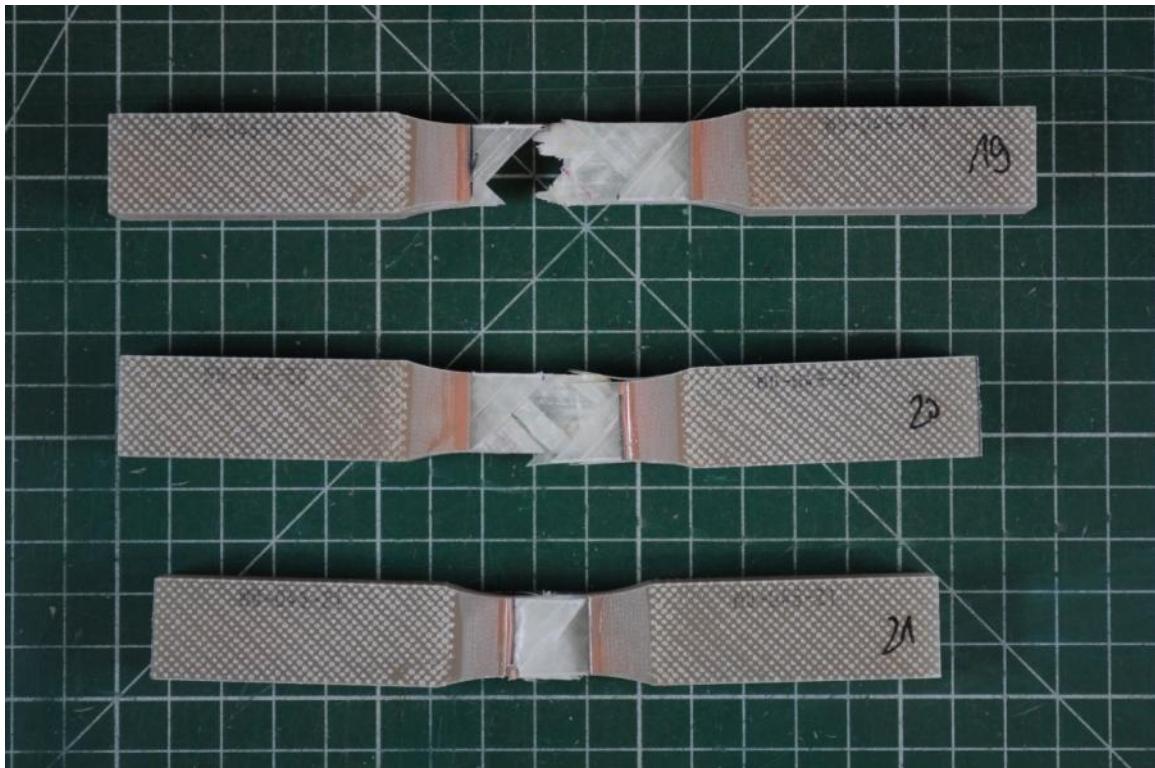


Figure 154: MU-45-19 to MU-45-21 front, after

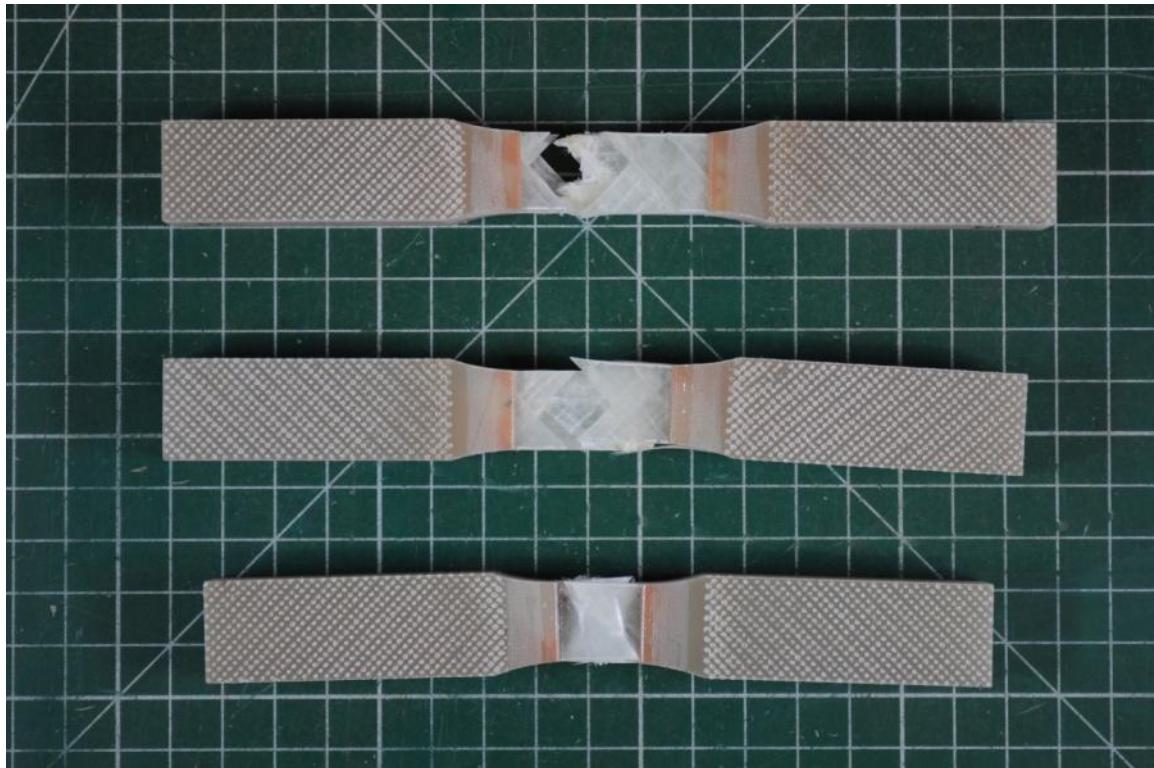


Figure 155: MU-45-19 to MU-45-21 back, after

8.3.7 UD-0-STT tension test. Benchmark test.

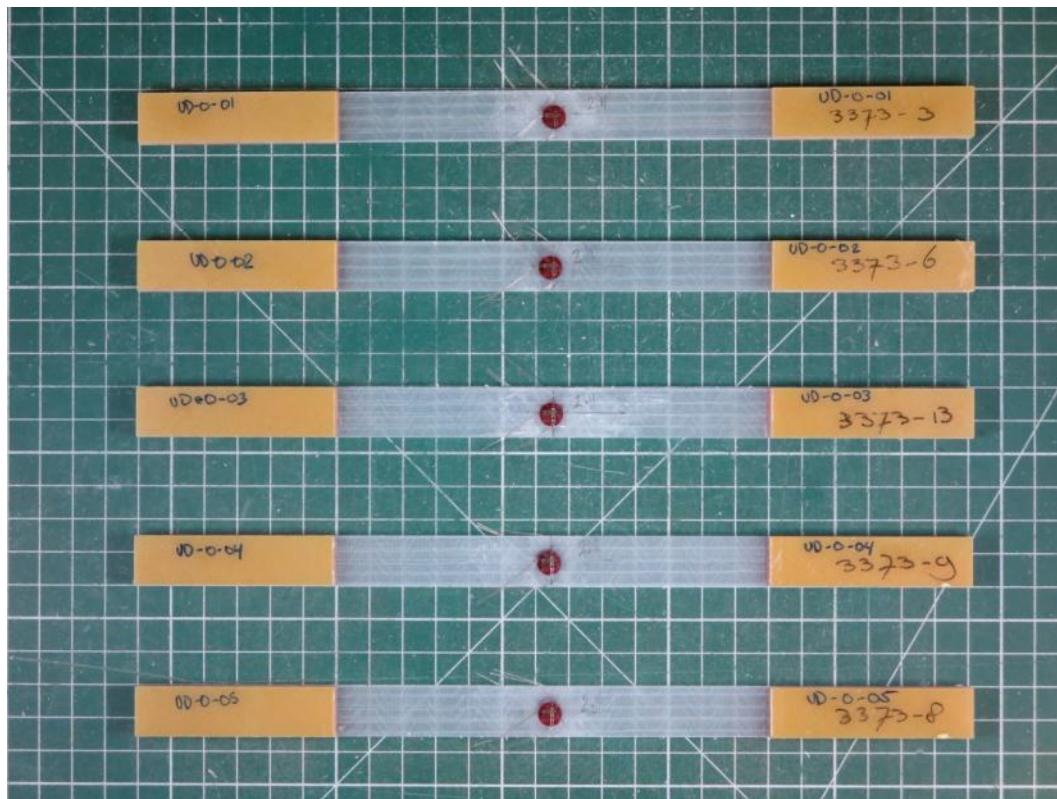


Figure 156: UD-0-01 to UD-0-05 front

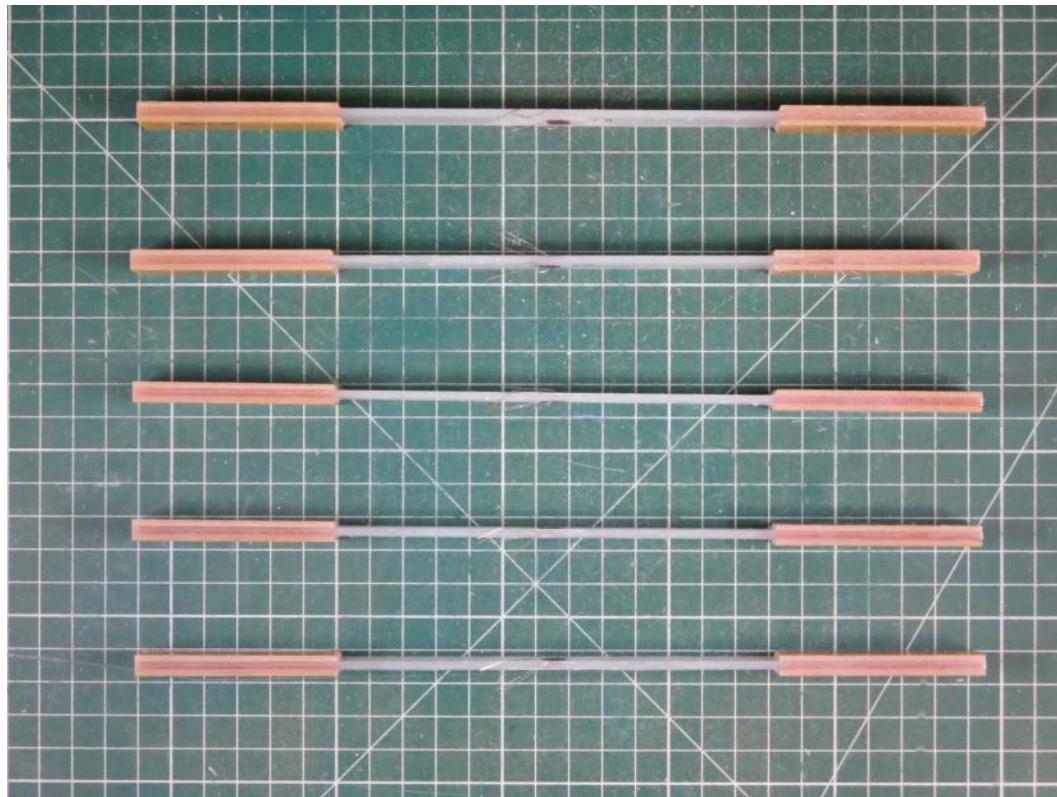


Figure 157: UD-0-01 to UD-0-05 side 1



Figure 158: UD-0-01 to UD-0-05 front, after



Figure 159: UD-0-01 to UD-0-05 back, after

8.3.8 UD-0-I-STT tension test. Benchmark test. Manufactured at IWES.

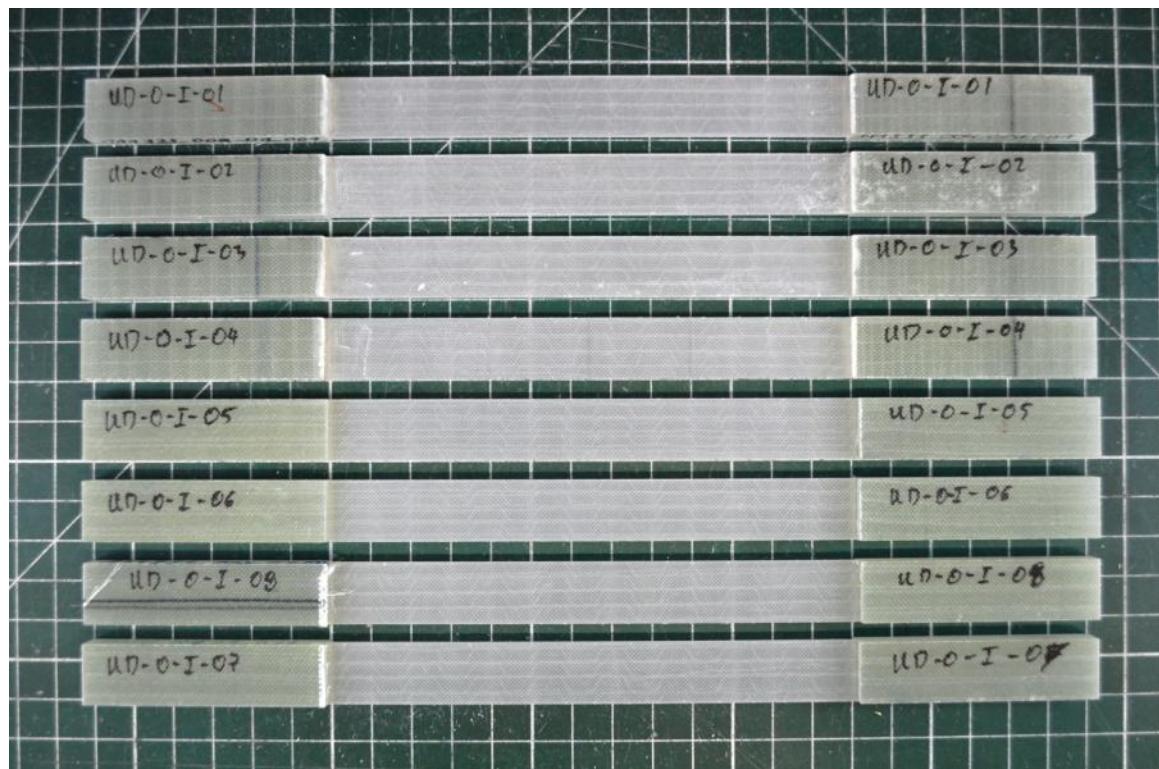


Figure 160: UD-0-I-01 to UD-0-I-08 front

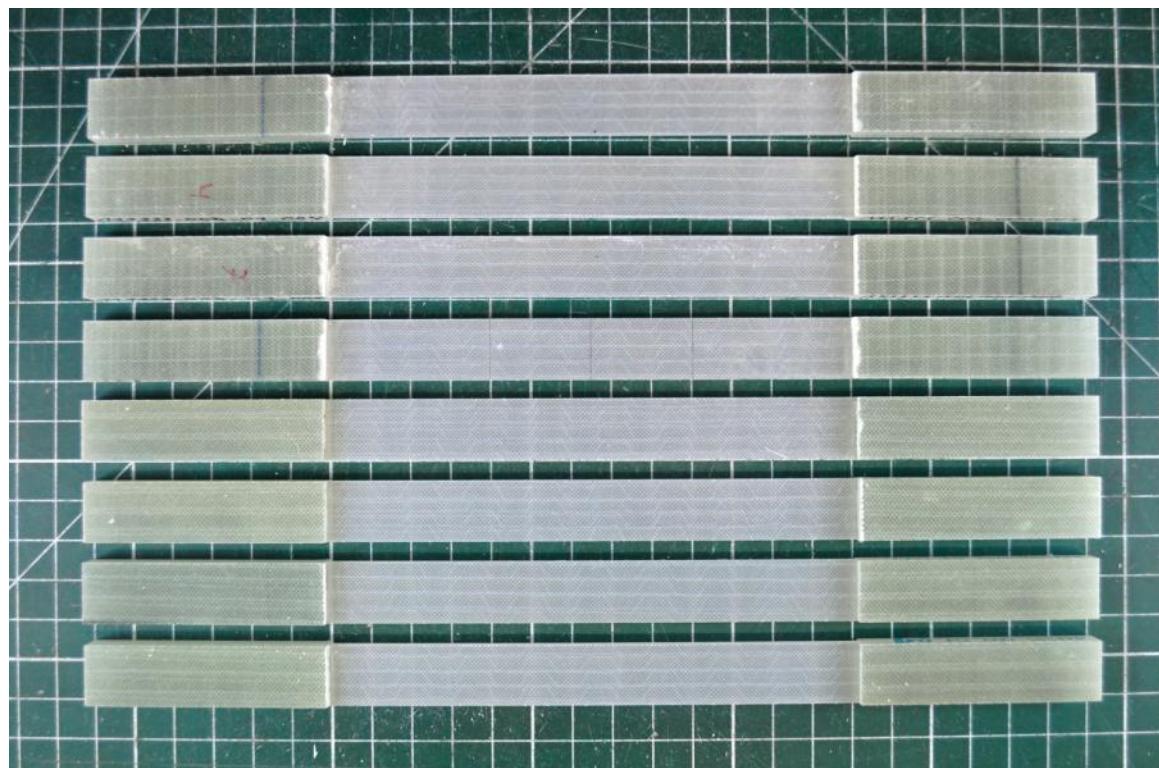


Figure 161: UD-0-I-01 to UD-0-I-08 back

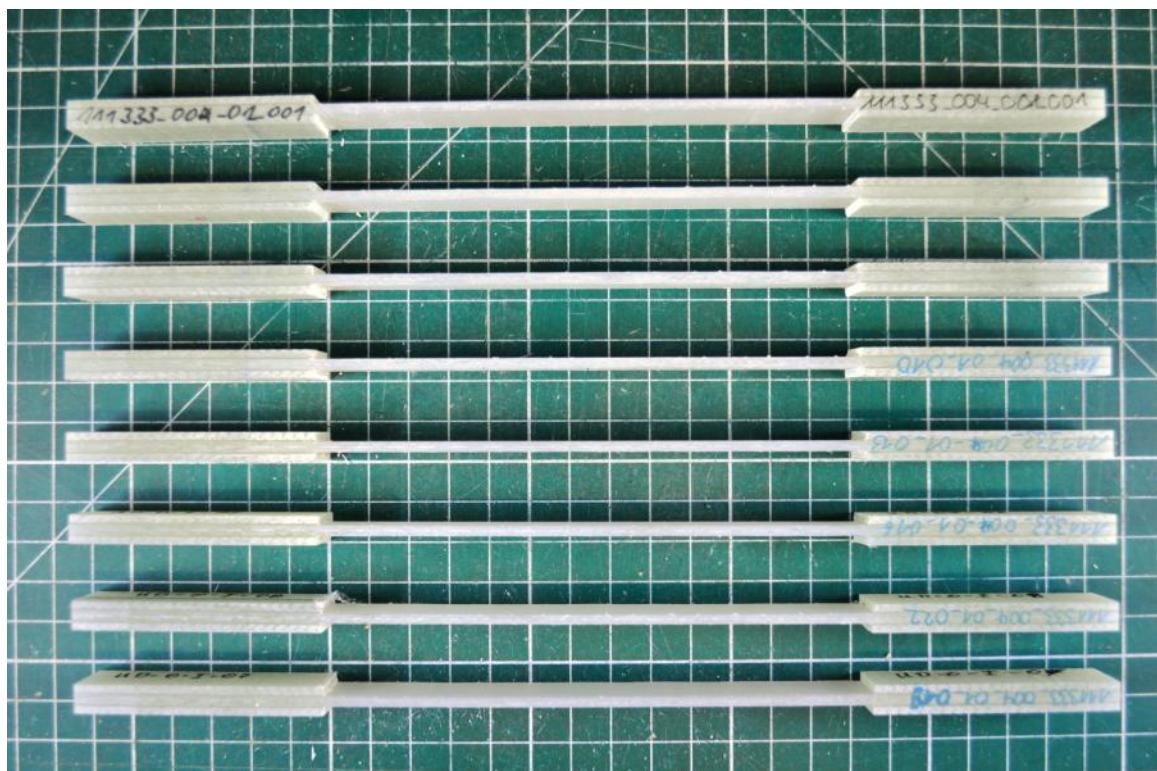


Figure 162: UD-0-I-01 to UD-0-I-08 side1

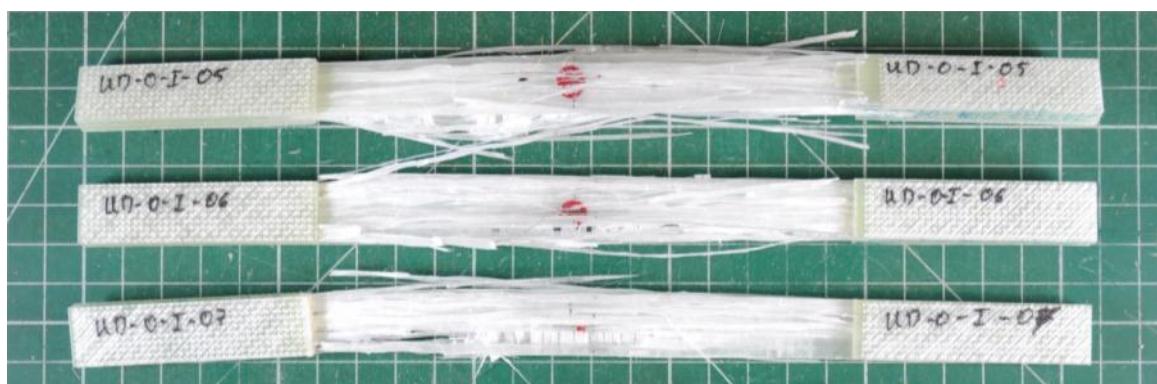


Figure 163: UD-0-I-02 to UD-0-I-07 front, after



Figure 164: UD-0-I-02 to UD-0-I-07 front, back