Fatigue of long reference and repaired MD specimens -WMC results-

OB_TG4_R012 rev. 000
doc.no. 10324

Confidential

OPTIMAT BLADES

TG 4

January 2006,

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Change record

Issue/revision	date	pages	Summary of changes
draft	Nov. 2005		draft (sent to CRES)
version 000	Jan 4th, 2006	11	initial version

1 Introduction

This document contains the results of fatigue tests on long reference, and repaired specimens carried out at the materials laboratory of WMC, according to the DPA of TG4 [1]. The tests were carried out in September 2005-January 2006. Specimens were manufactured by GAMESA and LM, and tested by CRES and WMC. Results of the static tests on reference and repaired specimens are found in [2] (GAMESA, tested at CRES) and [3, 4, 5] (LM, tested at WMC). General information on repair of composites, including experimental and theoretical observations, can be found in [6].

2 Specimens and Test Set-up

Specimen general geometries can be found in OptiDAT [7]. Original specimen definition was reported in [1], and [8], but significant modifications have been made for most of the specimens described herein, so these documents are no longer up to date. This is due to the fact that the repair geometries were defined by the industrial partners in a later stage of the OPTIMAT project, in order to best reflect the state-of-the art.
The repair method was ‘scarf repair’ for all repaired specimens tested at WMC, albeit with different slopes and repair depths (‘plug-and-patch’ repairs were tested by CRES). Scarf repair is a repair type where the edges of a damaged section are abraded at a certain slope and depth, and filled with new material. In the static test programme, several combinations of slope and repair depth have been explored, from which 2 candidates were chosen for the fatigue tests. These are the specimens with 1:50 slope, at repair depths of 1/3 and 2/3 of specimen thickness.

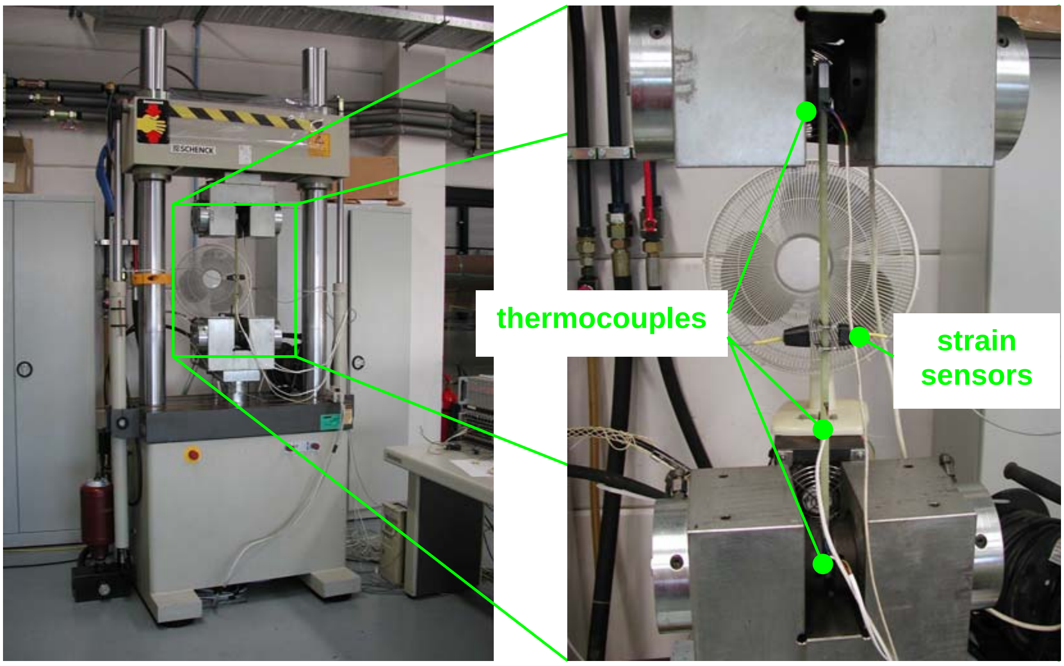


Figure 1: 400 kN Schenck test frame

All coupons were tested on the 400 kN Schenck load frame of WMC. Figure 1 shows a picture of the test set-up. The strains/moduli were measured using a back-to-back configuration of both strain gauges and clip gauges.
Because of the excessive length of the coupons, the specimens were equipped with three thermal sensors; one at each tab, and one in the middle near the strain sensors. Three fans were installed to ensure constant air flow around the entire length of the specimen.
The fatigue test was preceeded by a slow cycle at R=0.1 and 0.02 Hz, for detailed strain measurement and frame calibration. During the fatigue test, periodic records were created of force, displacement, strain ranges, and temperatures. See for an example the Appendix.
Grip pressure was 160 bar throughout the test. Test loads and frequencies were copied from the standard OB test levels as defined in [9]. For the specimens that were tested at the load level corresponding to a nominal life of (in excess of) 10^7 cycles (level 4), the frequency of level 3 (10^6 cycles) was used. For some repair types, lower loads were ocassionally applied than level 4.

3 Test results

In total, 49 coupons were tested. The test results are summarised in the project database, OptiDAT [7]. The results are tabulated in Table 1.

Table 1: Results of fatigue tests on long specimens

Repair type	Name	w	t	F_{max}	σ_{max}	N	Remarks
Unrepaired	***GEV207_S0300_0002***	25.85	6.435	33.84	203	119300	
	GEV207_S0300_0003	25.43	6.39	44.98	277	10873	
	GEV207_S0300_0004	25.58	6.425	33.49	204	106078	
	GEV207_S0300_0006	25.58	6.45	45.24	274	11053	
	GEV207_S0300_0007	25.8	6.33	57.5	352	2193	
	GEV207_S0300_0010	25.9	6.485	45.81	273	10838	
	GEV207_S0300_0013	25.83	6.51	45.68	272	9241	
	GEV207_S0300_0016	25.61	6.375	57.08	350	1972	
	GEV207_S0300_0014	25.57	6.56	20	119	10549401	runout
	GEV207_S0300_0017	25.74	6.495	33.7	202	111818	
	GEV207_S0300_0019	25.13	6.575	56.01	339	2151	
	GEV207_S0300_0025	25.21	6.36	26.19	163	1334485	
	GEV207_S0300_0026	25.22	6.49	26.2	160	1524481	
	GEV207_S0300_0027	25.24	6.51	26.22	160	1372317	
	GEV207_S0300_0032	25.21	6.365	33	206	165953	
	GEV207_S0300_0033	25.32	6.48	44.78	273	10502	
	GEV207_S0300_0034	25.38	6.485	33.23	202	49736	
	GEV207_S0300_0035	25.33	6.445	56.45	346	1540	
	GEV207_S0300_0036	25.14	6.465	44.46	274	8249	
	GEV207_S0300_0050	25.19	6.37	56.14	350	2225	
	GEV207_S0300_0051	25.26	6.385	33.07	205	117709	
	GEV207_S0300_0052	25.21	6.36	56.19	350	1944	
	GEV207_S0300_0053	25.22	6.345	33.02	206	133890	
1:50, 1/3	***GEV207_S3100_0007***	25.46	7.42	45.03	238	4364	
	GEV207_S3100_0008	25.44	7.34	26.43	142	510509	
	GEV207_S3100_0009	25.49	7.45	45.08	237	4093	
	GEV207_S3100_0001	25.35	6.63	33.19	197	55332	
	GEV207_S3100_0002	25.23	6.78	33.03	193	11136	Invalid
	GEV207_S3100_0003	25.37	7.43	33.21	176	102220	
	GEV207_S3100_0004	25.45	7.41	26.44	140	495304	
	GEV207_S3100_0005	25.42	7.42	26.41	140	385178	
	GEV207_S3100_0006	25.37	7.34	33.21	178	72780	
	GEV207_S3100_0016	24.31	7.48	43	236	1032	
	GEV207_S3100_0017	25.4	7.4	44.94	239	4959	
	GEV207_S3100_0019	25.36	7.4	44.85	239	5197	
	GEV207_S3100_0018	25.4	7.36	26.39	141	473897	
1:50, 2/3	***GEV207_S3200_0001***	24.55	6.4	25.5	162	37861	
	GEV207_S3200_0002	24.7	6.35	25.66	164	164550	
	GEV207_S3200_0003	24.83	6.47	21.96	137	27424	
	GEV207_S3200_0004	24.73	6.49	16.19	101	3280434	
	GEV207_S3200_0005	24.28	6.49	31.79	202	3668	
	GEV207_S3200_0016	25.2	6.11	32.99	214	1930	
	GEV207_S3200_0017	24.58	6.38	25.54	163	44057	
	GEV207_S3200_0018	24.45	6.51	16	101	6229685	
	GEV207_S3200_0019	25.56	6.43	26.55	162	27556	
	GEV207_S3200_0020	25.24	6.57	33.04	199	5229	
	GEV207_S3200_0023	25.65	6.27	45.36	282	669	
	GEV207_S3200_0024	24.82	6.38	25.79	163	28295	
	GEV207_S3200_0015	24.41	6.49	25.36	160	37642	

For the SN –curves, see figures 2-4.

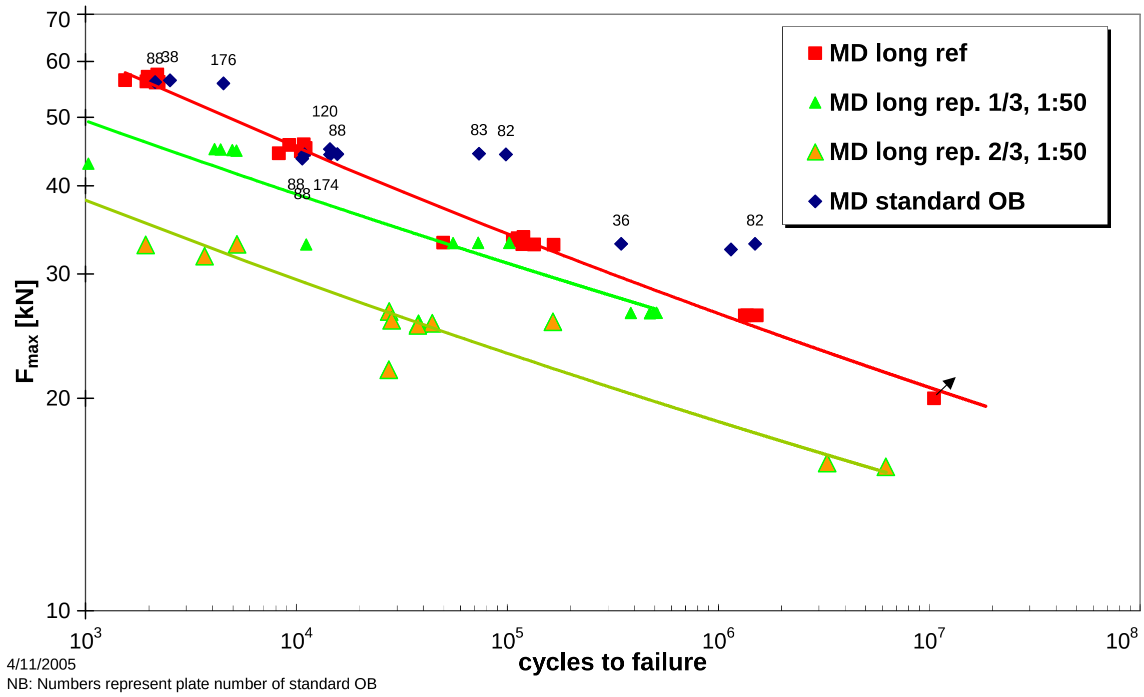


Figure 2: Fatigue comparison of standard OB, long reference and two repair types

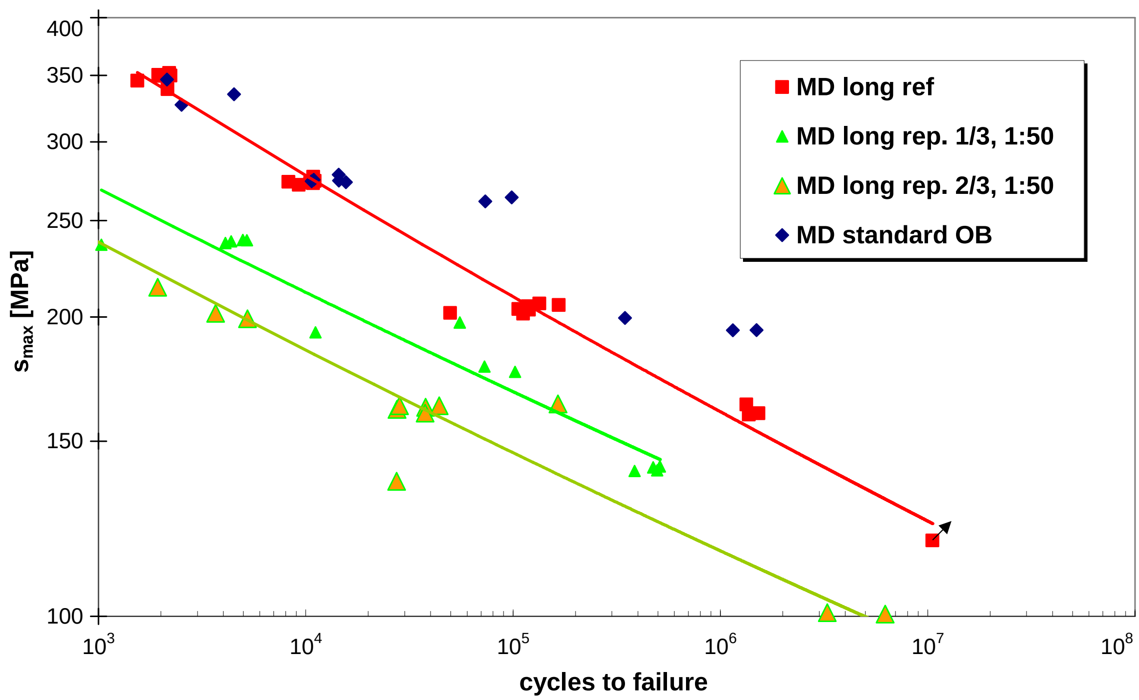


Figure 3: SN data, based on full cross sectional stress

Apparently, the long reference specimens generally have slightly shorter lives than the standard OB specimens in the high-cycle range. This is surprising, since the long gauge length is likely to lead to a more benign load introduction than in the standard OB specimens.

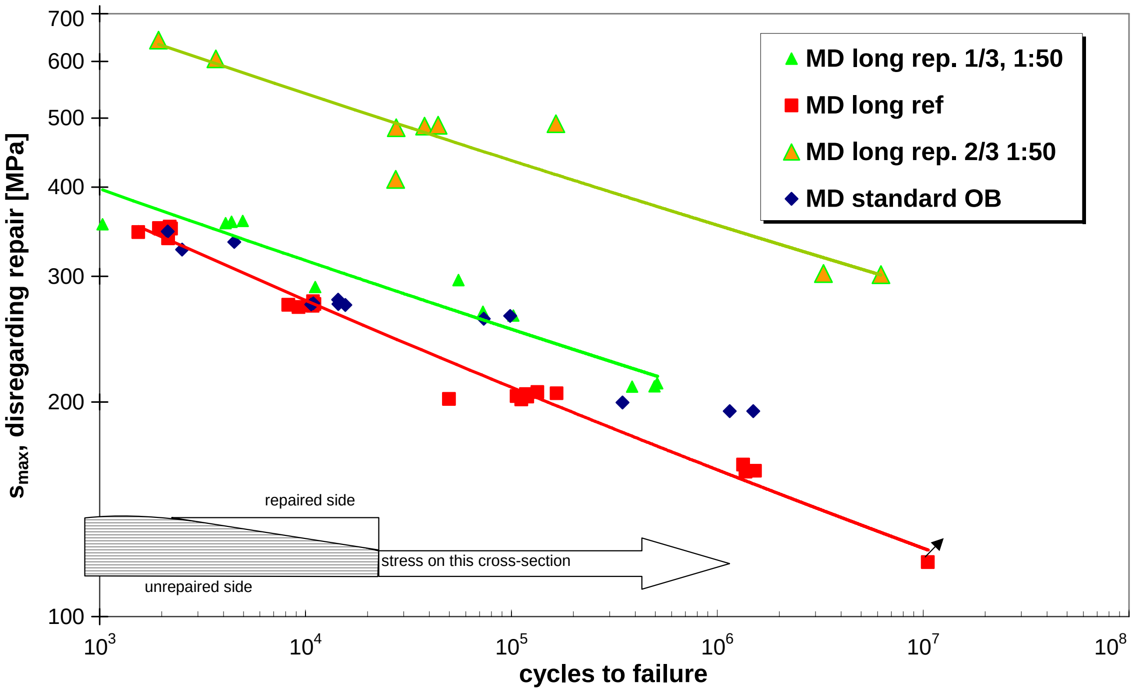


Figure 4: SN-curves, based on the stress in the unrepaired part of the cross section, assuming the repair does not carry any load

Furthermore, the 2/3 repair depth has significantly shorter fatigue lives than the 1/3 repair depth, when compared in terms of load. From the difference in slope, the difference in fatigue lives seems to diminish for low loads, converging to the unrepaired fatigue life for at least the 1/3 repair depth.
The S-N data are also plotted in terms of full cross-sectional stresses (figure 3), showing more clearly the different performance of unrepaired vs the different repair types. If the repair would be assumed not to contribute to any of the load transfer, the S-N curve can be plotted in terms of the stress in the unrepaired part of the cross-section. This amounts to multiplying the cross-sectional stress of figure 3 with 1.5 for the 1/3 repair (since only 67% of the cross section is assumed to carry load) and with 3 for the 2/3 repair (since only 33% of the cross section is assumed to carry load). This is done in figure 4, which shows, that the repair actually must be carrying some of the load. This is especially evident in the 2/3 repair depth case, where the S-N performance of the unrepaired part of the specimen is significantly enhanced by the presence of the repair material. In a sense, one could argue, that this makes the 2/3 repair depth the best performing repair type, as it is capable of significantly enhancing the stress-bearing capacity of the remaining cross-section. Nevertheless, the most honest basis for comparison is probably maximum load vs number of cycles, i.e. figure 2.
Moduli are reported from the strain gauges, where available (the clip gauges tended to tilt due to bending, giving exaggerated strain readings). See figure 5. The averages of the back-to-back moduli was roughly equal for all coupons, viz. 27 GPa. However, for the repaired specimens, a discrepancy between back-to-back moduli existed. The modulus of the repaired side was generally lower than that of the unrepaired side for the S31 specimens (1:50, 1/3 repair depth). For the 2/3 repair depth, the difference in back-to-back modulus was significantly smaller, although still slightly higher than for the reference specimens. In general, bending was higher for S31 than for S32. This is surprising, since the larger repair depth could be expected to show larger bending strains because of the larger mismatch in back-to-back moduli.

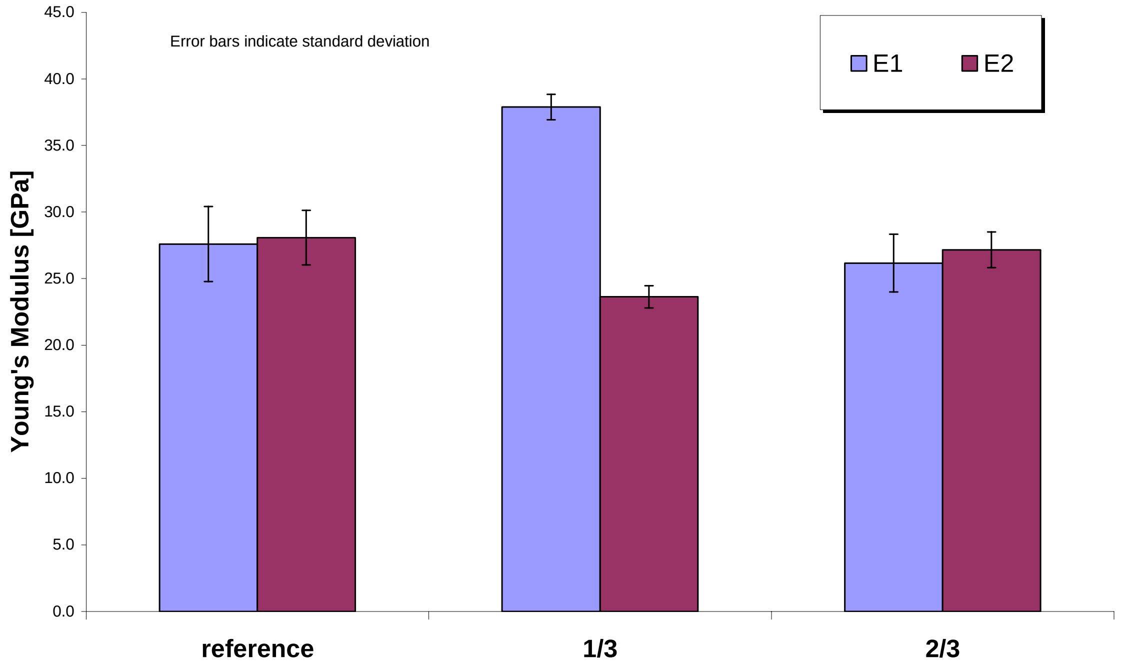


Figure 5: Modulus measurements from strain gauges E_1 (front) and E_2 (back)

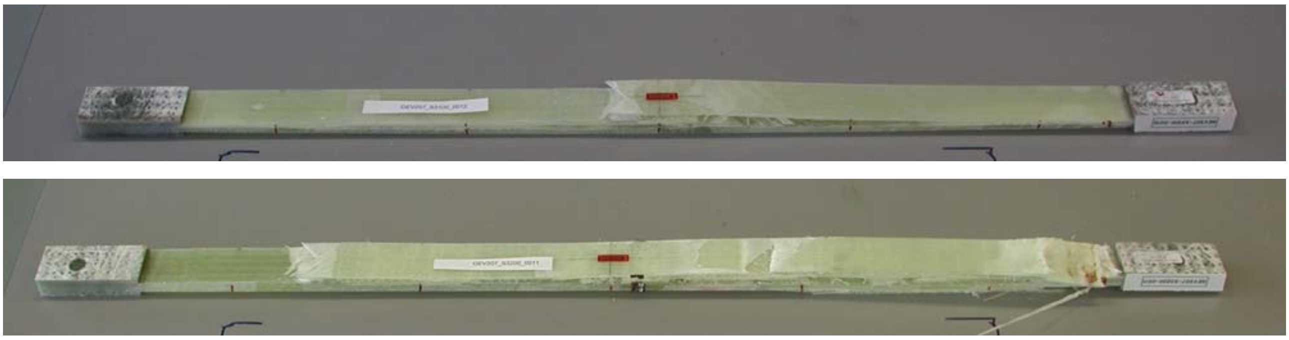


Figure 6: Typical failure modes for 1/3 repair (top) and 2/3 repair (bottom)

The 1/3 repair depths had shorter repair lengths, and thus failed closer to the center of the coupon. Typically, the 2/3 repairs failed further away from the specimen center. Typical failure modes are shown in figure 6.
It should be mentioned, that according to the ‘Delivery’ list in Optidat [7], which gives information on the plate numbers etc., a new batch of resin was used for the S32 repair type.

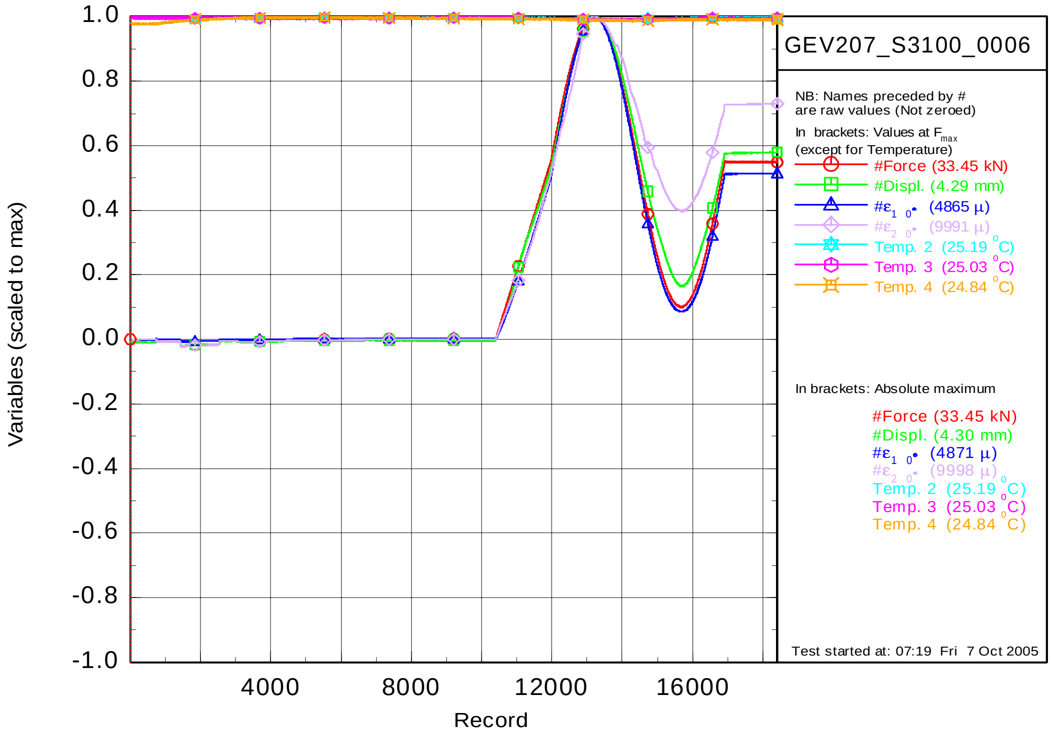
4 Concluding remarks

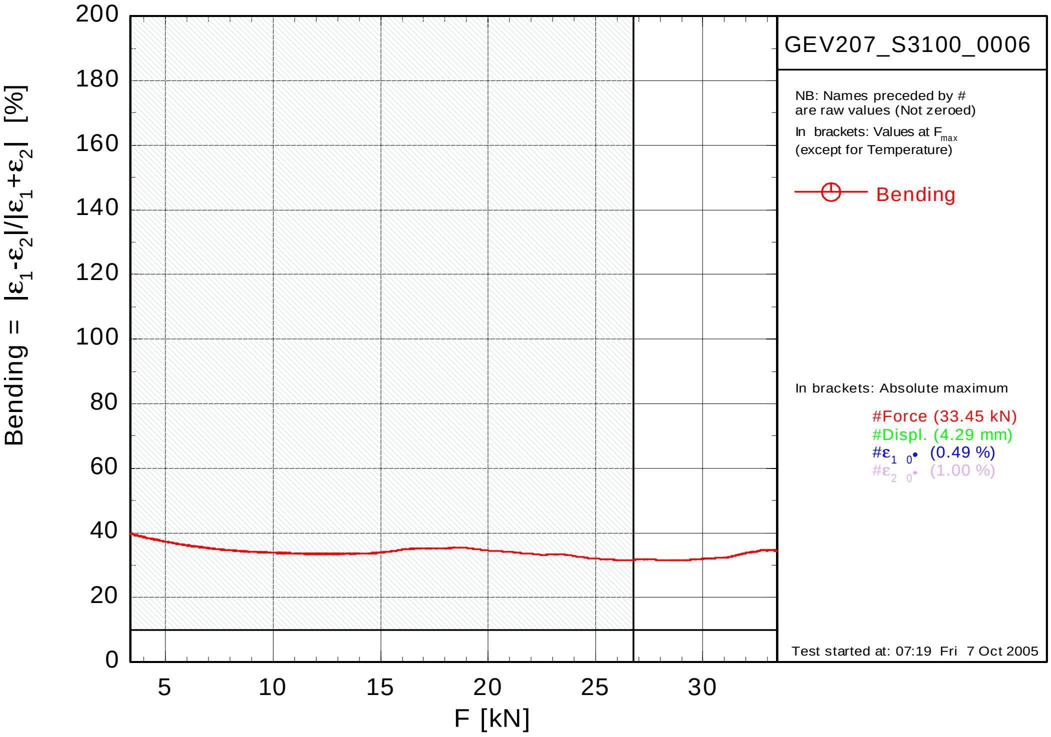
Fatigue performance of the long reference specimens seemed to be slightly inferior to the performance of MD specimens with the standard geometry. This is in contradiction with the expectation, that the longer gauge lengths lead to more benign load introduction and thus better performance in fatigue. This may be, however, a plate-to-plate, or machine-to-machine influence.
Another surprise was, that the 1/3 coupons showed greater discrepancy in back-to-back strains than the 2/3 specimens.

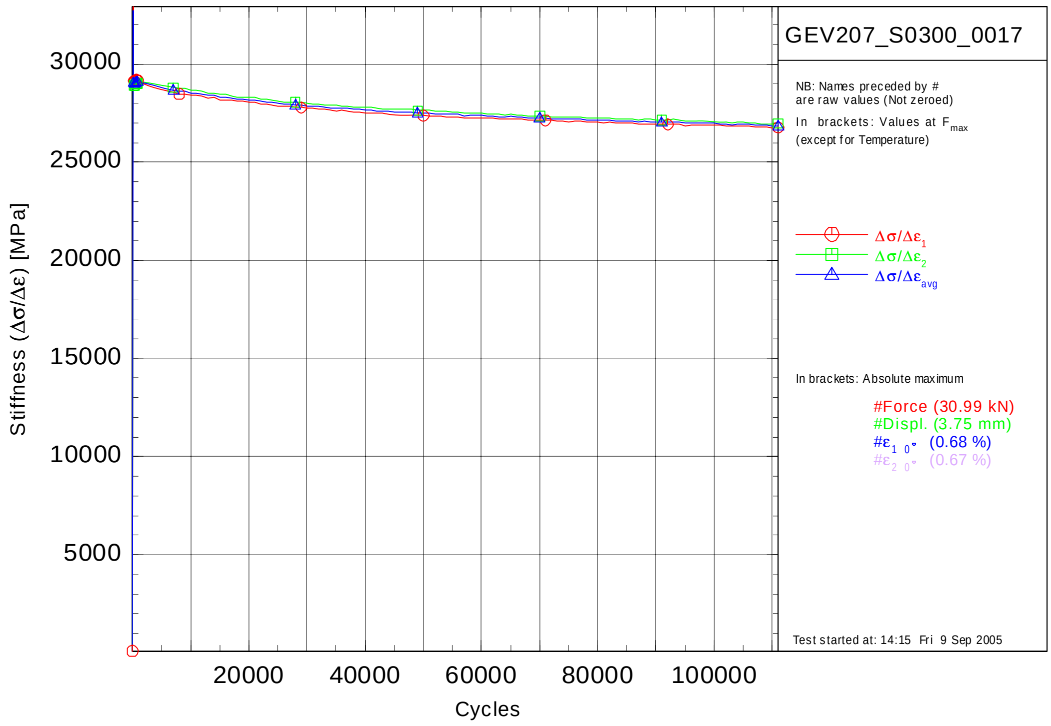
Summarising, the 1/3 repair depth gives the best agreement with fatigue performance of the reference specimens. The 2/3 repair depth specimens are able to carry a significantly lower load in fatigue. The difference between repair types is expected to diminish for very low load levels, as the SN-curve slope decreases for larger repair depth.

Appendix

Example of various measurement during initial slow cycle and of stiffness degradation measurements during fatigue test. The deviating strain measurement in the first picture indicates, that the repair may have disbonded during the first slow cycle already.






GEV207_S0300_0017
NB: Names preceded by # are raw values (Not zeroed)
In brackets: Values at F_{max} (except for Temperature)
$\Delta\sigma/\Delta\varepsilon_1$
$\Delta\sigma/\Delta\varepsilon_2$
$\Delta\sigma/\Delta\varepsilon_{avg}$
In brackets: Absolute maximum
#Force (30.99 kN)
#Displ. (3.75 mm)
#ε1 0° (0.68 %)
#ε2 0° (0.67 %)
Test started at: 14:15 Fri 9 Sep 2005
Stiffness (Δσ/Δε) [MPa]
30000
25000
20000
15000
10000
5000
20000
40000
60000
80000
100000
Cycles

References

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