

TEST RESULTS OF BENCHMARK FATIGUE TESTS ON UD COUPONS

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D. J. Lekou





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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 fatigue experiments from tests in unidirectional (UD) Glass/Epoxy coupons, which were carried out in the period August – November 2003, are outlined.

2. EQUIPMENT

During testing the following equipment has been used:

- MTS ± 250 kN coupon testing machine including:
 - Load cell of ± 100 kN range, with an accuracy of at least 0.2% full scale
 - LVDT of ± 75 mm range, with accuracy of at least 0.2% full scale
 - Hydraulic grip supply with maximum pressure adjusted to 14 MPa.
- HBM Strain gauges of nominal electric resistance 350 Ω , with a gauge length of 6 mm connected each through HBM ME30 amplifiers with an output range of ± 10 V 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 $\mu\text{e}/\text{V}$ for axial strain measurements.
 - Single strain gauges HBM 6/350 LY61, with amplifiers adjusted to 2000 $\mu\text{e}/\text{V}$ for axial strain measurements as an alternative to the previous type.
- PT100 with Microlec amplifier type CLT-RT-420 adjusted to $-10^{\circ}\text{C} \dots +60^{\circ}\text{C}$
- A 64 channel Data Acquisition System with a 16 Bits 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 Instrument Division Measurement Group Inc strain gauge simulator type 1550A, while line calibration for the PT100 Wahl calibrator type TRC-82B has been used.

3. COUPON DIMENSIONS AND PREPARATION

Composite material coupons in final dimensions, including the tabs, were delivered by LM. Specimen dimensions for the UD coupons are given in Fig. 1 according to [1]. Plate lamination sequence for the UD coupons was $[0_4]$, as given in [1], where layer of 0° stands for the Unidirectional reinforcement material 1258gr/m^2 , while specifications for the material layer are given in [2]. It is noted that the 0° 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 are also shown for comparison purposes.

Table 1 CRES test program

<i>Test case</i>	<i>Coupon Type</i>	<i>Type of load</i>	<i>Max. Load (kN)</i>	<i>Number of coupons</i>
1	GEV206-R0300	Fatigue, R=-1	28	1
2	GEV206-R0300	Fatigue, R=-1	25	3
3	GEV206-R0300	Fatigue, R=-1	20	3
4	GEV206-R0300	Fatigue, R=-1	17	3

All specimens were equipped with single strain gauges back to back measuring strain in the load direction.

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.

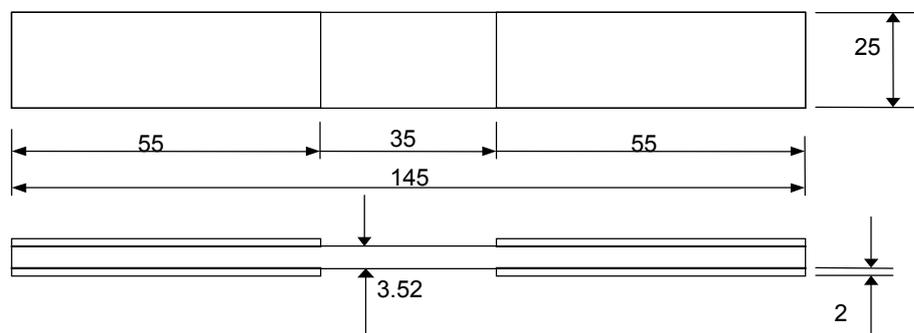


Fig. 1 Coupon dimensions for the GEV206-R0300



Table 2 Specimen dimensions

<i>Specimen No</i>	<i>Thickness (mm)</i>	<i>Width (mm)</i>	<i>Area (mm²)</i>
GEV206-R0300-0265	3.66	24.79	90.83
GEV206-R0300-0266	3.73	24.80	92.45
GEV206-R0300-0267	3.68	24.75	91.13
GEV206-R0300-0268	3.66	24.76	90.59
GEV206-R0300-0270	3.73	24.80	92.55
GEV206-R0300-0271	3.66	25.07	91.66
GEV206-R0300-0272	3.72	24.78	92.23
GEV206-R0300-0273	3.74	24.75	92.57
GEV206-R0300-0274	3.65	24.82	90.59
GEV206-R0300-0078	3.71	25.25	93.75
<i>Mean value</i>	<i>3.69</i>	<i>24.86</i>	<i>91.84</i>
<i>COV (%)</i>	<i>0.96</i>	<i>0.67</i>	<i>1.14</i>

4. TESTING PROCEDURES

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 [3]. 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 $500\mu\epsilon$ for any coupon. However, some bending strains were exhibited, which are an indication of an initially slightly curved surface of the coupons, as already discussed for coupons tested under static loading [4].

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.

Fatigue tests were performed under load control, with test frequency ranging from 0.9 to 4.5Hz, depending on the stress (strain) level. Strain was recorded using two single strain gauge attached on the central area of the coupons, one on each face. Moreover, a PT100 temperature sensor was attached near the tab of the lower grip to monitor any significant temperature rise in a number of coupons. During the whole test, applied force, actuator's displacement, as well as strain measurements by the strain gauges were continuously monitored with a sampling frequency of 16Hz, while the environmental conditions (room temperature, relative humidity and atmospheric pressure), as well as the temperature from the PT100 were monitored at 1Hz. Fig. 2 presents a picture of the coupon testing set-up.

It should be noted, however that strain gauge readings were lost early during the fatigue experiments, due to failure of the strain gauges attached on each specimen. Problems with temperature measurements with PT100 sensors, which were detached from the specimen probably due to failure of the glue after some cycles, were also observed. Therefore, since by the procedure followed one could not assure that the PT100 sensors would remain attached on the specimens for the whole duration of the fatigue test, thus measuring the exhibited temperature rise, it was decided to lower the testing frequency and skip the temperature measurements. Testing frequencies were reported in [3] and these were used as reference. Moreover, the effectiveness of the use of PT100 sensors for the specimen internal temperature increase measurement due to fatigue loading was questioned in [5], along with the method of forced cooling of the specimen by a fan during testing. Since at the time of testing air temperature inside the laboratory was above 30°C it was decided that the lower testing frequencies were necessary in order to produce results comparable to the other laboratories within the OPTIMAT BLADES project.

Apart for the initial stiffness of each specimen, stiffness was derived as the slope of the curve of the actuator displacement versus the applied load, measured from the machine load cell during the whole test.

At the beginning of each fatigue test 2 slow cycles were applied with the same amplitude and mean value for the load as for the rest of the experiment, but at a frequency of 0.02Hz for the measurement of the initial stiffness. After these 2 cycles the test continued immediately with the selected test frequency according to the applied stress level. In order to monitor the stiffness change during the test the slow fatigue cycles were repeated after a predefined number of cycles, e.g. every 10,000 cycles for tests targeting more than 100,000 cycles.

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 $500\mu\epsilon$ and $2500\mu\epsilon$, as described in ISO 527-1 [7] and ISO 14126 [9] for tests in tension and compression, respectively (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. 2 Setup of the coupon tests

Bending strains during testing were also monitored in the beginning of the fatigue test by use of the back to back strain gauge readings. For tests in compression according to ISO 14126 [9] 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:

$$\left| \frac{\epsilon_b - \epsilon_a}{\epsilon_b + \epsilon_a} \right| * 100 \leq 10\% \quad (1)$$

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 [6] 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:

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

while the measurement was taken when the axial strain was about $1500\mu\epsilon$.

5. RESULTS

5.1. Fatigue tests at R=-1

In total 10 fatigue tests have been performed at R=-1. Most coupons failed at their end tab, in tension, while part of the coupon between the tabs was torn out from the grip. A characteristic picture of a coupon after failure is shown in Fig. 3.

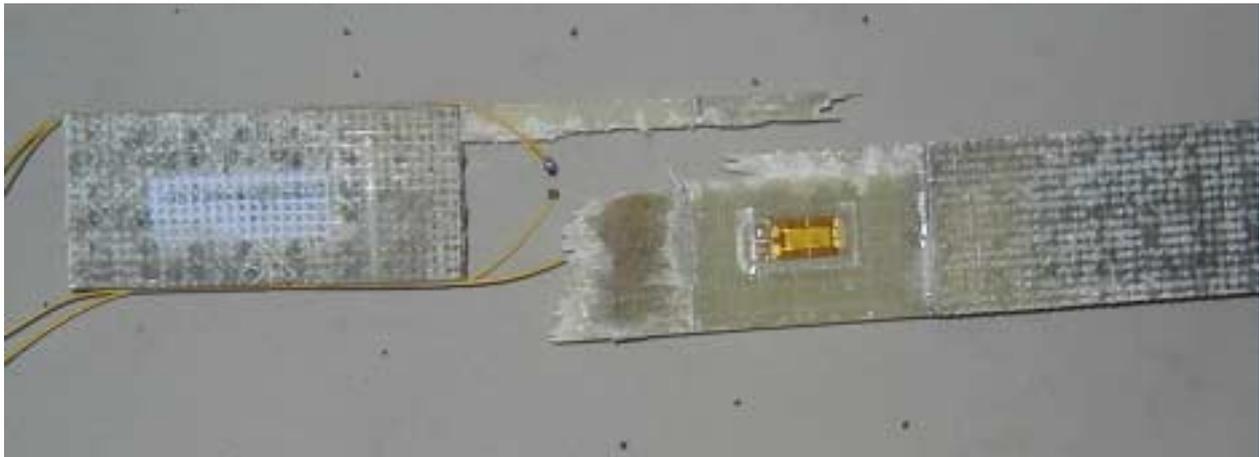


Fig. 3 Coupon GEV206-R0300-0273 after failure

Measurements were focused on the displacement and strain exhibited by the specimen during the fatigue loading at constant force (stress) amplitude and mean value. In Table 3 fatigue test data are collectively shown. Maximum stress value refers to the absolute maximum value of the stress recorded during the initial slow cycles. The corresponding strain recorded as the average of the two back-to-back strain gauges is given in the 4th column of the table. The bending as a percentage of the axial strain exhibited on the table corresponds to the bending recorded at the minimum load during the two initial slow cycles. Therefore, it can be seen that at least during the initial testing face no coupons exceeds the 10% bending limit set during the compression phase.

Table 3 Summary of fatigue tests conducted at R=-1

Specimen #	Load (kN)	Max. Stress (MPa)	Initial Max. Strain ($\mu\epsilon$)	Frequency (Hz)	Bending (%)	Cycles to failure
GEV206-R0300-0265	± 20.00	221.0	5569	2.25	6.600	433,521
GEV206-R0300-0266	± 17.00	185.1	4658	4.32	5.148	1,502,047
GEV206-R0300-0267	± 20.00	220.5	5513	2.25	7.502	479,546
GEV206-R0300-0268	± 28.00	309.8	7731	0.90	4.895	41,581
GEV206-R0300-0270	± 17.00	184.7	4783	3.00	2.032	1,063,405
GEV206-R0300-0271	± 20.00	219.0	5668	2.25	0.118	422,882
GEV206-R0300-0272	± 17.00	185.5	4763	3.00	2.513	1,307,035
GEV206-R0300-0273	± 25.00	270.7	6995	1.20	0.273	62,149
GEV206-R0300-0274	± 25.00	276.8	7005	1.20	1.410	76,709
GEV206-R0300-0078	± 25.00	268.2	7065	1.00	0.901	63,605

In Table 4 the 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. 4 presents the stress-strain response during the initial two loading cycles, part of which was also used according to ISO 527-5 [6] in tension and ISO 14126 [9] in compression for the derivation of elasticity modulus, as an example for two specimens with strain measured as the average of the two strain gauge readings on each coupon. The difference of the elasticity modulus determined by the two back-to-back coupons on each specimen seems to have a positive relationship to the bending strains observed during testing. The advantage of using the back to back configuration, apart from reassuring that no bending strains are imposed on the coupons, at least during the early stages of the experiments, is that the elasticity modulus can be determined giving a lesser coefficient of variation. In other words, the uncertainties involved in the elasticity modulus measurement are reduced by use of the two strain gauges. 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. The mean value and the coefficient of variation (COV) for the measured and estimated properties are also shown in this table.

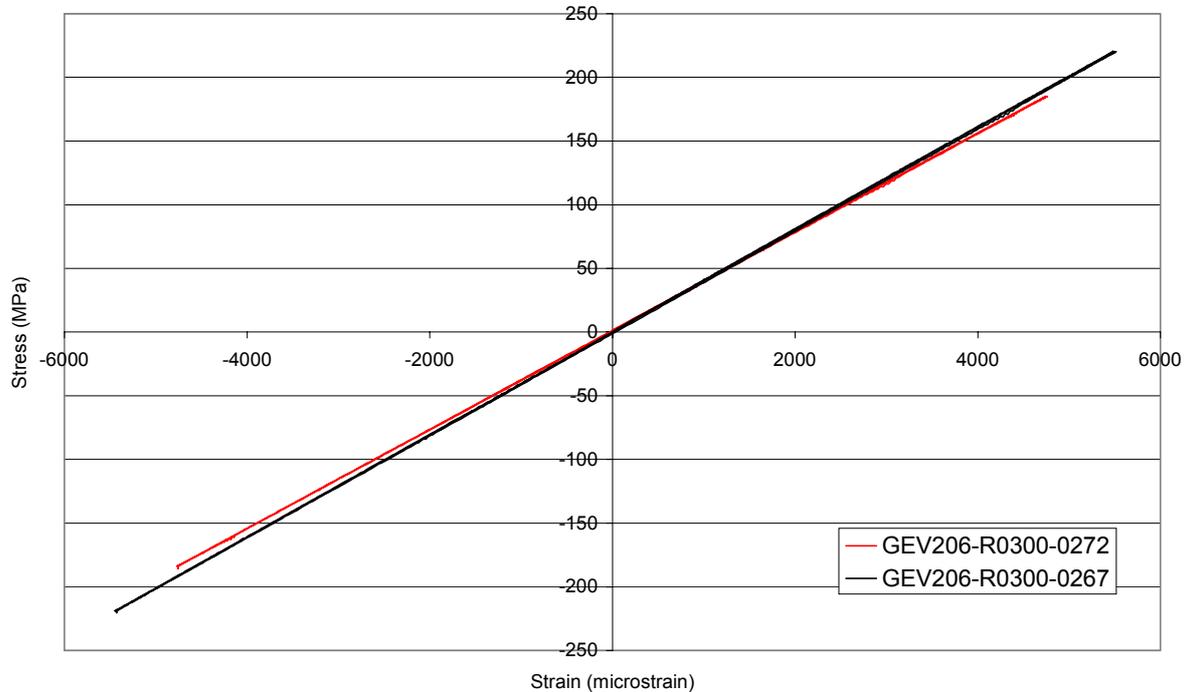


Fig. 4 Example of stress-strain curves during the initial slow cycles for two coupons

Table 4 Experimentally derived values of modulus of elasticity

Specimen #	<i>E</i> -modulus Tension (GPa)				<i>E</i> -modulus Compression (GPa)			
	E-1	E-2	E-ave	R ²	E-1	E-2	E-ave	R ²
GEV206-R0300-0265	38.85	40.82	39.91	0.9999	37.72	41.98	39.67	0.9991
GEV206-R0300-0266	41.26	37.95	39.59	0.9998	41.60	37.82	39.62	0.9999
GEV206-R0300-0267	42.06	38.85	40.24	0.9998	43.06	38.23	40.29	0.9995
GEV206-R0300-0268	39.08	41.64	40.42	0.9996	38.72	41.76	40.27	0.9999
GEV206-R0300-0270	38.66	39.69	39.23	0.9998	38.59	40.18	39.20	0.9998
GEV206-R0300-0271	38.64	39.45	38.93	0.9993	38.49	39.05	38.67	0.9979
GEV206-R0300-0272	39.17	38.97	38.82	0.9997	38.74	38.74	38.73	0.9999
GEV206-R0300-0273	39.20	39.01	39.25	0.9991	39.50	39.26	39.27	0.9969
GEV206-R0300-0274	40.18	39.44	39.99	0.9996	40.31	39.78	39.91	0.9970
GEV206-R0300-0078	38.31	38.67	38.64	0.9985	38.65	38.88	38.70	0.9974
<i>Mean value</i>	<i>39.54</i>	<i>39.45</i>	<i>39.49</i>		<i>39.54</i>	<i>39.57</i>	<i>39.42</i>	
<i>COV (%)</i>	<i>3.13</i>	<i>2.72</i>	<i>1.53</i>		<i>4.19</i>	<i>3.52</i>	<i>1.54</i>	

Fig. 5 presents the bending strain exhibited by coupon GEV206-R0300-0267 during the compression part of the first slow cycle. It is clearly seen that the smaller the applied stress the larger the bending strain exhibited. It should be noted that the largest bending strains recorded during the fatigue testing campaign were for this coupon.

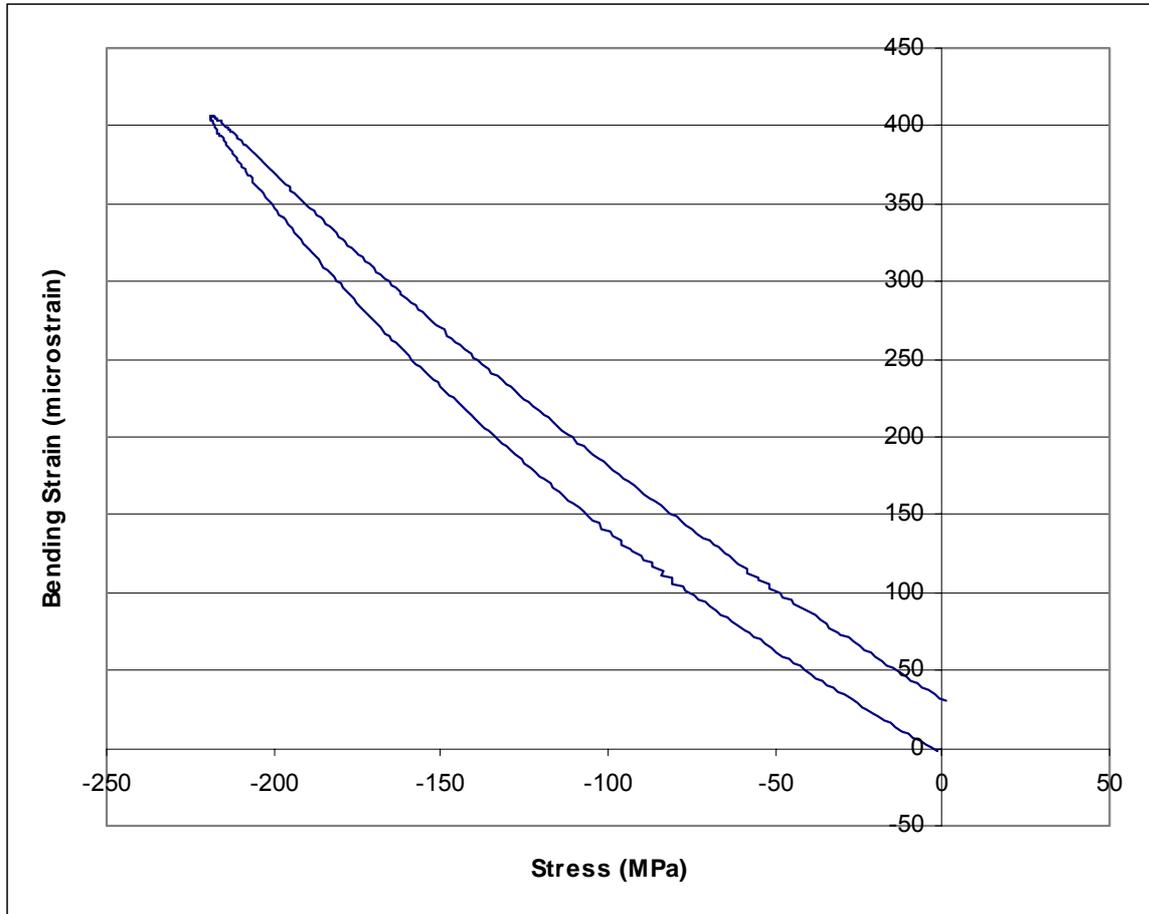


Fig. 5 Bending strain during the initial cycle (compression part) for coupon GEV206-R0300-0267

Since the strain gauges failed during the early stages of the fatigue test, stiffness was also calculated as the slope of the force versus displacement response during the slow cycles. This enables the monitoring of stiffness reduction during the fatigue test. Results for the stiffness reduction during the fatigue test are given for all tests in Fig. 6, while it should be noted that stiffness reduction is expressed relative to the initial stiffness value, i.e. starting from an initial level of 100% at the initial cycling.

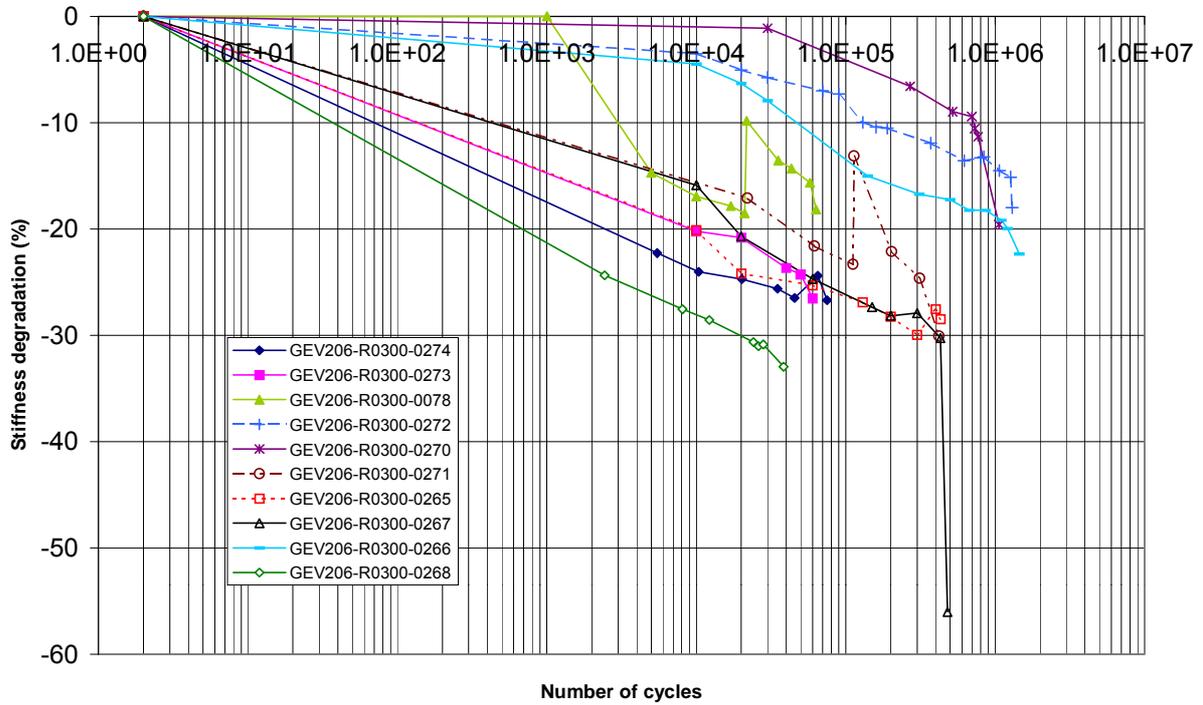


Fig. 6 Stiffness reduction with respect to number of fatigue cycles

6. CONCLUSIONS

Results of fatigue coupon tests with respect to their initial stiffness (elasticity modulus measurements) were found in good agreement with the static test results reported in [4], giving in tension a mean value of 39.5 GPa and in compression 39.4 GPa with a coefficient of variation of 1.5% for both tension and compression results.

Fatigue results of UD coupon tests are plotted in strain versus number of cycles to failure (ϵ_N)-graphs in Fig. 7 for R=-1 tests, while the respective stress versus number of cycles to failure (SN)-graph is shown in Fig. 8. It should be noted, that the experiments were conducted at constant force (stress), thus, the strain range presented in Fig. 7 is the initial one. Furthermore, the stress range shown in Fig. 8 is derived by dividing the applied force range by the section area, as calculated by measurements of the initial thickness and width of each specimen.

The logarithmic regression fit of maximum strain versus number of cycles to failure (ϵ_N) curve is given by:

$$\epsilon_a = -807.98 \ln(N) + 16089$$

where ϵ_a denotes the initial maximum exhibited strain measured in microstrain and N the number of cycles to failure, while the corresponding coefficient of determination, R^2 , is 0.9902.

The corresponding logarithmic regression fit of maximum stress versus number of cycles to failure is given by:

$$\sigma_a = -31.481 \ln(N) + 628.2$$

where σ_a denotes the maximum stress measured in MPa. The corresponding coefficient of determination, R^2 , is equal to 0.9662.

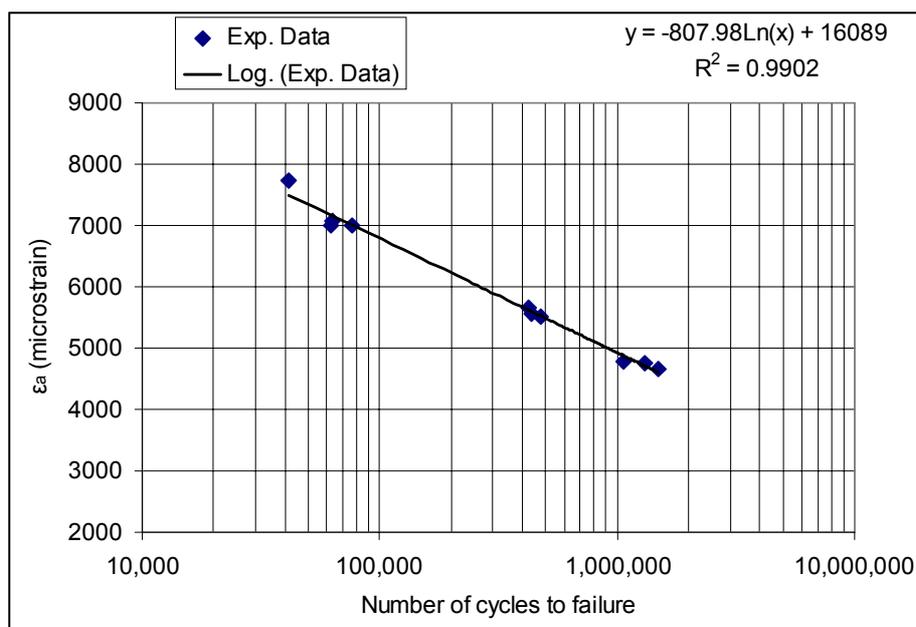


Fig. 7 Initial maximum strain versus cycles to failure

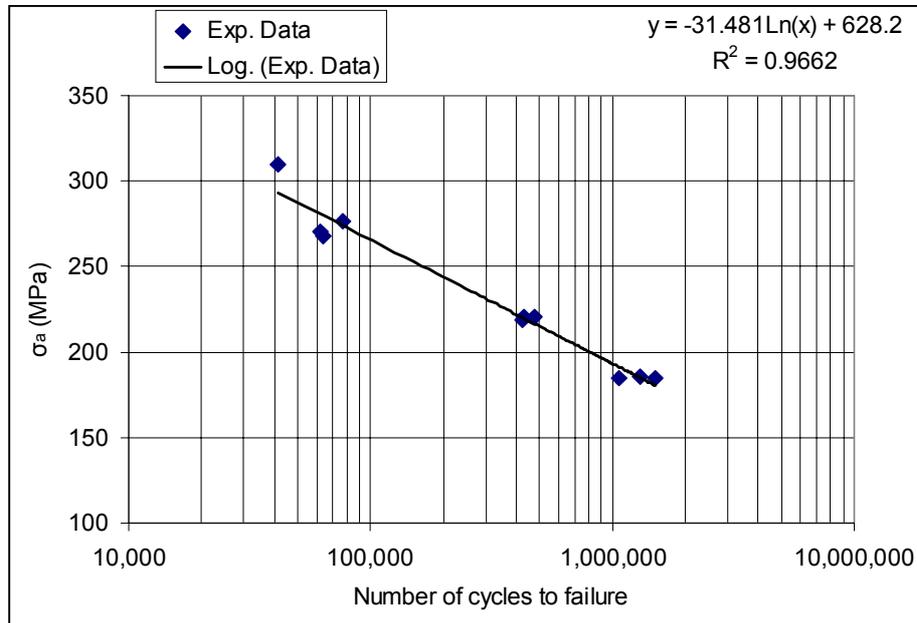


Fig. 8 Maximum stress versus cycles to failure

When comparing the obtained fatigue results for the UD coupons at $R=-1$ with results from other testing institutes within the OPTIMAT BLADES project, e.g. results from University of Patras [3], it is seen that the S-N curve is higher. This is probably the result of testing under different testing frequency, as for the current fatigue tests lower frequencies have been used than the ones reported in [3]. The important effect of testing frequency has been already discussed within the framework of the OPTIMAT BLADES project, with the aim of both producing reliable fatigue results and optimizing time needed for conducting the tests of the composite material coupons. The last recommendations for testing speeds were outlined in [3], however, each testing institute had to combine the recommendations with the available testing facility environment, so that the temperature of each fatigued coupons should not exceed 35°C. Therefore, it was decided that at CRES lower testing frequencies than those recommended should be used.



7. REFERENCES

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