TEST RESULTS OF BENCHMARK STATIC TESTS ON UD & MD COUPONS

OB_TG1_R007 rev. 000

Draft version

Confidential

OPTIMAT BLADES

TG 1

D. J. Lekou

Change record

Issue/revision	date	pages	Summary of changes
draft	27.11.2003	Na	na

Table of Contents

1. INTRODUCTION

The work described in this report has been co-financed by the European Commission in the framework of the project under contract no ENK6-CT2001-00552, *RELIABLE OPTIMAL USE OF MATERIALS FOR WIND TURBINE ROTOR BLADES* (OPTIMAT BLADES). Coupon tests have been carried out within the benchmark phase in order to be able to compare results between different laboratories. In this report a detailed description of the coupon testing conducted at CRES within the framework of the OPTIMAT BLADES project. Results of the static experiments from tests in unidirectional (UD) and multidirectional (MD) Glass/Epoxy coupons, which were carried out in the period April – November 2003, are outlined.

2. EQUIPMENT

During testing the following equipment has been used:

- MTS ±250 kN coupon testing machine including:
    - Load cell of ±100kN range, with an accuracy of at least 0.2% full scale
    - LVDT of ±75mm range, with accuracy of at least 0.2% full scale
    - Hydraulic grip supply with pressure adjusted to 14MPa.
- HBM Strain gauges of nominal electric resistance 350Ω, with a gauge length of 6mm connected each through HBM ME30 amplifiers with an output range of ±10V with HBM amplifier system MGA. Specifically following types of strain gauges have been used:
    - Single strain gauges HBM 6/350 LY41, with amplifiers adjusted to 2000 με/V for axial strain measurements during static tests.
    - Single strain gauges HBM 6/350 LY61, with amplifiers adjusted to 2000 με/V for axial strain measurements during fatigue tests.
    - 0°/90º strain gauge rosettes HBM 6/350 XY11, with amplifiers adjusted to 2000 με/V for axial strain and 1200 με/V for transverse to the loading direction strain measurements during static tests in tension.
- A 64 channel Data Acquisition System with a 16Bits A/D conversion card.
- A Vaisala Temperature and Humidity sensor type HMP131Y
- A Vaisala analog barometer type PTB100A

All abovementioned equipment is calibrated according to the procedures of laboratory and certificates of traceable to NIST calibration data are kept at CRES facilities. Line calibration has been performed on all incoming signals to the data acquisition system used during testing. In particular strain gauge line calibration has been performed using the strain gauge simulator type 1550A of Instrument Division Measurement Group Inc.

3. COUPON DIMENSIONS AND PREPARATION

Composite material coupons in final dimensions, including the tabs, were delivered by LM. Specimen dimensions are given in Fig. 1 and Fig. 2 for the UD and MD coupons, respectively, according to [1]. Plate lamination sequence for the UD coupons was $[0_4]$ and $[(\pm45/0)_4/\pm45]$ for the MD coupons, as given in [1], where layer of 0º stands for the Unidirectional reinforcement material 1258gr/m^2 and layer of ±45º stands for the biaxial reinforcement material 810gr/m^2, while specifications for the material layers are given in [2]. It is noted that the 0º reinforcement coincides with the axis along the length of the coupon.

The test program, which was followed, is tabulated in Table 1. Section dimensions have been measured at three locations along the gauge length for all specimens. Mean values of the measured specimen dimensions, along with the calculated area of each specimen are shown in Table 2. In this table the mean value and the coefficient of variation (COV), i.e. the ratio of the standard deviation over the mean value is also shown for comparison purposes.

Table 1 ***CRES test program***

Test case	*Coupon Type*	*Type of load*	*Number of coupons*
1	GEV206-R0300	Static, Tension	5
2	GEV206-R0300	Static, Compression	5
3	GEV207-R0400	Static, Tension	5
4	GEV207-R0400	Static, Compression	5

All specimens were equipped with single strain gauges back to back measuring strain in the load direction, except two coupons. On coupon GEV206-R0300-0073 one single strain gauge and one 0/90 cross strain gauge rosette for the estimation of the Poisson ratio were attached on the opposite sides of the specimen respectively and on coupon GEV206-R0300-0074 three single strain gauges were used to determine if there is bending not only in the thickness direction, but also in the width direction, with strain gauge positioning as described in ISO 527-5 [3].

For the attachment of each strain gauge on the specimen proper procedures following strain gauge manufacturer directions have been followed. According to these procedures the surface of the specimens where the strain gauges were attached was slightly roughened. Specimen thickness was measured immediately after this procedure. Strain gauges were then attached using HBM type X60 adhesive.

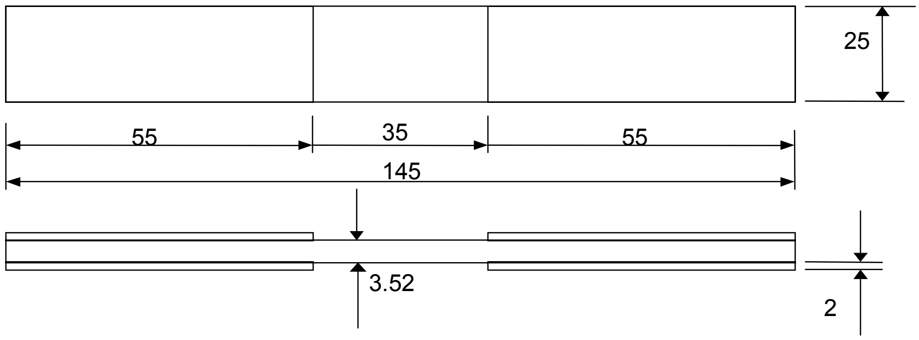

Fig. 1 Coupon dimensions for the GEV206-R0300

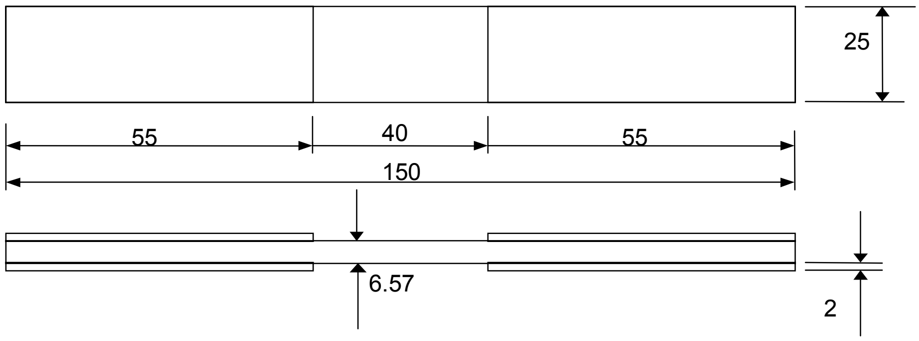

Fig. 2 Coupon dimensions for the GEV207-R0400

Table 2 ***Specimen dimensions***

Specimen No	*Thickness (mm)*	*Width (mm)*	*Area (mm^2)*	*Test type*
GEV206-R0300-0073	3.68	25.4	93.36	Static Tension
GEV206-R0300-0074	3.67	25.3	92.58	Static Compression
GEV206-R0300-0075	3.75	25.3	95.07	Static Tension
GEV206-R0300-0076	3.78	25.4	95.82	Static Compression
GEV206-R0300-0077	3.71	25.3	93.94	Static Tension
GEV206-R0300-0079	3.70	25.3	93.76	Static Compression
GEV206-R0300-0080	3.69	25.2	92.98	Static Tension
GEV206-R0300-0081	3.75	25.3	94.85	Static Tension
GEV206-R0300-0082	3.70	25.1	92.94	Static Compression
GEV206-R0300-0269	3.83	24.8	95.77	Static Compression
Mean value	*3.73*	*25.2*	*94.11*	
COV (%)	*1.36*	*0.70*	*1.27*	
GEV207-R0400-0082	6.86	25.3	173.34	Static Tension
GEV207-R0400-0083	6.77	25.3	171.09	Static Tension
GEV207-R0400-0084	6.86	25.4	174.59	Static Tension
GEV207-R0400-0085	6.77	25.3	171.16	Static Tension
GEV207-R0400-0086	6.84	25.3	173.05	Static Tension
GEV207-R0400-0087	6.79	25.2	171.11	Static Compression
GEV207-R0400-0088	6.70	25.3	169.51	Static Compression
GEV207-R0400-0089	6.80	25.2	170.94	Static Compression
GEV207-R0400-0090	6.68	25.2	169.19	Static Compression
GEV207-R0400-0091	6.74	25.2	170.24	Static Compression
Mean Value	*6.78*	*25.3*	*171.42*	
COV (%)	*0.92*	*0.27*	*1.01*	

4. TESTING PROCEDURE

For all experiments conducted coupons were aligned and mounted on the MTS 810 system, first in the moving grips of the machine and then in the fixed grips, with a procedure similar to the one described in [4]. Maximum hydraulic pressure of the grip system was set at 14MPa, with a minimum of 10MPa. Initial strain during the mounting procedure did not exceed 500με for any coupon. However, some bending strains were exhibited, which are an indication of an initially slightly curved surface of the coupons. This was also confirmed when checking the specimen surface against a flat surface, which is seen in Fig. 3 where the light between the specimen and the straight corner is seen, when holding one tab of the coupon close to the edge.

Fig. 3 Check of coupon's surface against a flat surface

After the gripping of the coupon on the test machine by load control, any initial pre-stress due to clamping of the specimen was minimized at a ramp rate of 0.2kN/sec. The initial conditions (strain gauge and displacement readings) for each test were taken after this minimization of pre-stresses.

Static tests were carried out at stroke control mode, whether tension or compression. During tension the constant stroke rate was 0.25mm/min for coupons GEV206-R0300-0073 and GEV206-R0300-0080, following [4], while for the rest the constant stroke rate was set to 0.5mm/min, as the strain rate during the two initial tests was found much lower than 1%/min, which is recommended for measurement of the elasticity modulus in [5] and [6]. All tests in compression were carried out at a stroke rate of 1.00mm/min.

During each test actuator force, actuator displacement and strain in the central coupon area from strain gauge(s) were measured and recorded simultaneously at a sampling rate of 8Hz, along with ambient conditions during testing, including temperature, relative humidity and atmospheric pressure, which were measured with a sampling rate of 1Hz. Fig. 4 presents a picture of the coupon testing set-up.

Stress was calculated by dividing force with measured cross sectional area. Two stress-strain curves were derived for each specimen using the two strain gauges on the specimen. Three different moduli of elasticity were calculated using linear regression procedure applied on the part of stress-strain curve corresponding to a strain range between 500με and 2500με, as described in ISO 527-1 [5] and ISO 14126 [7] for tests in tension and compression, respectively, for both types of measured strain (using strain gauge readings and the mean value of the strain gauge readings). The linearity of stress-strain curves is checked by use of the coefficient of determination, R^2.

Fig. 4 ***Setup of the coupon tests***

Bending strains during testing are also observed for both tension and compression experiments by use of the back to back strain gauge readings. For tests in compression according to ISO 14126 [7] bending is acceptable if the difference between strains recorded on each face of the specimen throughout the duration of the tests until failure is such that:

$$\left|\frac{\varepsilon_b - \varepsilon_a}{\varepsilon_b + \varepsilon_a}\right| * 100 \leq 10\% \qquad (1)$$

where ε_a and ε_b are the strains along the length of the specimen on each face.

For tests in tension for the UD coupons according to [3] bending strains with respect to the thickness and the width of the specimen should not exceed 3% of the axial strain, when measured at the mid span of the elasticity modulus calculation range. However, for the experiments conducted, the bending strains were only measured with respect to the thickness of the coupon. Therefore, the condition that must be satisfied is:

$$\left|\frac{\varepsilon_b - \varepsilon_a}{\varepsilon_b + \varepsilon_a}\right| * 100 \leq 3\% \qquad (2)$$

while the measurement is taken when the axial strain is about 1500με.

5. RESULTS

5.1. UD coupons results

Ten static tests have been preformed for the UD coupons, namely five in tension and five in compression. Results of tensile static tests are given in Fig. 5, where the applied stress versus strain curves until total failure, with strain measured by the two strain gauges is presented. Tension test ultimate load and stress are presented collectively in Table 3. It should be noted that the mean value and coefficient of variation (COV), namely the ratio of the standard deviation to the mean value in percent, for each property is also shown in the same table.

Table 3 ***Coupon test results for Static tests in Tension***

Specimen #	*Ultimate load (kN)*	*Ultimate Stress (MPa)*	*Remarks*
GEV206-R0300-0073	78.177	837.368	
GEV206-R0300-0080	70.657*	759.938*	First loaded to 20kN
GEV206-R0300-0075	75.946	798.83	
GEV206-R0300-0081	77.588	817.549	
GEV206-R0300-0077	73.819	786.455	
Mean	*76.382*	*810.051*	
COV (%)	*2.556*	*2.747*	

In Table 4 experimentally derived values for the modulus of elasticity are presented, determined by each strain gauge separately and by averaging the two strain gauge readings, as described in Section 4. Fig. 6 presents the stress-strain curve part that was used according to ISO 527-5 [3] for the derivation of elasticity modulus, with strain measured as the average of the two strain gauge readings on each coupon. The difference between the estimation of using one strain gauge reading or both is minimal. The coefficient of determination, R^2, is shown on the table only for the linear estimation of the E-modulus from the average strain for reference purposes, since all estimations gave a R^2 value better than 0.9999. The two last columns of the table present the bending strain in per cent of the axial strain when the axial strain is about 1500με, and the Poisson ratio measured from cross strain gauge rosette, respectively. The mean value and the coefficient of variation (COV) for the measured and estimated properties are also shown in this table.

Table 4 ***Experimentally derived values of modulus of elasticity in tension***

Specimen #	*E-modulus (GPa)*					
	E-1	E-2	Average	R^2	Bending (%)	v_{12}
GEV206-R0300-0073	38.11	37.83	38.03	0.999900	0.855	0.2951
GEV206-R0300-0080	39.58	39.21	39.39	0.999905	0.322	na
GEV206-R0300-0075	40.13	38.97	39.54	0.999923	1.546	na
GEV206-R0300-0081	40.66	38.15*	39.31	0.999911	3.020	na
GEV206-R0300-0077	39.67	39.16	39.41	0.999912	0.730	na
Mean value	*39.63*	*38.79*	*39.14*	-	-	*0.2951*
COV (%)	*2.402*	*1.676*	*1.594*	-	-	-

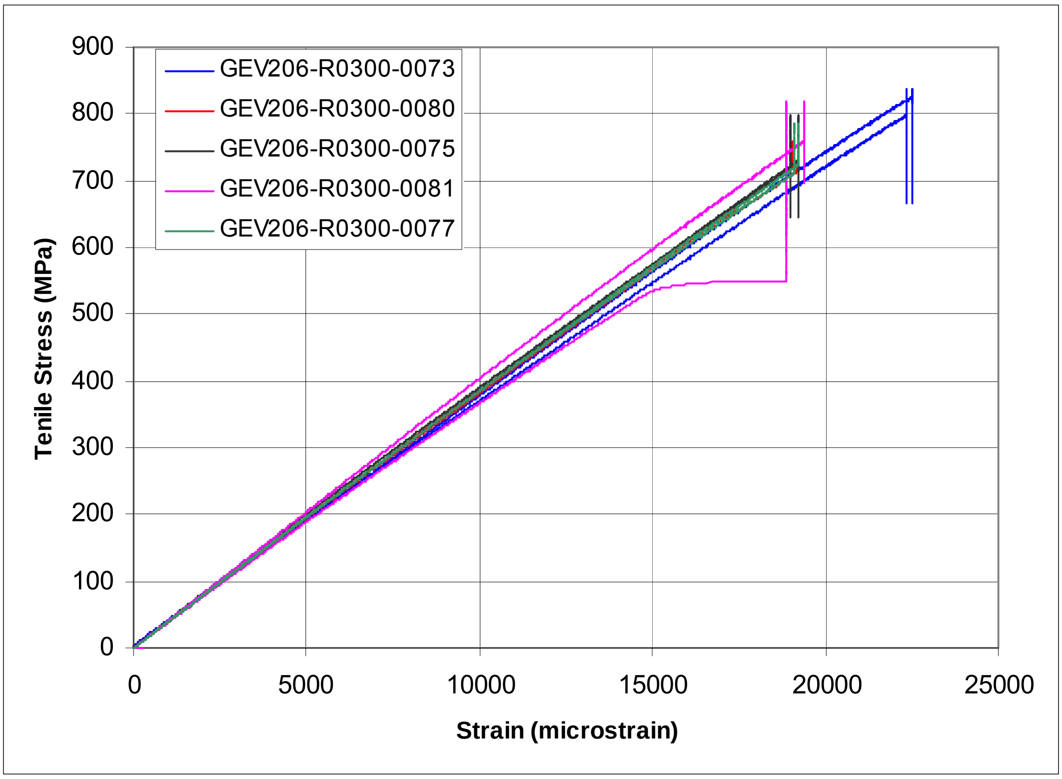

Fig. 5 ***Stress-strain curves for specimens under Static Tensile loading***

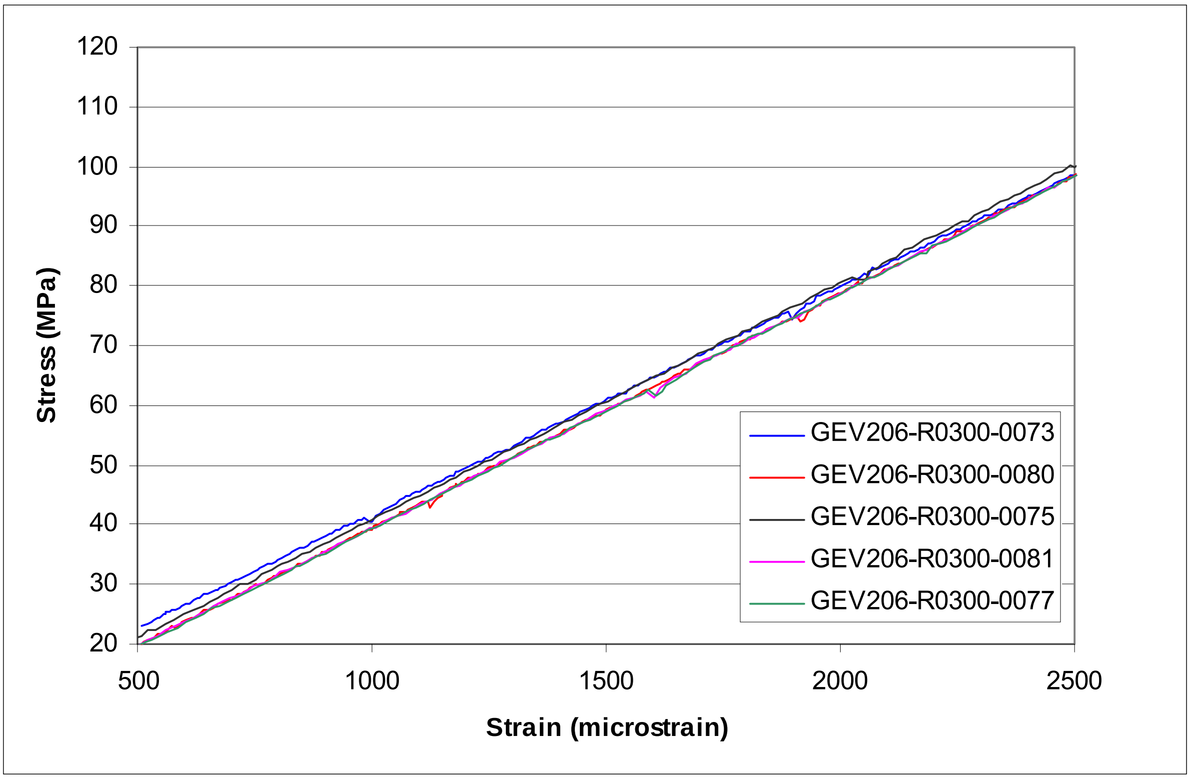

Fig. 6 ***Detail of stress-strain curves for elasticity measurements according to ISO 527-5 [3]***

In Table 5 the ultimate load and the corresponding stress is presented for coupons tested in compression including the mean value and the COV. On the last column of the table, under the heading of buckling stress indicates the stress where the first crossing of the 10% bending limit is noticed for tests in compression according to ISO 14126 [7]. It is clearly seen that none of the UD specimens (GEV206-R0300) fulfill the limit of lower than 10% bending under compression, indicating that the specimens buckle before reaching their ultimate compressive stress. In Fig. 7, where the stress-strain response of each coupon tested in compression is depicted, the buckling of the coupons tested in compression becomes evident.

Table 5 ***Coupon test results for Static tests in Compression***

Specimen #	*Ultimate load (kN)*	*Ultimate Stress (MPa)*	*Buckling Stress (MPa)*
GEV206-R0300-0074	-46.817	-505.674	-236.67
GEV206-R0300-0079	-55.063	-587.287	-518.18
GEV206-R0300-0082	-51.474	-553.817	-479.94
GEV206-R0300-0076	-42.649	-445.042	-244.02
GEV206-R0300-0269	-51.852	-541.446	-419.59
Mean	*-49.571*	*-526.653*	*-379.68*
COV (%)	*9.80*	*10.28*	*34.76*

In Table 6 experimentally derived values for the modulus of elasticity in compression are presented, determined by each strain gauge separately and by averaging the two strain gauge readings, as described in Section 4. Fig. 8 presents the stress-strain curve part that was used according to ISO 14126 [7] for the derivation of elasticity modulus, with strain measured as the average of the two strain gauges on each face of the coupon. The difference between the estimation of using one strain gauge reading or both is minimal, except for coupon GEV206-R0300-0074. This difference however, for the specific coupon is attributed to two reasons, the first is that E-2 has been derived from measurements of two strain gauges on the two edges of the coupon, while E-1 has been derived by single strain gauge measurement on the center of the coupon, and the difference could be attributed to small differences in the strain field in the middle and on the two sides of the coupon. The second reason is that this coupon revealed bending strains very early, indicating buckling at low stress values.

Table 6 ***Experimentally derived values of modulus of elasticity in compression***

Specimen #	*E-modulus (GPa)*			
	E-1	E-2	Average	R^2
GEV206-R0300-0074	36.85*	43.96*	40.00	0.99996
GEV206-R0300-0079	39.35	40.76	40.04	0.99984
GEV206-R0300-0082	40.77	40.98	40.88	0.99997
GEV206-R0300-0076	36.00*	41.51*	38.56	0.99987
GEV206-R0300-0269	35.59*	38.50*	36.99	0.99997
Mean value	*38.57*	*40.08*	*39.29*	-
COV (%)	*6.94*	*3.43*	*3.90*	-

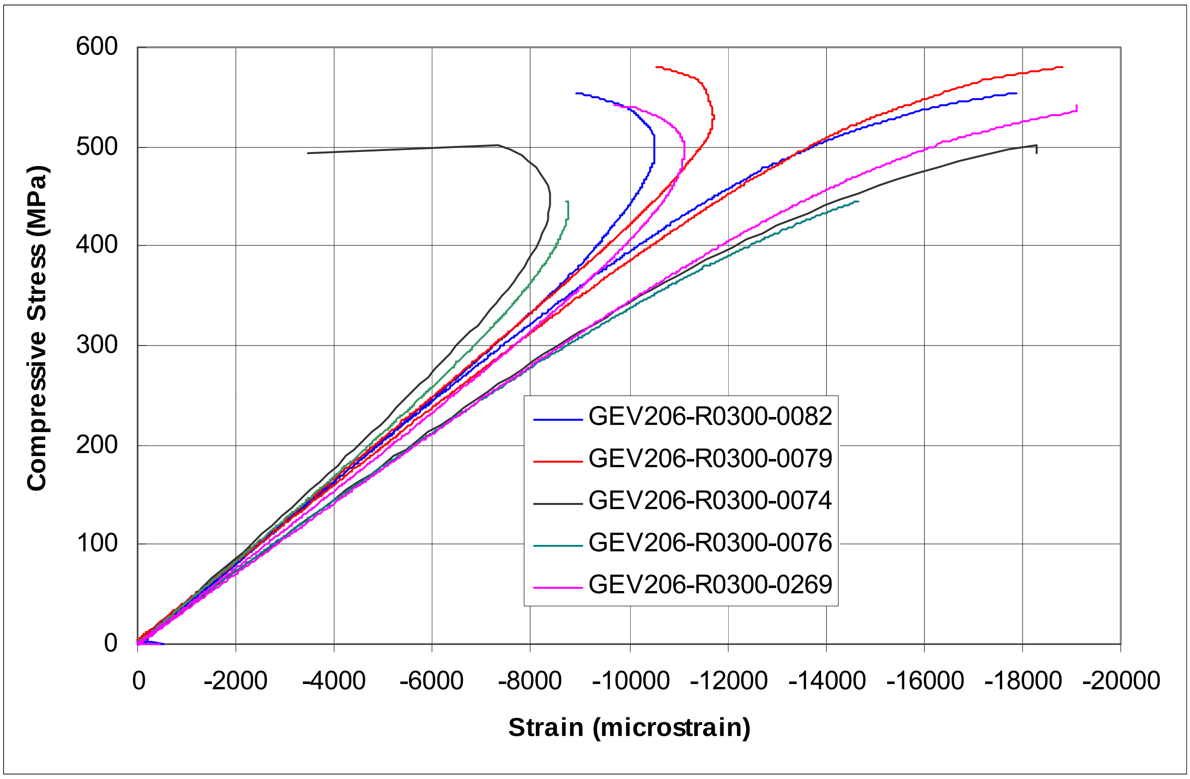

Fig. 7 Strain response versus stress during tests in compression (both strain gauges displayed)

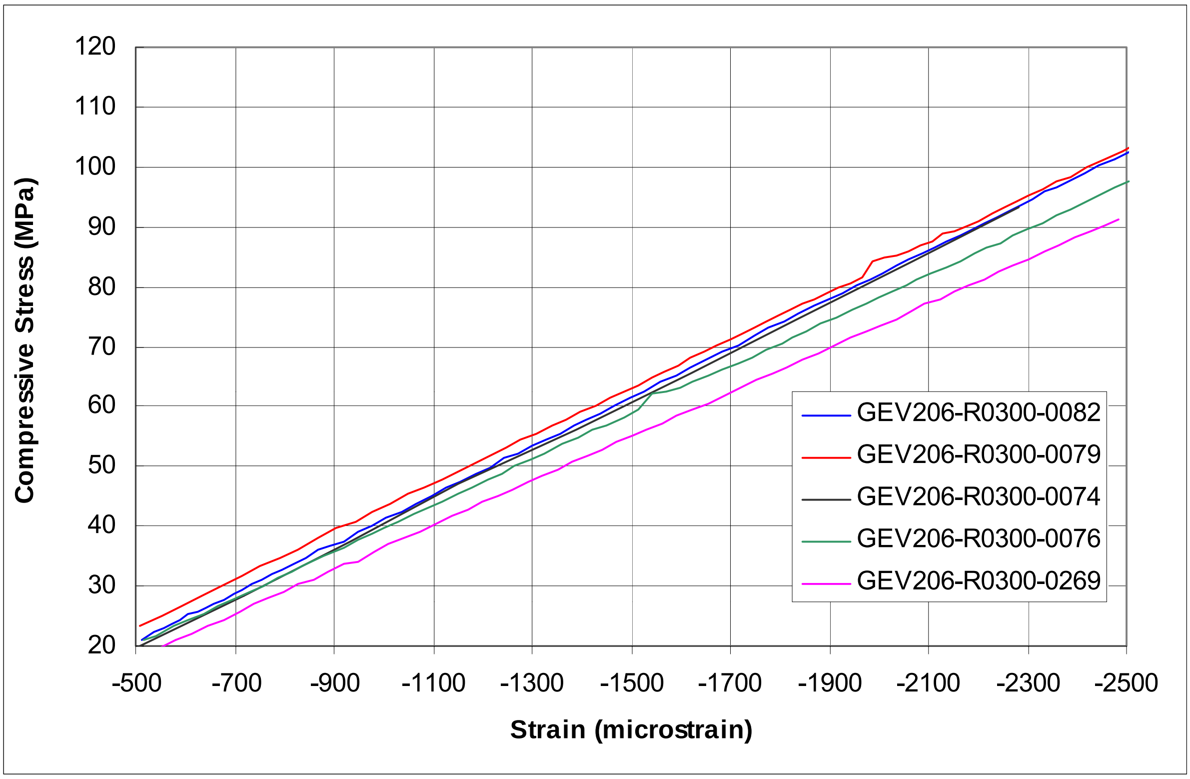

Fig. 8 ***Detail of stress-strain curves for elasticity measurements according to ISO 14126 [7]***

Moreover, according to ISO 527-5 [3] the loading rate during static tests should be such as producing a strain rate of 1%/min when testing for the determination of modulus of elasticity. Comparing the results to this it was found that the 0.25mm/min stroke rate resulted in a strain rate of 0.36%/min for the tests in tension, which is lower to the specified one, while the 1mm/min stroke rate resulted in a strain rate of 1%/min for the tests in compression.

5.2. MD coupons test results

Ten static tests have been preformed for the MD coupons, namely five in tension and five in compression. Results of tensile static tests are given in Fig. 9, where the applied stress versus strain curves until total failure, with strain measured by the two strain gauges, is presented. As opposed to the UD coupons, which exhibit a linear behavior up to failure, the MD stress-strain response exhibit some non-linearity, which is however expected, due to the presence of the ±45º fabric in the lamination sequence. Tension test ultimate load and stress are presented collectively in Table 7. It should be noted that the mean value and coefficient of variation (COV), namely the ratio of the standard deviation to the mean value in percent, for each property is also shown on the same table.

Table 7 *Coupon test results for Static tests in Tension for MD coupons*

Specimen #	*Ultimate load (kN)*	*Ultimate Stress (MPa)*	*Remarks*
GEV207-R0400-0082	87.430	504.394	
GEV207-R0400-0083	86.938	508.132	
GEV207-R0400-0084	89.829	514.520	
GEV207-R0400-0085	86.359	504.543	
GEV207-R0400-0086	90.186	521.972	
Mean	*88.148*	*510.712*	
COV (%)	*1.978*	*1.472*	

In Table 8 experimentally derived values for the modulus of elasticity are presented, determined by each strain gauge separately and by averaging the two strain gauge readings, as described in Section 4. Fig. 10 presents the stress-strain curve part that was used according to ISO 527-4 [5] for the derivation of elasticity modulus, with strain measured as the average of the two strain gauge readings on each coupon. Similar to the results of the UD coupons, the difference between the estimation of using one strain gauge reading or both is minimal. The coefficient of determination, R^2, is shown also on this table only for the linear estimation of the E-modulus from the average strain for reference purposes, since all estimations gave a R^2 value better than 0.999. The last column of the table presents the bending strain in percent of the axial strain when the axial strain is about 1500με. The mean value and the coefficient of variation (COV) for the measured and estimated properties are also shown in this table.

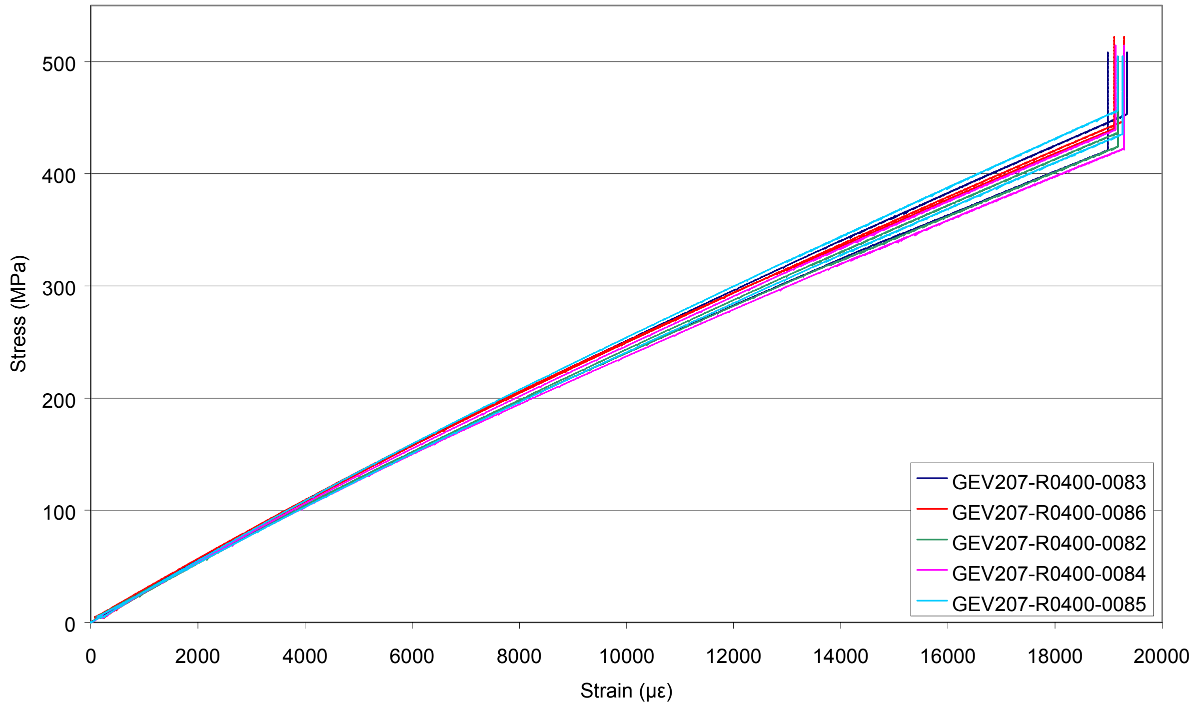

Fig. 9 Stress-Strain response of MD coupons tested in Tension

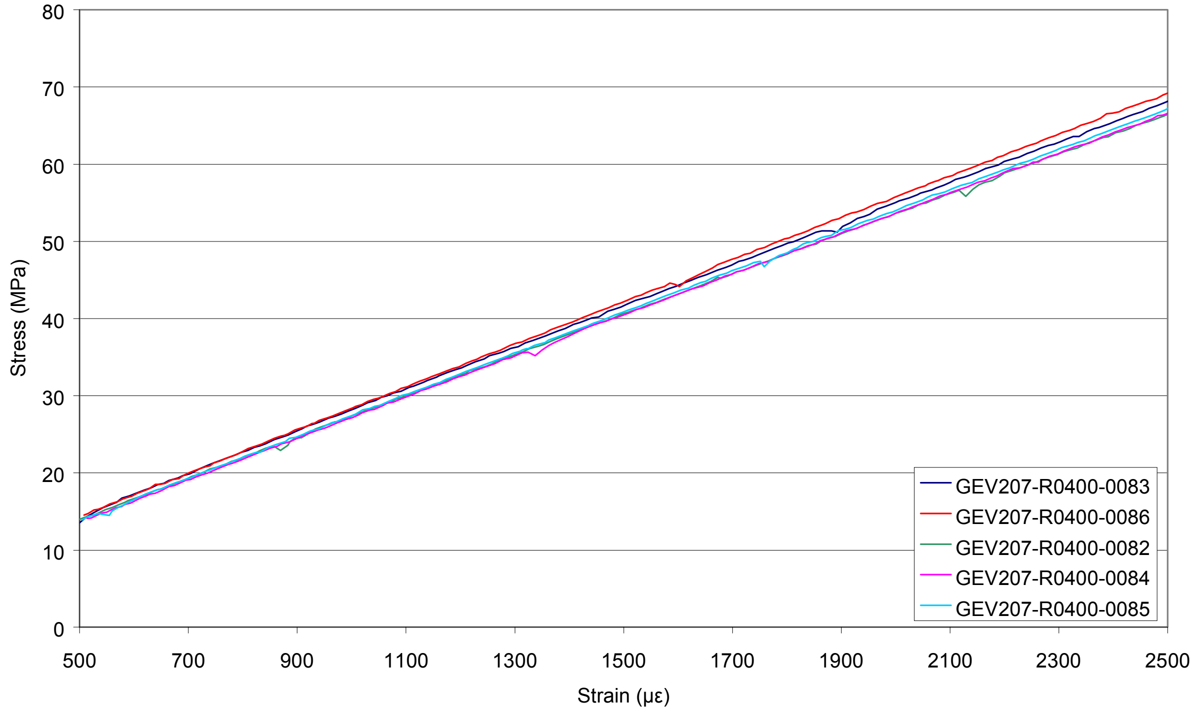

Fig. 10 Stress-strain response part used for the derivation of E-modulus for the MD coupons tested in tension

Table 8 ***Experimentally derived values of modulus of elasticity in tension for the MD coupons***

Specimen #	*E-modulus (GPa)*				
	E-1	E-2	Average	R^2	Bending (%)
GEV207-R0400-0082	26.47	26.05	26.26	0.999854	2.400
GEV207-R0400-0083	27.52	26.13	26.81	0.999874	2.649
GEV207-R0400-0084	27.31	25.71	26.49	0.999914	0.610
GEV207-R0400-0085	27.79	25.63	26.67	0.999871	1.546
GEV207-R0400-0086	27.79	27.10	27.44	0.999910	3.355
Mean value	*27.38*	*26.12*	*26.73*	-	-
COV (%)	*1.991*	*2.243*	*1.665*	-	-

In Table 9 the ultimate load and the corresponding stress, as well as the strain at failure are presented for the MD coupons tested in compression including the mean value and the COV. Ultimate strain is the average value of the two back to back strain gauge reading for each coupon, except for coupons GEV207-R0400-0090 and GEV207-R0400-0091, for which one strain gauge failed prior to the failure of the coupon and therefore, only the value of the other strain gauge is reported. In Fig. 11 the stress-strain response of each MD coupon tested in compression is depicted.

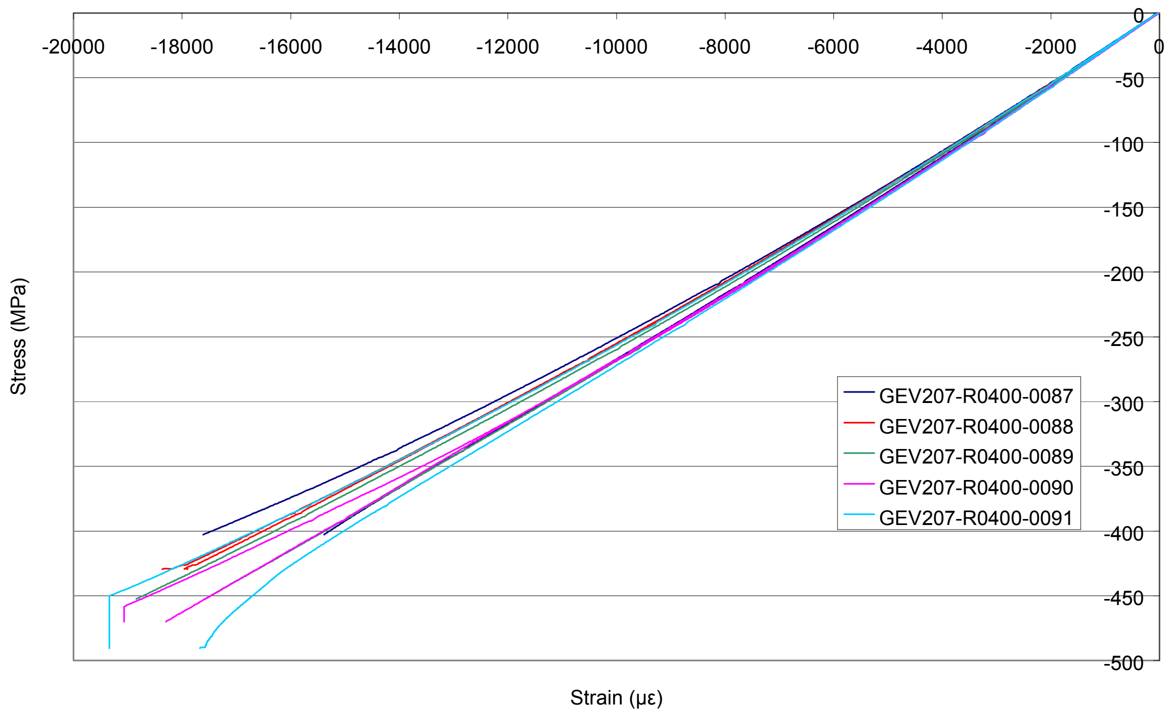

Fig. 11 Stress-Strain response of MD coupons tested in compression

In Table 10 experimentally derived values for the modulus of elasticity in compression for the MD coupons are presented, determined by each strain gauge separately and by averaging the two strain gauge readings, as described in Section 4. Fig. 12 presents the stress-strain curve part that was used according to ISO 14126 [7] for the derivation of elasticity modulus, with strain measured as the average of the two strain gauges on each face of the coupon. The difference between the estimation of using one strain gauge reading or both is minimal, as in the case of the UD coupons. On the last column of the table, under the heading of bending at failure indicates the bending strain in percent of the axial strain at failure, according to ISO 14126 [7]. It is clearly seen that none of the MD specimens exceed the 10% limit set by ISO 14126. For coupons GEV207-R0400-0090 and GEV207-R0400-0091 the bending at failure was not confirmed since one of the two strain gauges failed prior to the coupon and the number reported refers to the last valid reading. Nevertheless, judging by the failure mode and the rest of the coupon results none of the two coupons must have passed the 10% bending limit set for tests in compression.

Table 9 ***MD coupon test results for Static tests in Compression***

Specimen #	*Ultimate load (kN)*	*Ultimate Stress (MPa)*	*Ultimate strain (%)*	*Remarks*
GEV207-R0400-0087	-68.83	-402.77	-1.650	
GEV207-R0400-0088	-72.79	-429.53	-1.813	
GEV207-R0400-0089	-77.33	-452.40	-1.822	
GEV207-R0400-0090	-79.53	-470.07	-1.830*	only one strain gauge at failure
GEV207-R0400-0091	-83.51	-490.55	-1.767*	only one strain gauge at failure
Mean	*-76.40*	*-449.06*	*-1.762*	
COV (%)	*7.51*	*7.63*	*5.50*	

Table 10 ***Experimentally derived values of elasticity modulus in compression for the MD coupons***

Specimen #	*E-modulus (GPa)*				
	E-1	E-2	Average	R^2	Bending at failure (%)
GEV207-R0400-0087	27.14	28.37	27.74	0.999800	6.76
GEV207-R0400-0088	27.10	27.39	27.25	0.999958	1.29
GEV207-R0400-0089	28.33	27.71	28.02	0.999967	3.48
GEV207-R0400-0090	28.70	28.44	28.57	0.999957	>3.37
GEV207-R0400-0091	29.04	27.47	28.23	0.999828	>7.25
Mean value	*28.06*	*27.88*	*27.96*	-	-
COV (%)	*3.19*	*1.79*	*1.79*	-	-

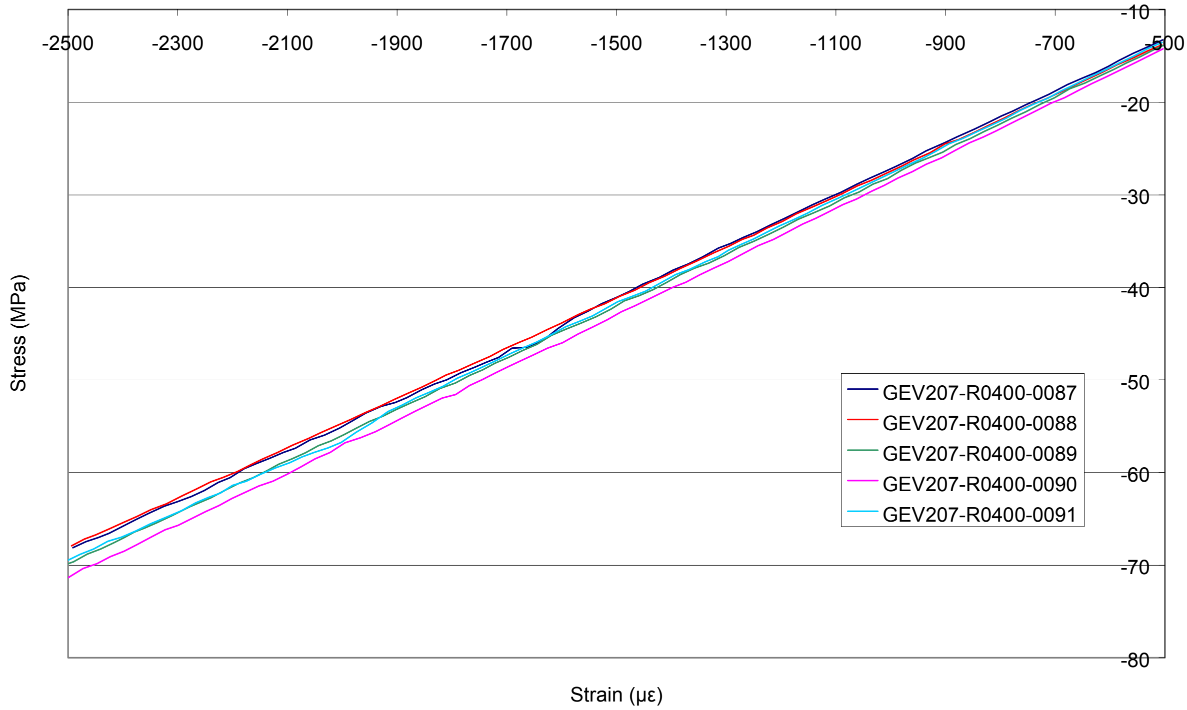

Fig. 12 Stress-strain response part used for the derivation of E-modulus for the MD coupons tested in compression

6. CONCLUSIONS

Experimental results are summarized in following tables.

Table 11 Static Tests results for the UD coupons

Property	*Mean Value*	*COV (%)*	*Notes*
E-Modulus in tension E_T (GPa)	39.14	1.59	
E-Modulus in compression E_C (GPa)	39.29	3.90	
Tensile strength X_T (MPa)	810.05	2.75	
Compressive strength X_C (MPa)	526.65	10.28	Buckling noted before failure

Table 12 Static Tests results for the MD coupons

Property	*Mean Value*	*COV (%)*
E-Modulus in tension E_T (GPa)	26.73	1.67
E-Modulus in compression E_C (GPa)	27.96	1.79
Tensile strength X_T (MPa)	510.71	1.47
Compressive strength X_C (MPa)	449.06	7.43
Compression strain to failure $\varepsilon_{C,ult}$ (%)	1.762	5.50

UD coupons tested in compression exhibited large bending strains mainly when stress exceeded 380MPa as an average, giving an indication that buckling preceded compressive failure of the specimen. Moreover, for the UD coupons, although failure modes when tested in tension gave acceptable results, in many cases failure was located near the end tab, which in general should not be accepted. Nevertheless, this is probably the result of the shorter than recommended coupon free length and was not rejected.

7. REFERENCES

[1] O. Krause, *Test plan report of TG1; Describing material, laminates and tests*, OPTIMAT BLADES, ENK6-CT2001-00552, OB_TG1_R001, Rev.0, 2003

[2] T. K. Jacobsen, *Reference material (OPTIMAT); Glass-epoxy material*, OPTIMAT BLADES ENK6-CT2001-00552, OB-SCR001, 2002

[3] BS EN ISO 527-5: 1997, Plastics – Determination of tensile properties, Part 5: Test conditions for unidirectional fibre-reinforced plastic composites.

[4] T. P. Philippidis, A. P. Vassilopoulos, T. T. Assimakopoulou, V. Passipoularidis, *Static and Fatigue tests of OPTIMAT UD coupons; Benchmark Tests*, OPTIMAT BLADES, ENK6-CT2001-00552, OB_TG2_R012, Rev.0, 2003

[5] BS EN ISO 527-1: 1996, Plastics – Determination of tensile properties, Part 1: General principles

[6] ASTM D 3039M-93, Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials

[7] ISO 14126: 1999, Fibre-reinforce plastic composites – Determination of compressive properties in the in-plane direction