OptiDAT data summary
-strength and life of standard OB specimens-

OB_TG1_R022 rev. 004 (final)
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OPTIMAT BLADES

TG1

Rogier Nijssen
Denja Lekou
Arno van Wingerde

Change record

Issue/revision	date	pages	Summary of changes
draft (000)	June 14, 2005	28	
revision 001	July 11, 2005	28	corrected data of CRES, correction initiated by Denja's e-mail of july 1st, 2005
revision 002	dec 9th, 2005	40	added limited stiffness data
			revised/updated all tables and plots
			slightly expanded sections on plate-to-plate variations
revision 003	february 2006	42	added iso geometries to static table and updated table 1 added S-N curves including dogbone geometries for comparison of ISO vs OB fatigue performance, moved modulus data to table 1
revision 004 (final)	June 19th, 2006	48	Added results for phase II material in fatigue Added Vf influence on fatigue life Delete complex and not very useful table with detailed static data Updated all figures and tables with latest data from OptiDAT

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1. Introduction

This document contains a general description of the most important data gathered in the OptiDAT-database. It contains a summary of the static strength data and a description of fatigue lives.
This overview is an addition to the various reports on static strength and fatigue produced to date. The detailed description provided here is useful in comparison of coupon performance in non-standard conditions (e.g. TG3 Extreme Conditions), and can serve as a basis for the residual strength and spectrum fatigue analysis of TG5 and TG1.

2. Static strength

Static strength has been described extensively in earlier reports, for example see [1] for static tests on UD and MD performed at DLR, [2] for benchmark static and fatigue tests on UD at DLR, [3] for those at UP, and [4] for phase I tensile and R=-1 fatigue tests from UP, [5] for static benchmark tests at VUB, [6] for static benchmark tests carried out at CRES, [7-8] for the static tests carried out at (CCLRC/RAL), [9] for an overview of preliminary tests.
For comparison of static results to non-OPTIMAT-standard geometries, refer to [10] for the results of static tests on ISO-geometries, [11] for a comparison with off-axis strength, and [12] for the results of static tests on long and repaired specimens.

In Table 1, a summary is given of all static tests from OptiDAT up to June 2006. This table contains more static strength data than were foreseen in the DPA, since data from the preliminary programmes are included. Static tests were carried out by different laboratories for different task groups. Most were strengths measured for the standard specimens at room temperature, and a grip displacement rate of 1 mm/min for compressive tests, and 0.25 mm/min for tensile tests. In practice, the database contains records with loading rates varying between 0.25 – 5 mm/min.

The table shows the tensile and compressive strengths for the standard OB UD2 and MD2 laminates. Various geometries are included, mainly the standard geometries R0300 and R0400 are shown. Mean, standard deviation, and number of tests are shown. Also, the initial tensile and compressive moduli E_{it} and E_{ic} are included, as well as the strains at failure (where available).

Some static tests were done in the framework of TG3 (Extreme Conditions). In these tests, the load was applied using a so-called LUR sequence, which stands for loading-unloading-reloading. This means, that the load was increased up to a predefined value, then released, and subsequently increased to a higher level than the previous step. In other words, the load was not applied as a ramp, but the waveform followed an increasing saw-tooth pattern (e.g. 10). The static strengths for these tests were slightly lower than for the single-ramp (‘loading’) load pattern. Therefore, the lines inTable 1 show values including these LUR tests by default. Where the values excluding LUR-tests are significantly different, the data are shown excluding the LUR tests (excl. LUR).

From Table 1 it is seen, that the scatter (indicated by standard deviation σ) in static strengths (mean static strength indicated by μ) seems largest for the UD material in compression, and larger for compressive strength than for tensile strength. A σ/μ of 5% is a good estimate of minimum scatter in most cases.

When compared to ISO coupons, the performance of the standard OPTIMAT is worst for compression of the UD laminate (ca. 30% smaller compressive strength), although the scatter in the results is comparable. Tensile strength is almost equal.
For cases other than compression, there is no indication that the ISO coupons give better material properties than the OPTIMAT standard.

Table 1: Summary of static data from OptiDAT

Laminate	Test type	Sub-Laminate	Geometry	μ	σ	n	ISO/ OB	σ/μ	E_{it}	E_{ic}	ε_{max}
MD	***STC***	***MD2***	***I0200***	-495	29	9	1.08	6%		27.1	-2.13
			R0400	-459	34	54		7%		28.3	
		MD4	***R0400***	-472	29	9		6%	28.4	29	-1.89
	STT	***MD2***	***I0100***	536	42	10	1.00	8%	28.5		2.30
			I0100 (no LUR)	548	16	5					
			R0400	537	31	51		6%	27.1		2.35
		MD4	***R0400***	657	36	9		5%	28.1	28.6	2.85
UD	***STC***	***UD2***	***I0200***	-658	90	10	1.30	14%		39.9	-1.75
			I0200 (no LUR)	-694	74	3					
			I0300	-622	64	5		10%		37.8	
			R0300	-507	53	74		10%		38.9	-0.68
		UD3	***R0300***	-577	33	5		6%		41.7	-1.40
			R0390	-162	6.5	39		4%		15.1	-2.00
		UD5	***R0390***	-169	3.14	5				15.5	-1.89
		UD4	***R0300***	-561	61	10		11%		40.4	-1.38
	STT	***UD2***	***I0100***	778	42	9	0.96	5%	38.8		2.22
			I0100 (no LUR)	808	19	4					
			R0300	811	50	87		6%	38.8		2.18
		UD3	***R0390***	54	2.7	37		5%	14.1		0.43
		UD5	***R0390***	45	2.6	5			14.5		0.31
		UD4	***R0300***	908	28	5		3%	41.2		2.37
±45°	***STT***	***MD3***	***I1000***	112	2.2	26		%	14.1		
		MD5	***I1000***	94	2.41	10			13.1		

MD=Multi-directional laminate, UD=Uni-Directional laminate;
STT=Static Tensile strength, STC=Static Compressive strength;
MD2, UD2 standard OB laminates
MD4, UD4=standard laminates with alternative resin (phase II material)
UD3=thick unidirectional laminate (UD2+extra layer of UD)
MD3=±45° laminate
UD5,MD5=UD3 and MD3 with alternative resin (phase II material)
Geometries starting with 'I'= coupon geometry from ISO-standard
Geometries starting with 'R'=Rectangular OPTIMAT coupon
R03=used for UD laminate
R04=used for MD laminate (5 mm longer free gauge length than R03)

m*=mean value; =standard deviation*
E= Modulus of elasticity,
e*= strain, n= number of coupons tested*
LUR=coupon tested using saw-tooth load pattern, with incremental increase in load

The alternative material (MD4) has equal performance to the reference material in compression, whereas in tension, it seems to perform better. This is surprising, since the resin is the only reported aspect that changed in the coupon, and a 10% increase in strength due to a different resin system is higher than expected.

Fig. 2-Fig. 6 show the cumulative distribution of the static data. On the abscissa the median rank of the static data is plotted. The median rank *P* is, according to [14], defined as:

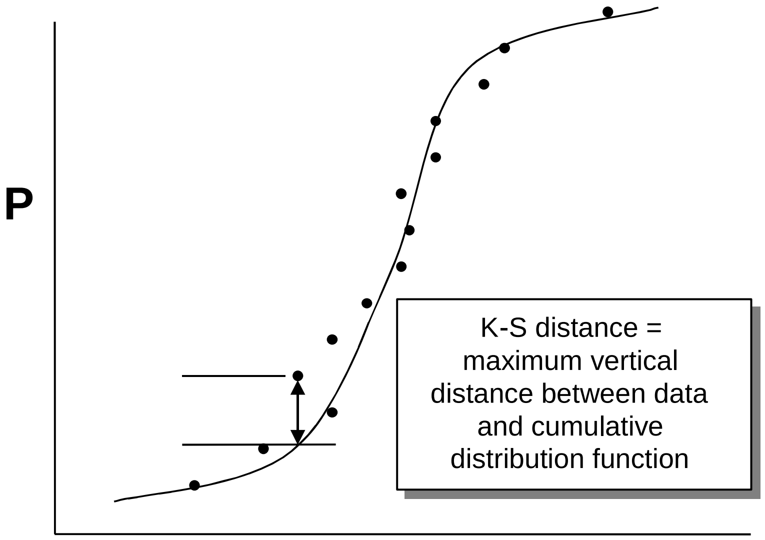


Fig. 1: Schematic of K-S distance

$$P_1 = 1 - P_n$$
$$P_i = \frac{i - 0.3}{n + 0.4} \qquad (1)$$
$$P_n = 0.5^{1/n}$$

, where *i* is the rank of the datapoint within the dataset of *n* datapoints.

The Weibull, Normal, and Lognormal distribution were fit through the data. The Normal and Weibull parameters are displayed in the databoxes in the plot. The numbers next to the datapoints indicate the plate number. The numbers between brackets in the legend indicate the Kolmogorov-Smirnoff distance parameter (see Fig. 1), which is a measure for the quality of the fit; the smaller the number the better the fit of the distribution to the data. For none of the investigated cases, there is no clear indication that either of the distribution functions is superior in describing static data.
Some dedicated tests have been done for Task Group 3, at extreme conditions (-40°C, 60°C, 100% R.H.). For Task Group 4, static strengths have been measured for long reference and repaired specimens. These are not shown here.

The results of these tests can be used for comparison with tests at extreme conditions, static tests on ISO-geometries, for the evaluation of repair strategies, and analysis of strength degradation after fatigue.

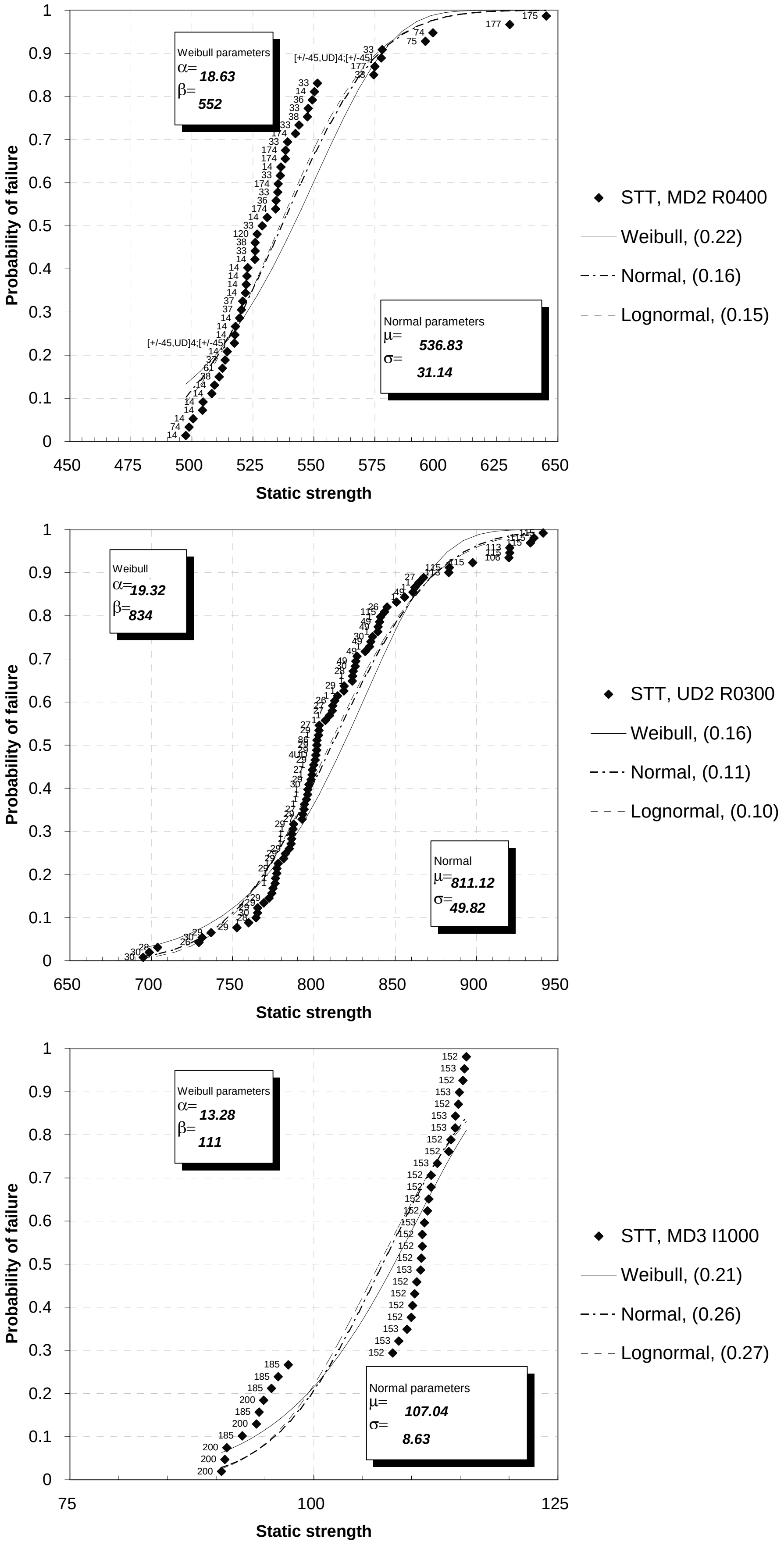


Fig. 2: Tensile strengths of phase I material

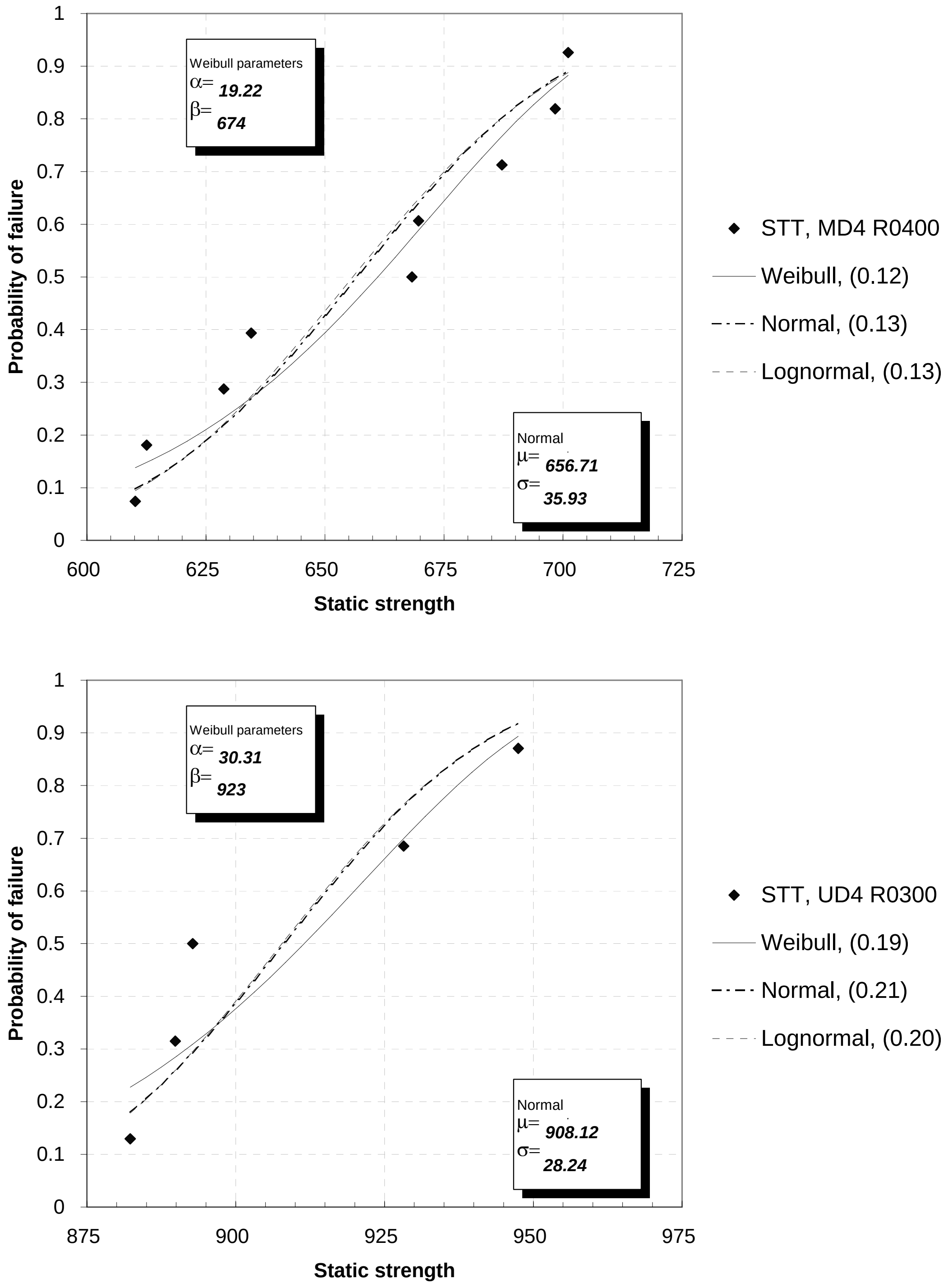


Fig. 3: Tensile strengths of phase II material

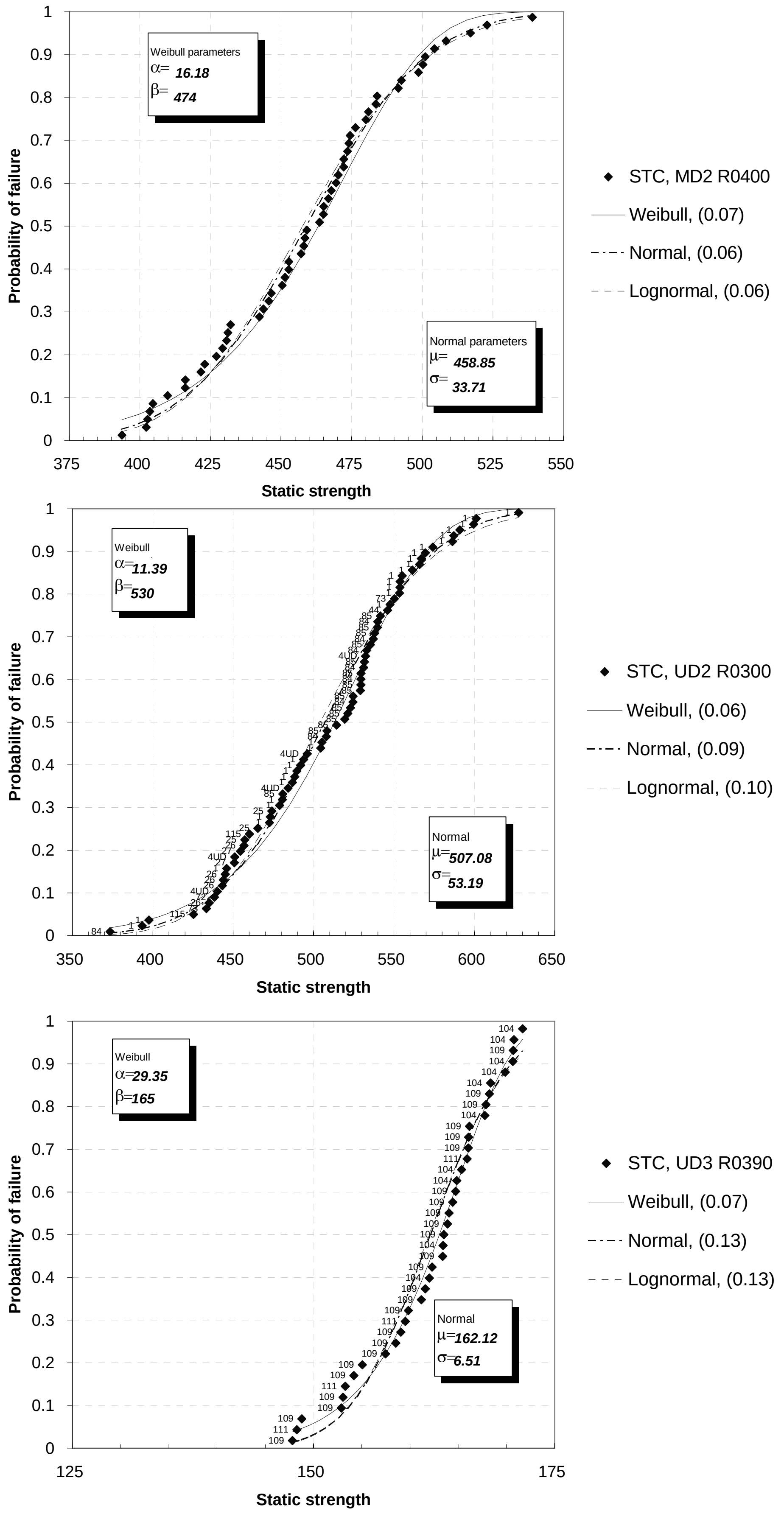


Fig. 4: Compression strengths

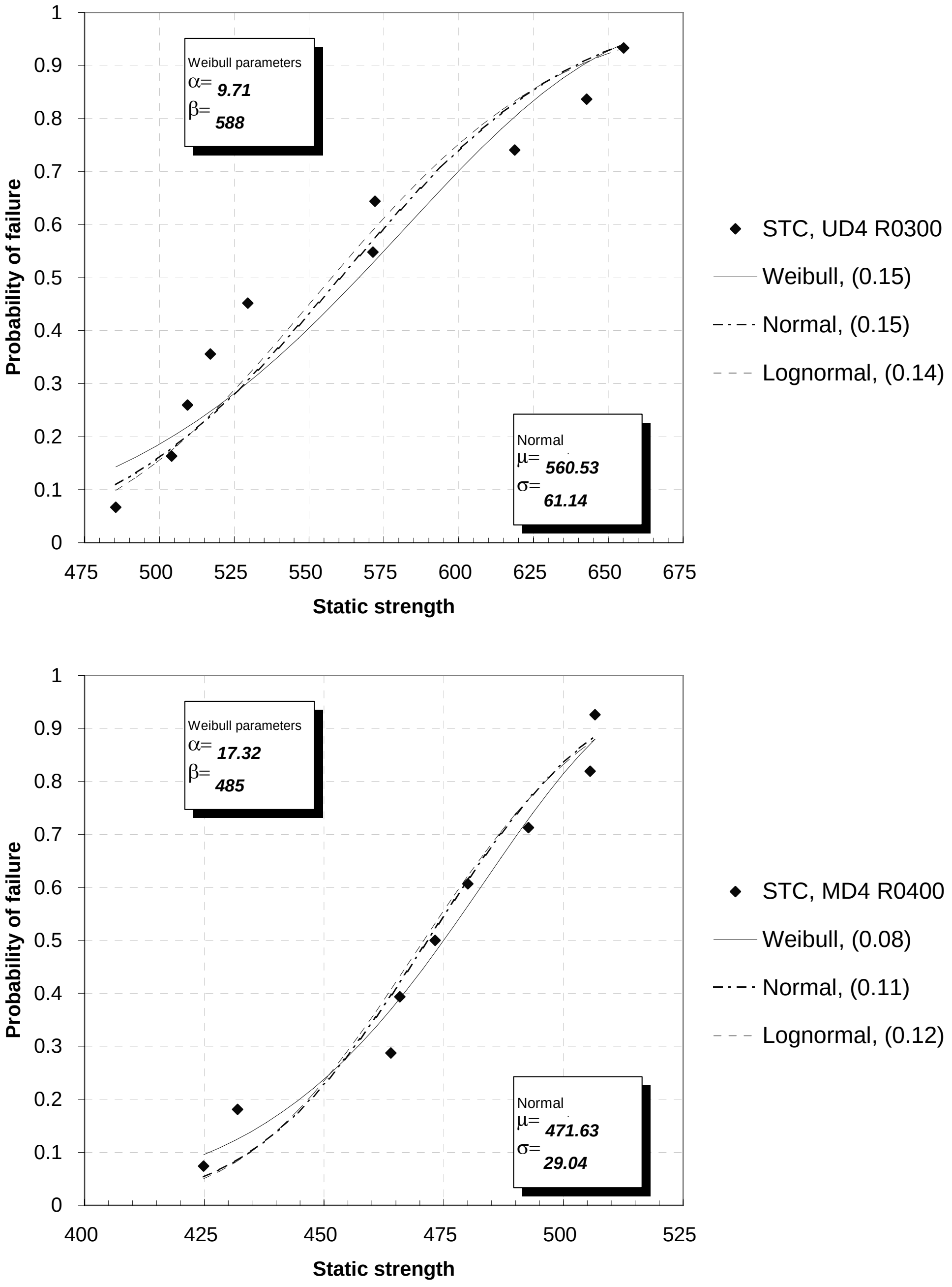
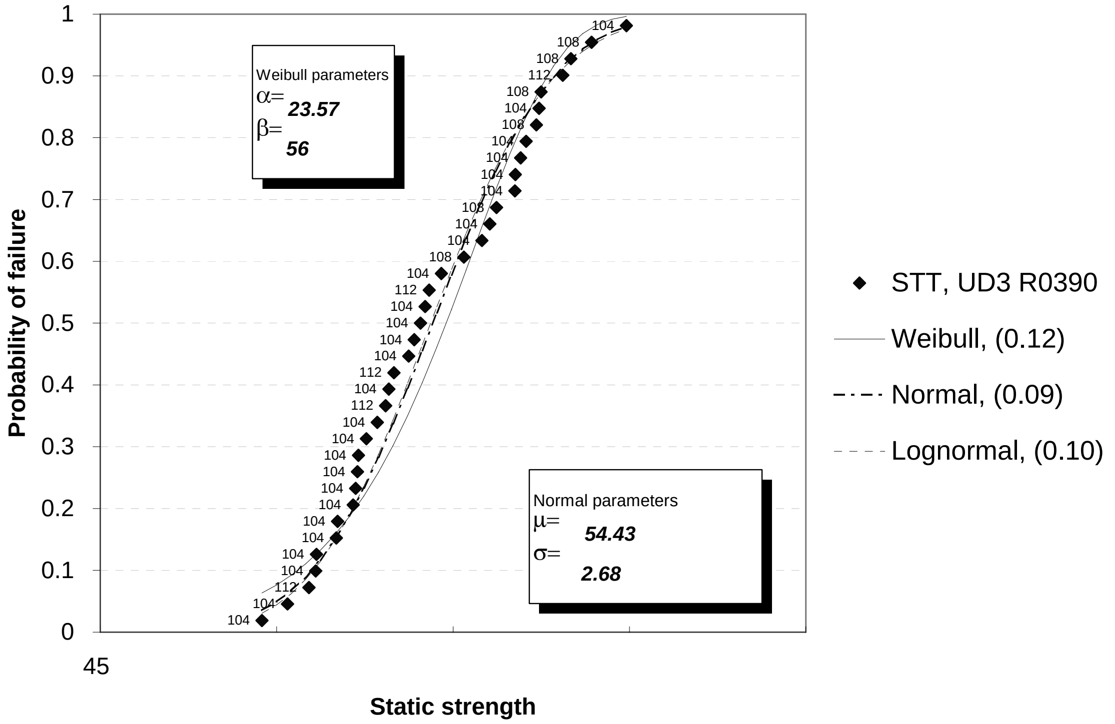


Fig. 5: Compression strengths of phase II material



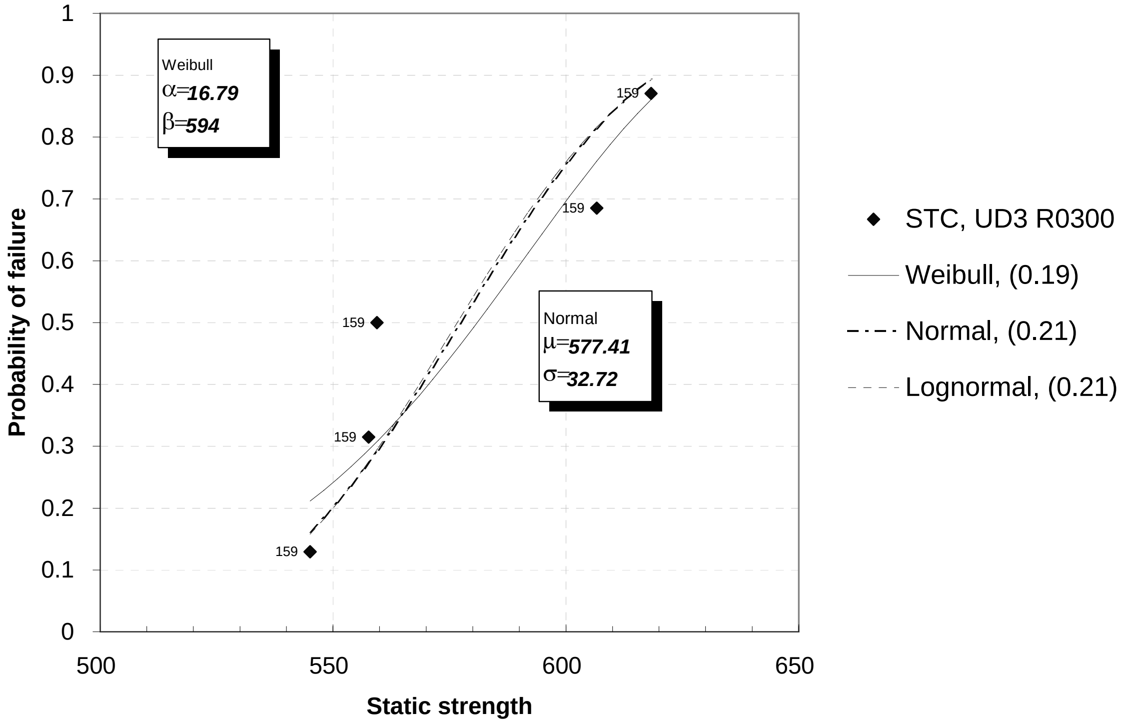


Fig. 6: Static strengths of transverse unidirectional laminate

3. Plate-to-plate and lab-to-lab variation (static)

Due to the nature of the project and the coupon distribution method, plate-to-plate variations could be expected. In the course of the project, some plate-to-plate variations were suspected. The main question is, what is the influence of plate-to-plate variations on static strengths and fatigue behaviour.

Most of the plates delivered were analysed in the laboratory of LM, and the resulting data on plate characteristics were provided to the partners [26]. In addition, a shipment log [27] contains all the information on where all plates were sent. Combining this information with the test results should enable, to a certain extent, to find (unwanted) anomalies or dependencies of certain characteristics on plate number.

In this chapter, the potential influence of plate number on static strength is investigated. The plate number and laboratory information presented in the plots and tables, as well as [26], allow for a rudimentary variability analysis.

This can be done in two ways:

- plot a performance characteristic vs plate characteristic and check for anomalies;
- plot plate characteristic vs plate and check for anomalies

An example of the first approach is shown in

. There, for the standard coupons, static tensile strength is plotted vs plate number. For the UD2 laminate, tensile strength is significantly higher than the average for plates 106, 113, and 115. For the MD2 laminate, plates 175 and 177 show relatively high strength. It should be noted however, that in both cases, the number of coupons tested is fairly low. Nevertheless, these plots should trigger a further investigation into the exact circumstances of these static tests and possible sources for the higher strength.

The second approach is exemplified in Fig. 8. This figure shows the Fiber content (by volume: Fibre volume fraction FvF) and glass-transition temperature (Tg) of all standard OB coupons (R0300 and R0400). The fiber volume fraction is between 49 and 55, which is not a very wide range. Nevertheless, this could account for 10% different static strengths.

Although in some cases, the cause for relatively high strength can be correlated to higher fibre volume fraction (such as for plate 175), a universal dependency of static strength on Fiber Volume Fraction is, at best, mild within the range of FvF available, see Fig. 9. In this figure, fiber volume is plotted against strength. Since single fiber volume fraction values are available per plate, the horizontal bands at a given fiber volume fraction can be correlated to plates.

It is possible, that plate-to-plate variations are compensated for by lab-to-lab variations. In order to quantify lab-to-lab variations, the same plate should be tested in various conditions, at various laboratories. This has not been done, except for a few plates. Plate 1 (UD2) has been tested in compression in various laboratories, and so has plate 14 (MD2).

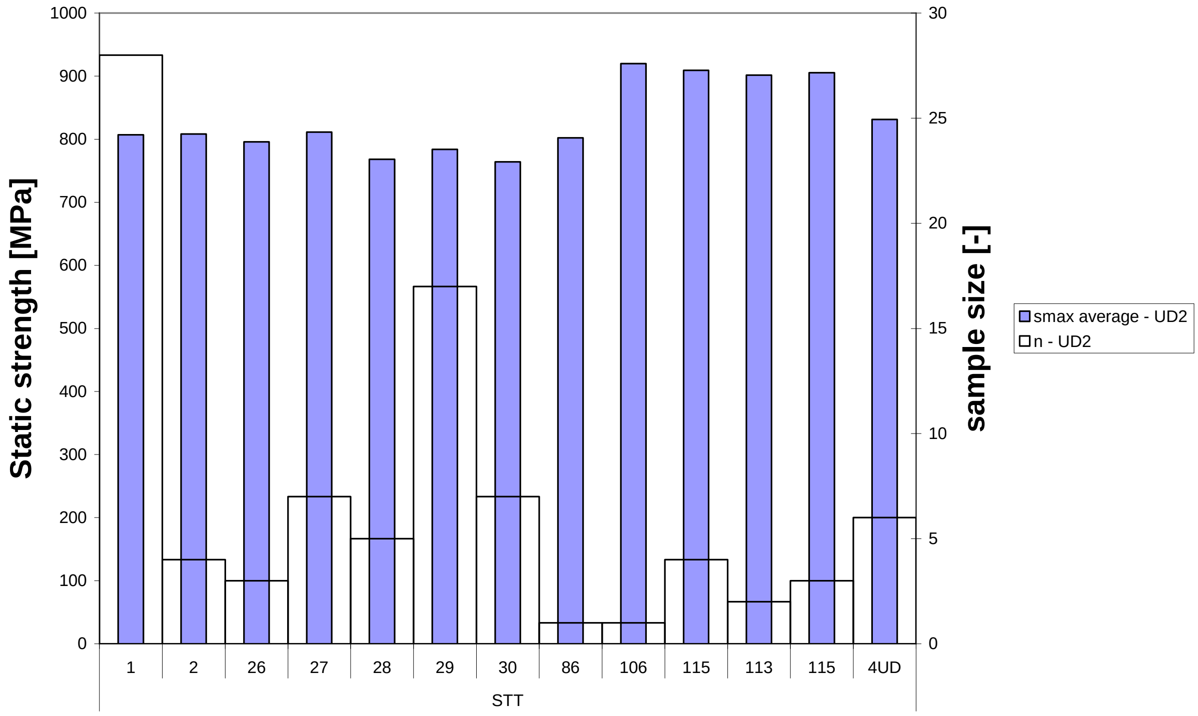
Fig. 10 shows the results for plate 1. Clearly, the complete dataset with standard deviation ca. 12% of the mean strength, falls apart in two populations with σ/μ of 5%, indicating 'good' tests (by RAL, DLR, UP), and 'bad' test results (VUB and WMC). For WMC, these tests were done on the 250 kN homebuilt frame with mechanical grips, which has not been used for STC on UD afterwards. To a slightly lesser degree, two sub-populations may also be distinguished for the STT tests.

For the MD2 material, plate 14 is a good example of a plate that has been tested at different laboratories, see Fig. 11. Here, the VUB data seem slightly on the low side. The division between good and bad results is not as clear as in Fig. 10 and seems to be absent for tensile tests.

From the limited data, no clear correlation is seen between tensile and compressive strength of specimens from the same plate, between plate number and static strength, or between laboratory

and average static strength, except for some cases Summarising, it can be stated that plate-to-plate variations are generally smaller than lab-to-lab variations (or rather: machine-to-machine variations). Using this information implies that a σ/μ of 5% is a representative estimate of the minimum scatter in static results for a material made in different batches Plate-to-plate variations can be explained, at least partly, by the fiber volume fraction.
In addition, the MD2 material seems less sensitive to being tested in different machines than the UD2 material, which might be attributed to the larger sensitivity of UD2 to machine alignment and test frame stiffness.

Obviously, this plate-to-plate/lab-to-lab investigation is by no means a full-fledged statistical analysis, and it can only be very limited, as the test programme was not designed explicitly to quantify the potential sources of scatter. By far not all plates are included, since static tests were only done for a limited number of plates. A more detailed (multiple, non-linear) regression analysis is recommended for closer analysis of potential sources of variation, taking into account, for example, plate characteristics such as fiber volume fractions.



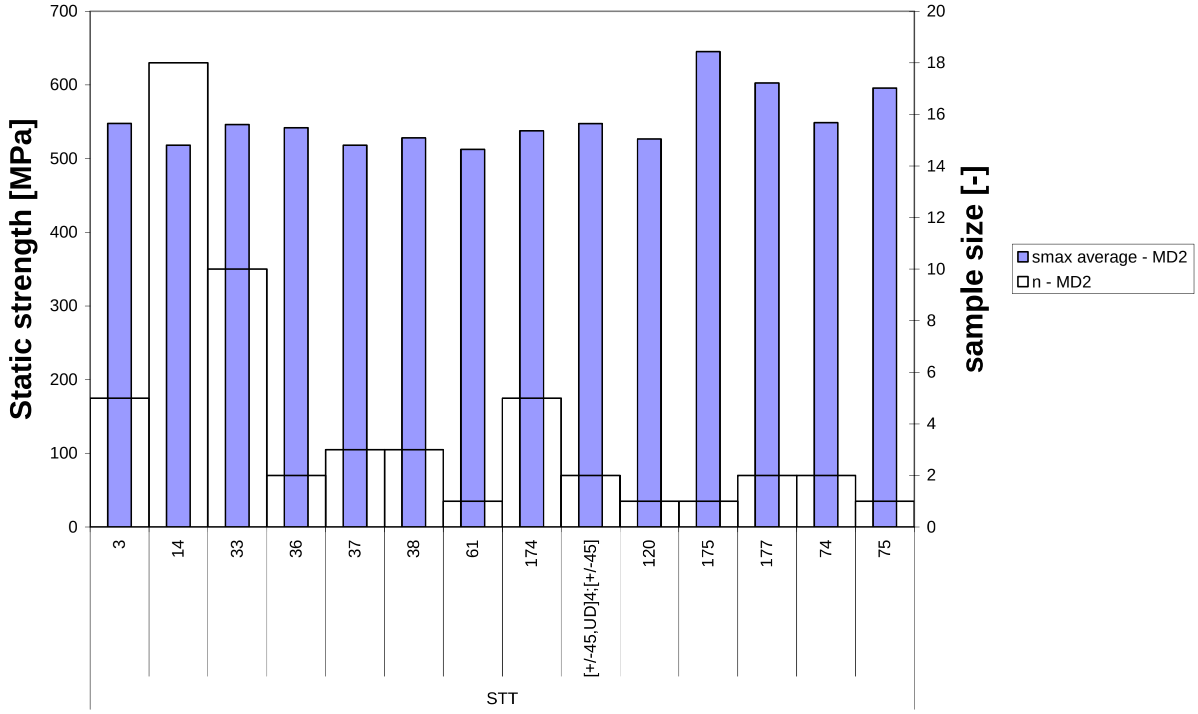


Fig. 7: Static strength vs plate number

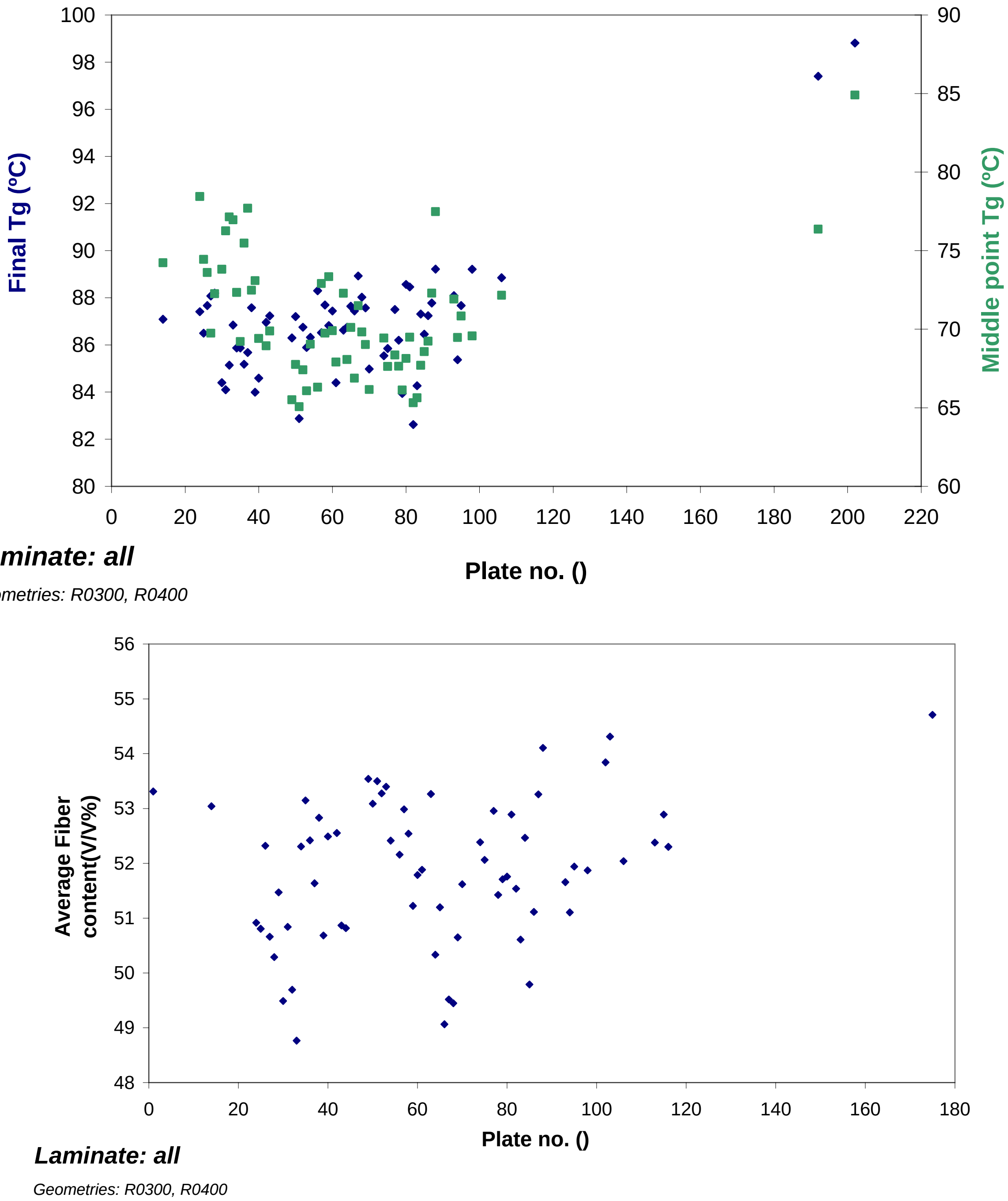


Fig. 8: Glass-transition temperature (top) and Fibre volume fractions per plate

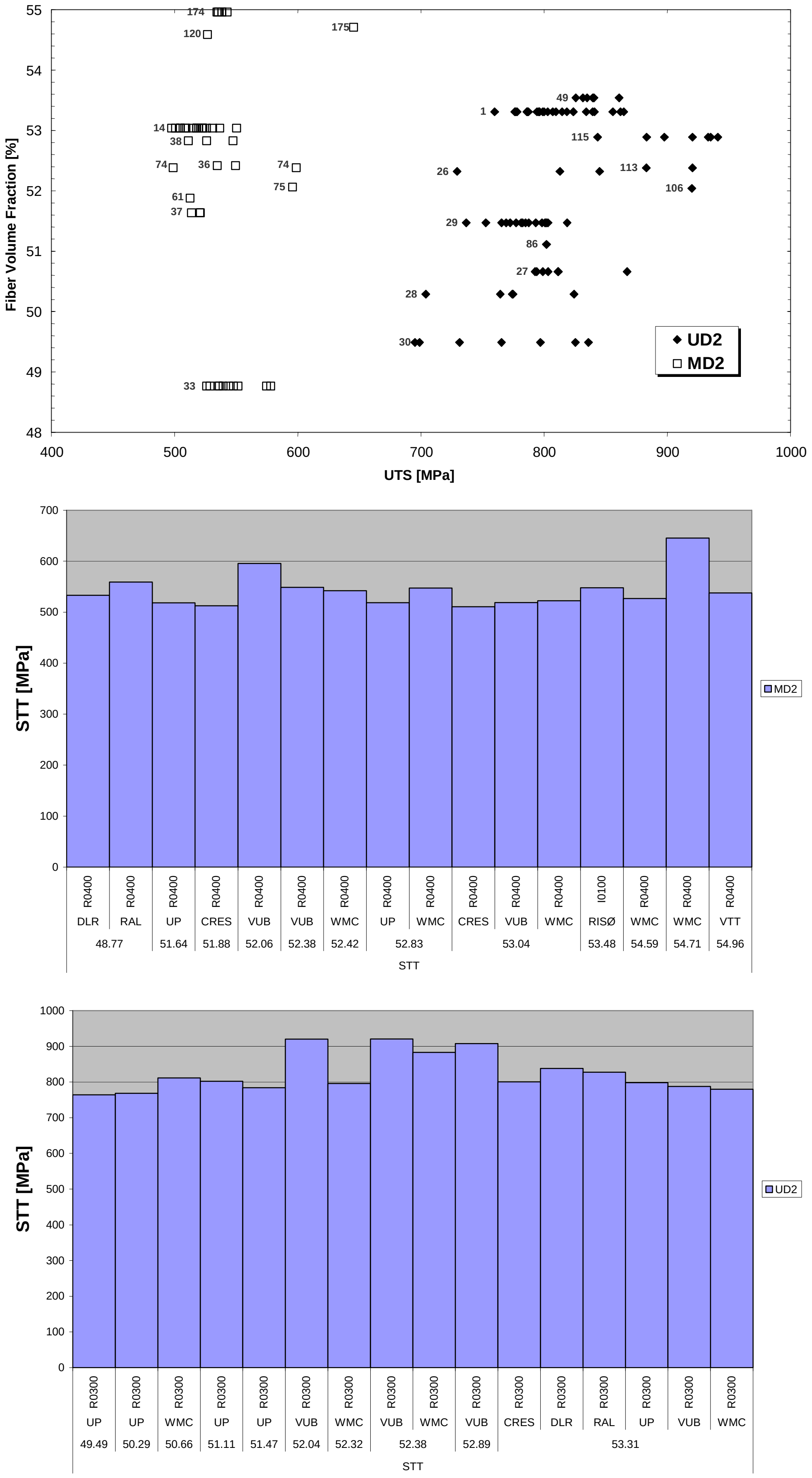


Fig. 9: Influence of Fibre Volume Fraction on strength

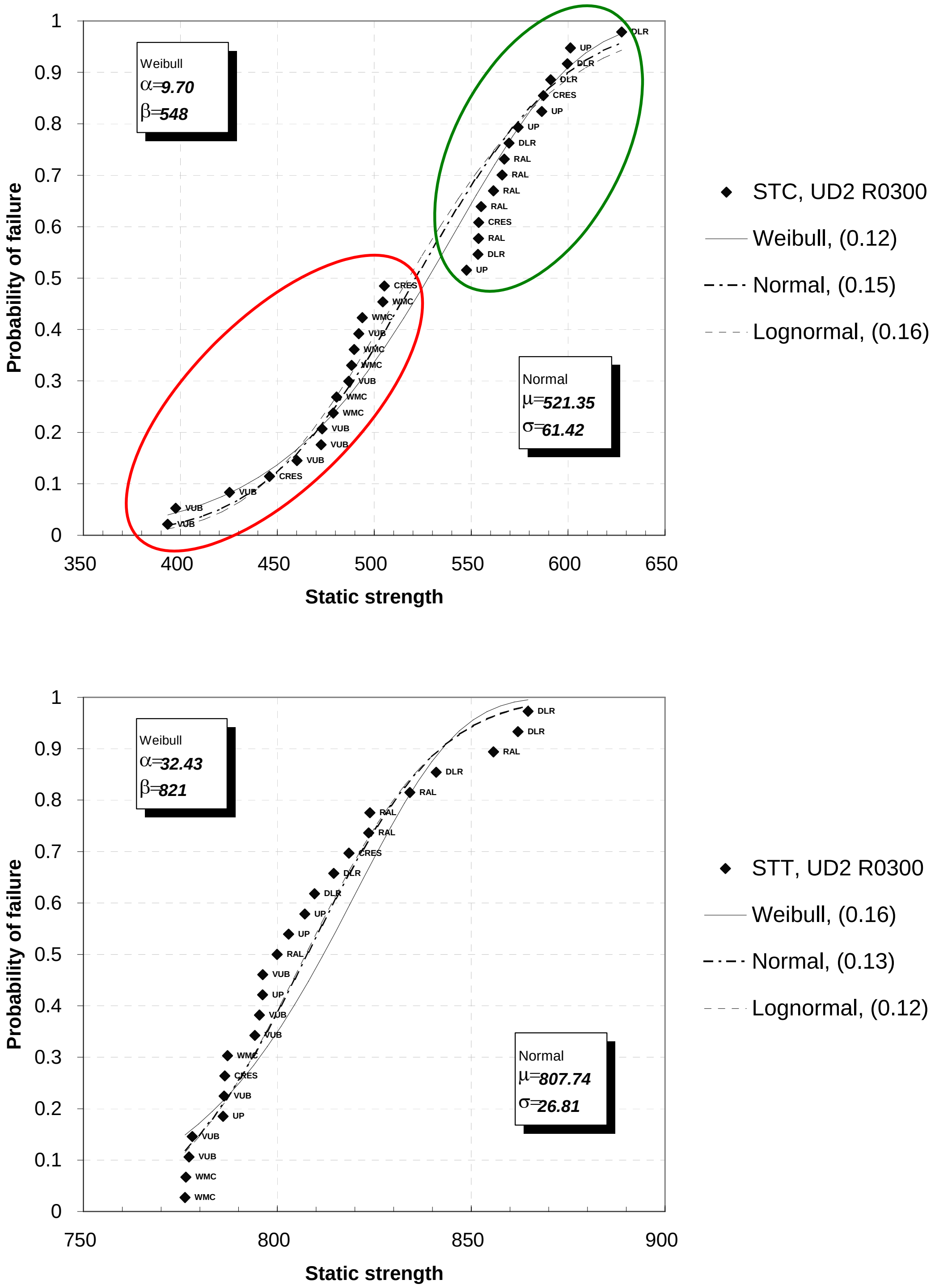


Fig. 10: Static strengths for single plate, plate 1

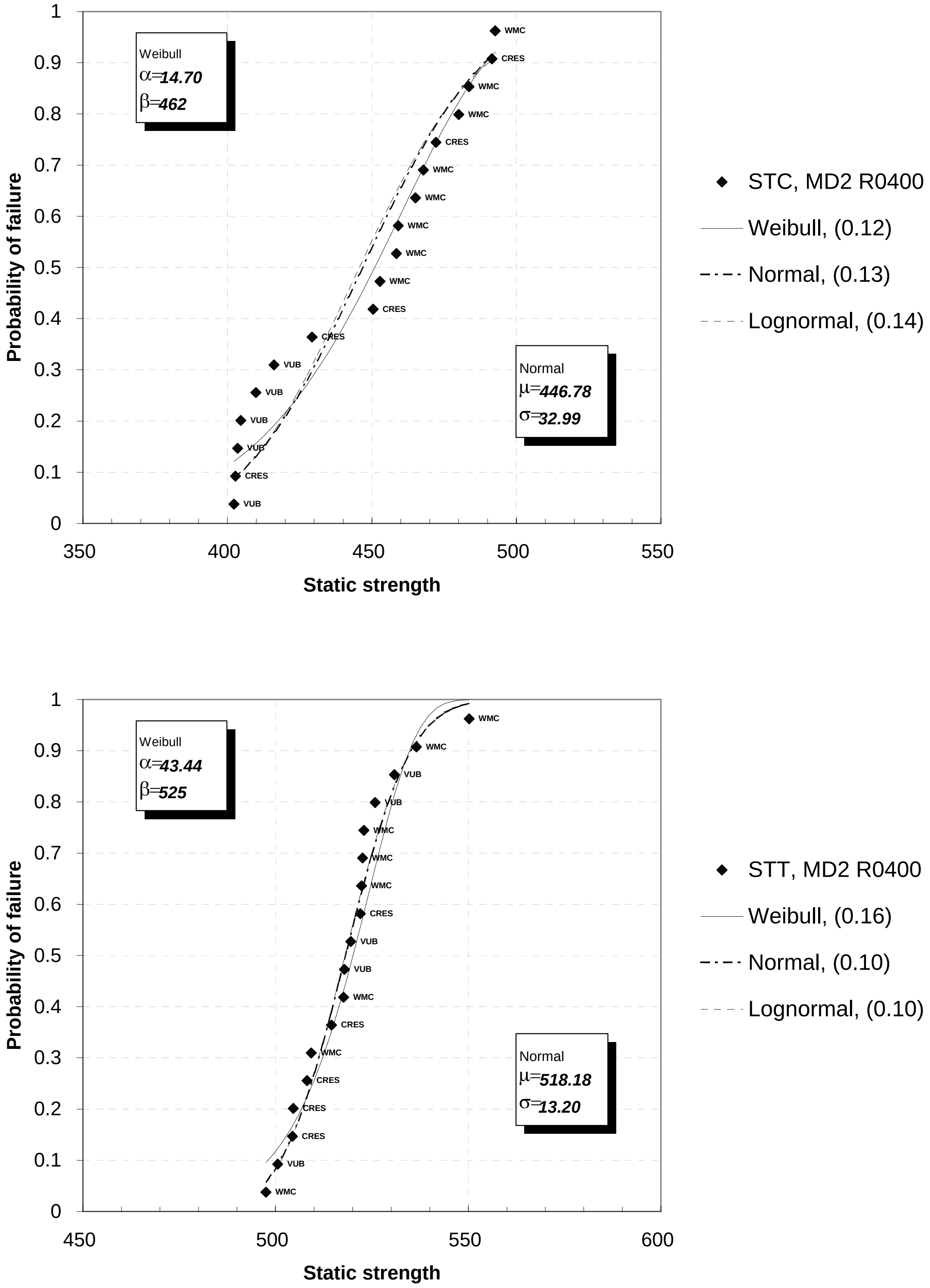


Fig. 11: Static strengths for single plate, plate 14

4. Fatigue behavior

Fatigue lives were planned at three distinct loading levels, numbered 1, 2, and 3, and aimed at a nominal lifetime of 1.000, 50.000, and 1.000.000 cycles to failure. Fatigue lives were to be obtained for 3 baseline R-ratios for both the UD2 and MD2 lay-ups in standard geometries. Additional R-ratios were tested for a detailed description of the constant life diagram of MD2, viz. R=-2.5, -0.4, 0.5, and 2.

In the course of the project it was decided to lower the load for level 1 to a nominal lifetime of 5000 cycles to mitigate buckling problems. This level is termed ‘1b’ in the remainder of this document and in OptiDAT. The magnitude of the load levels were determined by UP and DLR for a limited dataset and included in the general test specification [15]. From this document, all laboratories used the load and frequency prescription to carry out subsequent fatigue, spectrum, and residual strength tests.

For most of the constant amplitude, and residual strength tests, the load level definition was not included in the database. Therefore, it has been added to the data later on, in a separate column. The load level in this column was computed from R-ratio and load. This is ‘load level$_{calc}$’ in OptiDAT, as opposed to ‘level’, which contains the raw submitted data.

The fatigue data include data from the preliminary testing programme. One of the outcomes of the preliminary programme was, that the test frequency needed to be limited to prevent excessive heating of the specimen. The preliminary test programme therefore includes data that were collected at frequencies that were later deemed too high.

The relationship between load level (as load per mm width or maximum stress), nominal number of cycles, test load, and test frequency is given in Table 2 for the standard geometries and lay-ups, which summarises the prescriptions from the general test specification [15].

Table 2: load level definitions from test specification [15]

		R-ratio	-1		-0.4		-2.5		0.1		0.5		10	
	level	N	F/mm	f	F/mm	f	F/mm	f	F/mm	f	F/mm	f	F/mm	f
MD 0°	1	1000	1.83	0.63	2.42	0.62	2.42	0.62	2.62	1.52	2.62	1.52	2.23	1.95
	1b	5000	1.55	0.88	2.01	0.90	2.01	0.90	2.23	2.10	2.23	2.09	2.11	2.18
	2	50000	1.21	1.44	1.54	1.53	1.54	1.53	1.77	3.34	1.77	3.35	1.95	2.55
	3	1000000	0.89	2.57	1.09	3.07	1.09	3.07	1.31	6.10	1.31	5.80	1.76	3.15
	4	1E+07	0.69	4.39	0.83	5.22	0.83	5.22	1.04	9.68	1.04	9.69	1.62	3.69
UD 0°	1	1000	1.58	0.82					2.14	1.50				
	1b	5000	1.29	1.23					1.81	2.10				
	2	50000	0.97	2.17					1.43	3.35				
	3	1000000	0.67	4.56					1.05	6.19				
	4	1E+07	0.50	8.09					0.83	9.93				
UD 90°	1	1000	1.76	0.95									5.93	2.92
	1b	5000	1.43										5.58	
	2	50000	1.05	2.66									5.11	3.94
	3	1000000	0.71	5.89									4.55	4.96
	4	1E+07	0.52	10.83									4.17	5.92

Fig. 12-Fig. 33 give the S-N diagrams that were collected to date, including a log-log regression line, and a comparison with the general test specification.

As is noted in most of the graphs as ‘prescribed frequencies, standard levels’, only the S-N data that comply with the test specification are shown. In practice, small deviations in actual test settings and test spec might exist, so therefore a test was considered valid if the load/mm and the frequency were within 10% of the test specification.

In all plots, only the specimens tested at dry conditions and room temperature are listed. Invalid tests are excluded, but bending and buckling is included. Run-outs are included, and indicated by arrows attached to the symbol. The legend includes a count of specimens per lab. The S-N data are colour-coded per lab.

For load levels that have sufficient specimens, a probability plot is included, similar to the static probability plots. One of the objectives of the constant amplitude programme is to create a statistically significant amount of data to base life estimates for a particular load level on. The plots show single-level data for most of the standard levels 1, 1b, 2, and 3. Weibull, Normal, and log-Normal cumulative distribution functions were fit through the datapoints. The goodness-of-fit was expressed in the KS-distance parameter, as was done in the static tests. There is no evidence, that either of the investigated distribution functions (Weibull, Normal, or Lognormal) describes static data best per standard level. For level 4, due to time constraints, typically only 1 or 2 tests were done; not enough for a probability plot.

For MD2 and UD2 at R=0.1, the available fatigue data generated with dogbone specimens are included in the plot. This helps to compare the OPTIMAT coupons (with questionable grip failures) to coupons which had a supposedly relatively benign load introduction. For the MD material, the difference between the two geometries diminishes for long fatigue lives. In case of the UD material, the dogbone geometry seems to perform worse than the rectangular coupons, especially at long fatigue lives.

As for the scatter in constant amplitude fatigue, it is seen from the figures, that the standard deviation of the Normal distribution is between the mean life and 1/3rd of the mean life for R=0.1. See also the next section on variations.

For R=-1 and R=10, scatter was generally higher for the MD material; viz. in the order of magnitude of mean fatigue life itself. Scatter for UD R=10 is not discussed here.

The strain based S-N curves of Fig. 32 reveal, that on a strain basis, the S-N curves are identical for UD and MD, as was evident from (calculated strains in [18]). This corroborates the notion that the MD material, although containing fibers in 3 directions, is actually a fiber dominated laminate.

Detailed information on the UD fatigue tests at CRES is found in [19] (R=-1), and [20] (R=-1 and R=0.1), and for R=0.1, -1, 10, and ∞ in [21]. Some sensitivity to misalignment of the UD specimens in R=0.1 fatigue was reported in [22].

For the R=10 of the UD material, no test specification was made available during the project. This is due to the sensitivity of the standard UD specimen to buckling, see e.g. [23]. Additional testing has been done at UP to investigate the feasibility of a thicker UD specimen, to perform CA and RST testing on [24]. At WMC, constant amplitude tests and RST tests were done on the standard UD specimen, without much success. Also, attempts have been made using an Anti-Buckling Guide. These results indicate, that the fatigue life of the specimen is correlated with initial bending, see Fig. 33.

Table 3: parameters of equation (2), according to test specification [15] (normal font), and linear regression (italics)

		MD R0400		**UD R0300**	
		A	**B**	**A**	**B**
R-ratio	*-1*	3.7939	-9.4933	3.73	-8.04
		3.4206	*-9.777*	*3.1967*	*-8.8197*
	0.1	5.2419	-9.9585	4.35	-9.743
		4.9913	*-10.136*	*4.3699*	*-9.333*
	10	2.8356	-28.82		
		2.999	*-25.958*		

Table 3 shows the parameters of equation (2) according to both the test specification and the linear regression line (in italics).

$$\frac{F_{\max}}{w} = A \cdot N^{1/B} \qquad (2)$$

where *N* is number of cycles to failure, and *w* is the width of the specimen. In general, the data are close to the test specification. This indicates a minimum number of experiments necessary to determine accurately the mean S-N curve. The effect of (small) variations in the parameters of the S-N curve on a variable amplitude life prediction using classical fatigue analysis can be investigated using the interactive spreadsheet tool of [16].

Table 4 gives a general overview of all CA data, at standard load levels, all frequencies, and including run-outs.

To date, each combination of load level and R-ratio contains a minimum of 3 datapoints at the conditions (load, frequency) prescribed by the general test specification. Generally, 5 coupons per load level are considered a suitable basis for statistical analysis of the S-N curve.
On the other hand, the S-N curves as a whole contain (much) more data than was initially planned. This is because some levels contain more data than initially intended. Constant amplitude data from the early phase of the programme can be included in most cases. These data are at non-standard load levels. In addition, data have been collected at non-standard frequencies. Some of these data are included in the overview of Table 4, which also gives an indication where the buckling and bending problems arise. In cases where the frequency was close to the prescribed frequency one can imagine including these data in a statistical analysis. In addition, these data can be used for investigations into e.g. the effect of loading frequencies.

Table 4: Overview of S-N data at standard load levels, including run-outs and non-standard frequencies

Laminate	R	level	N*	Min cycles	Max cycles	standard deviation	f**	Bending	Buckling	Overheating	Tab failure	Incomplete data	n
MD2, R0400	-2.5	1	105	105	105		0.90	1				1	1
		2	143148	93144	193151	70716	1.53	1			1	1	2
		3	2111417	1460292	3095164	866706	3.07					3	3
		1b	12371	1041	23701	16023	0.90	1				1	2
	-1	1	822 (402	168	3910	1157	1.31	1	2		2	2	10
		2	38429 (43679)	744	112810	36112	1.74				5	7	20
		3	1032135 (870108)	637298	2098460	489980	2.59	1		1	5	2	9
		4	2400649	3857	7223777	2860621	4.76	1		1	2		10
		1b	2825 (5097)	402	8234	2433	0.73			1	5	2	12
	-0.4	2	35676	6878	103657	29384	1.51						11
		3	565318	10863	2308278	778891	2.96	1					9
		4	39393907	39393907	39393907		7.90				1		1
		1b	4579	868	14519	4597	0.83						7
	0.1	1	1104 (1104)	771	1548	288	1.53				5		5
		2	43773 (43773)	10661	98460	32112	3.39				4	1	11
		3	1182236 (1182236)	346505	1550777	464599	6.10				3		6
		4	5167411	5167411	5167411		9.04				1		1
		1b	3054 (3054)	2139	4504	1038	2.10				1		4
	0.5	2	201391	72890	852309	288397	3.59				1		7
		3	7718968	2150910	13287026	7874423	6.65				1		2
		1b	18950	8738	47983	14719	2.10				1	2	6
	10	1	1481	917	1986	537	1.97						3
		2	60995 (60995)	4206	217737	65957	2.55	3				1	11
		3	1301457 (1437590)	74741	4744812	1382127	3.05	1				1	10
		4	10173865	10173865	10173865		3.70						1
		1b	88995 (79835)	2303	263886	96060	1.99						8
UD2, R0300	-1	1	468 (315)	32	1603	412	1.07		1	1	3	4	12
		2	36417 (50762)	898	130393	33182	2.85	2		2	11	1	43
		3	912482 (921547)	37601	2000011	493559	4.35	2		2	8	2	42
		4	19854604	19854604	19854604		8.09			1	1		1
		1b	2427 (4384)	480	5787	1518	2.01	3			5	2	17
	0.1	1	860 (954)	202	1213	360	1.44				3	5	8
		2	41002 (45177)	13010	78760	23150	3.60	2		1	4	6	12
		3	789259 (955516)	159510	1830946	587133	5.80				6	6	15
		4	1547632	185426	2909837	1926449	7.47						2
		1b	3624 (3624)	2522	5285	1213	2.11	2		1	3		4

** in brackets: mean life using standard frequencies from Table 4*
*** for standard frequencies, see Table 4*

5. Plate-to-plate and lab-to-lab variation (fatigue)

In all plots, the plate numbers are included for each coupon. The laboratory is indicated by color and marker shape. This facilites checking for plate-to-plate, or lab-to-lab (machine-to-machine) variations. Using the information on laboratory, plate-to-plate and machine-to-machine variations can be distinguished. At WMC, multiple machines were used, adding an extra variable. the machines at WMC are indicated by h (for homebuilt), S (for 100 kN Schenck), and I (for 100 kN Instron). At the other laboratories, single machines were used in most cases.

In the previous section it was stated that scatter in R=0.1 is characterised by σ/μ of 30% This is true for both MD2 and UD2 material, and taking into account machine-to-machine variations. For example, look at Fig. 21, (UD2 R=0.1 level 2). The standard deviation is about 60% of mean life (23k vs 45 k cycles) according to the plot. However, if the data are grouped according to laboratory, standard deviation is about half of that smaller. In this case, this could be due to a plate-to-plate variation (65/66 vs 43/44), or due to a lab-to-lab variation (UP vs CRES).

Plate-to-plate variations are difficult to qualify, let alone quantify. The reason is, that typically, each combination of R, level, plate was only tested at a single laboratory. As an example, consider plate 88. This plate was pointed out by DLR as suspectedly being of inferior quality, based on the results at R=-0.4 (Fig. 31). This is confirmed by WMC tests at R=0.1, see Fig. 12. However, from WMC tests conducted at R=10 and R=-1 (Fig. 15&**Error! Reference source not found.**), the inferiority of plate 88 specimens is not so obvious. This could be due to the fact that it was tested at different machines, or at compression-dominated R-ratios rather than tension dominated R-ratios. The frequency for similar loads is slightly lower for R=10 than R=0.1, but it is not likely that this accounts for plate 88 showing better behaviour in R=10.

In Fig. 34 and Fig. 35, the fatigue life is plotted versus Fibre Volume Fraction. Different symbols are used for different load levels. From these figures, fibre volume fraction does not seem to influence fatigue life within the (small) range of fibre volumes tested.

Summarising, lab-to-lab variations seem to be larger than plate-to-plate variations, similar to the static tests. Plate-to-plate variations are difficult to quantify due to the set-up of the test programme. In addition, fatigue behaviour does not show a correlation with fibre volume fraction. Therefore, in view of work done in other task groups, it does not seem feasible to correct mean life estimates based on plate number (based on this rudimentary variability analysis).

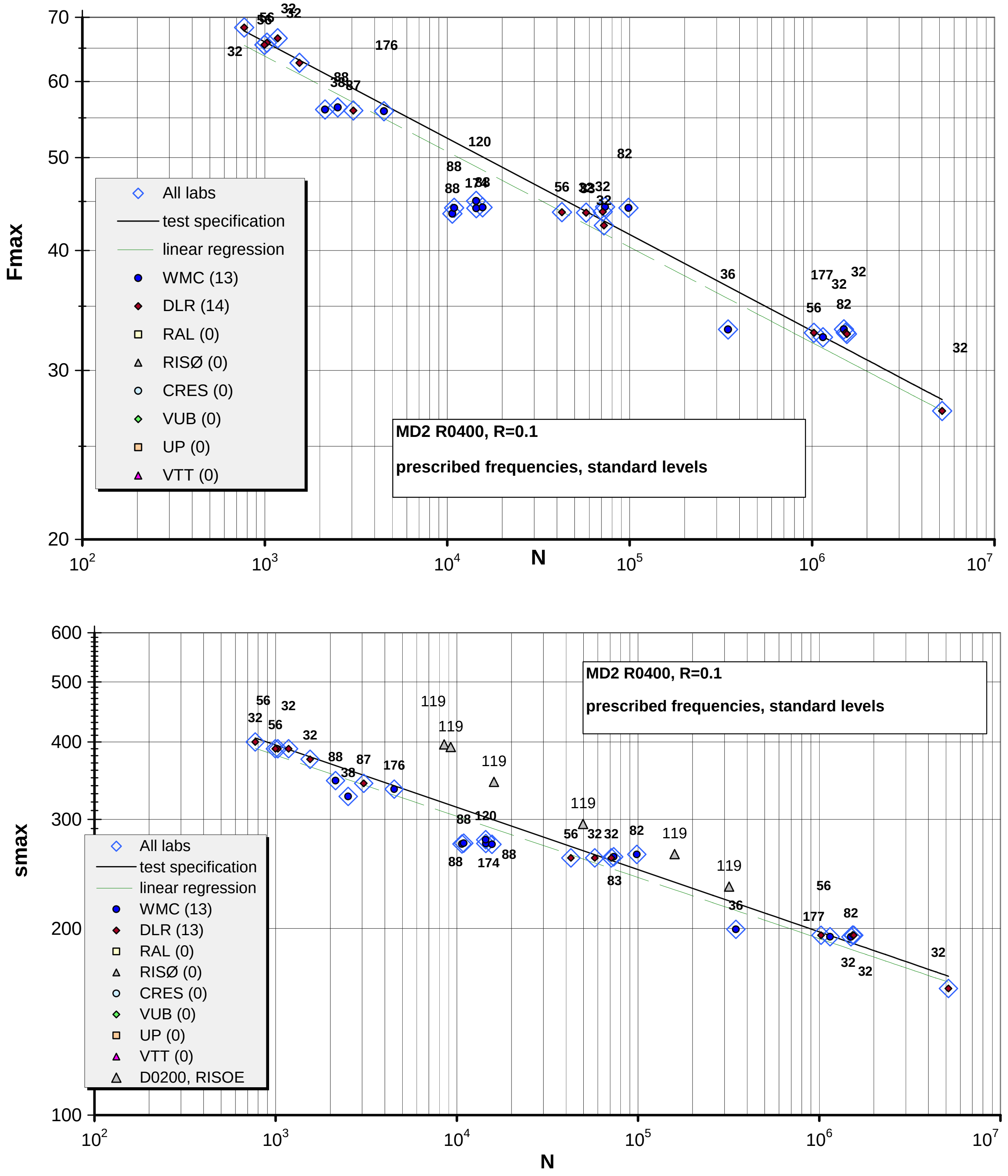


Fig. 12: MD R0400 R=0.1 S-N curve (lower including dog-bone D0200 geometry (grey triangles))

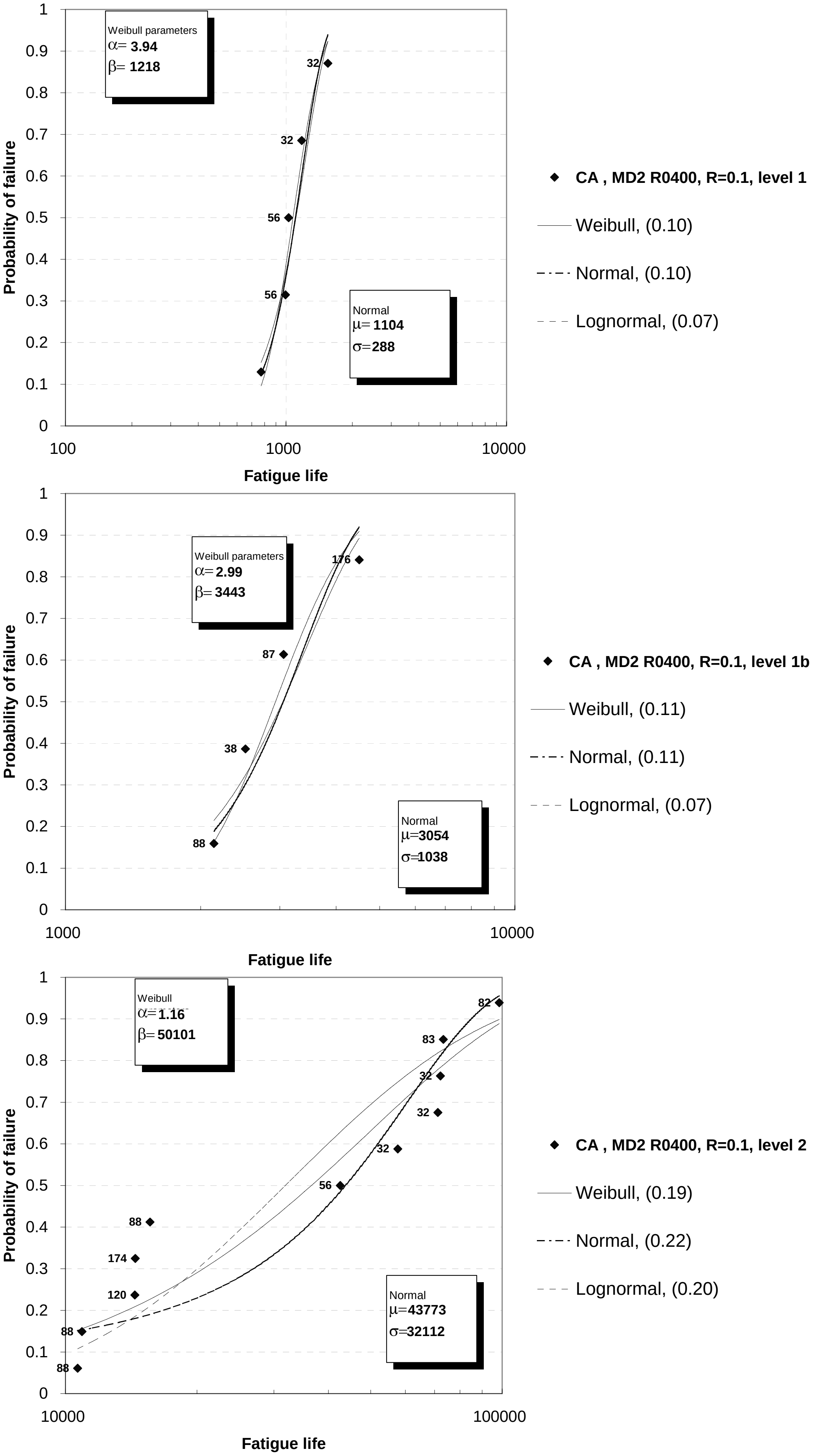


Fig. 13: MD R0400, R=0.1 level 1-2 probability plots

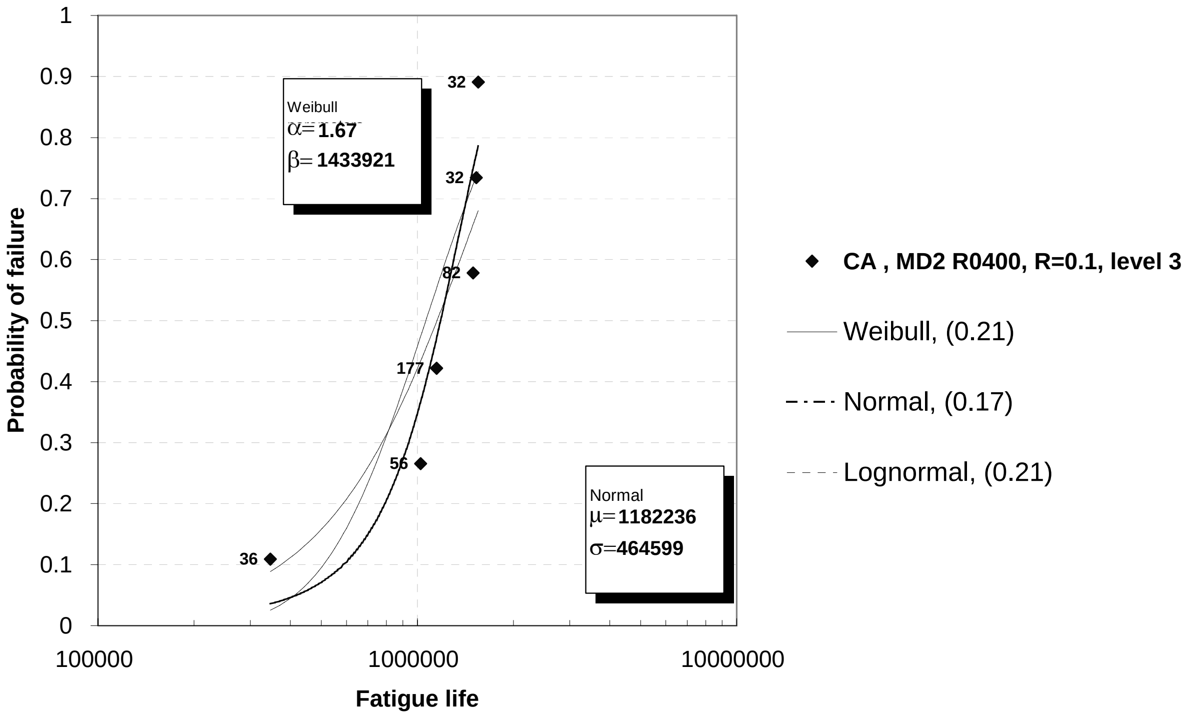


Fig. 14: MD R0400, R=0.1 level 3 probability plot

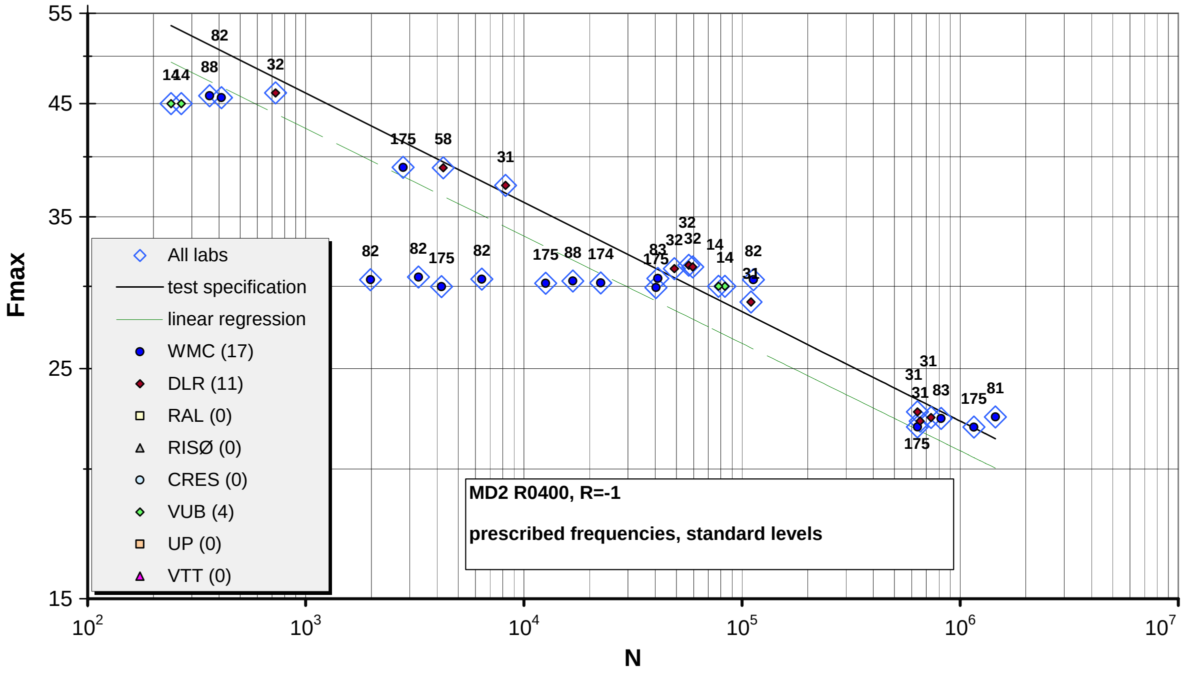


Fig. 15: MD R0400 R=-1 S-N curve

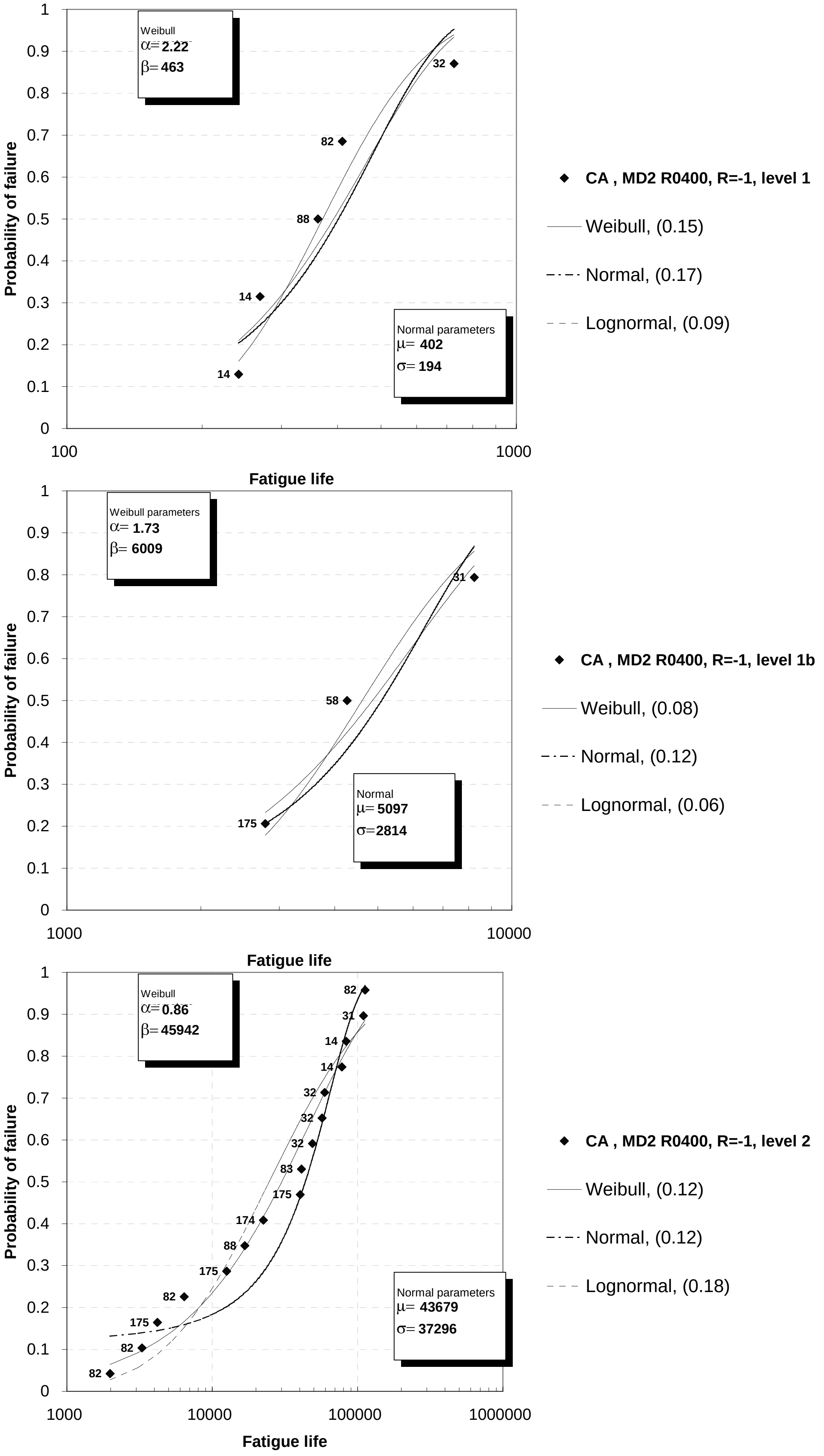


Fig. 16: MD R0400 R=-1 level 1-2 probability plots

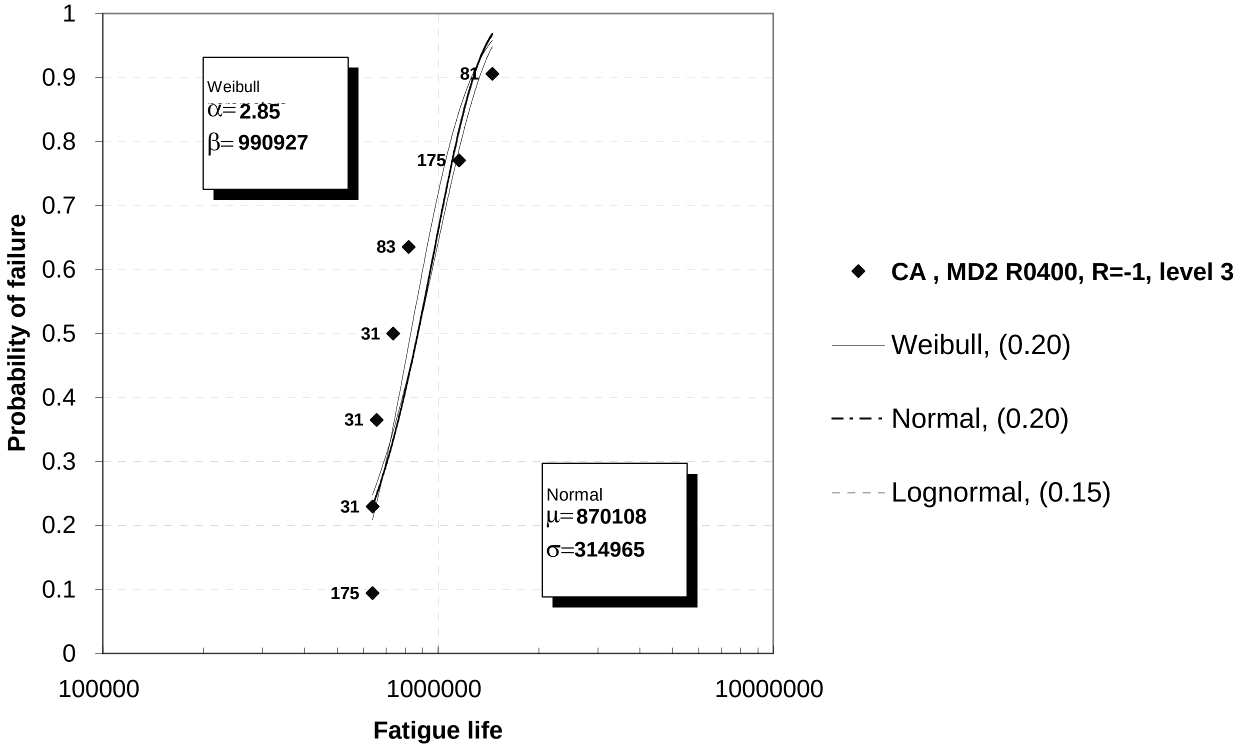


Fig. 17: MD R0400 R=-1 level 3 probability plot

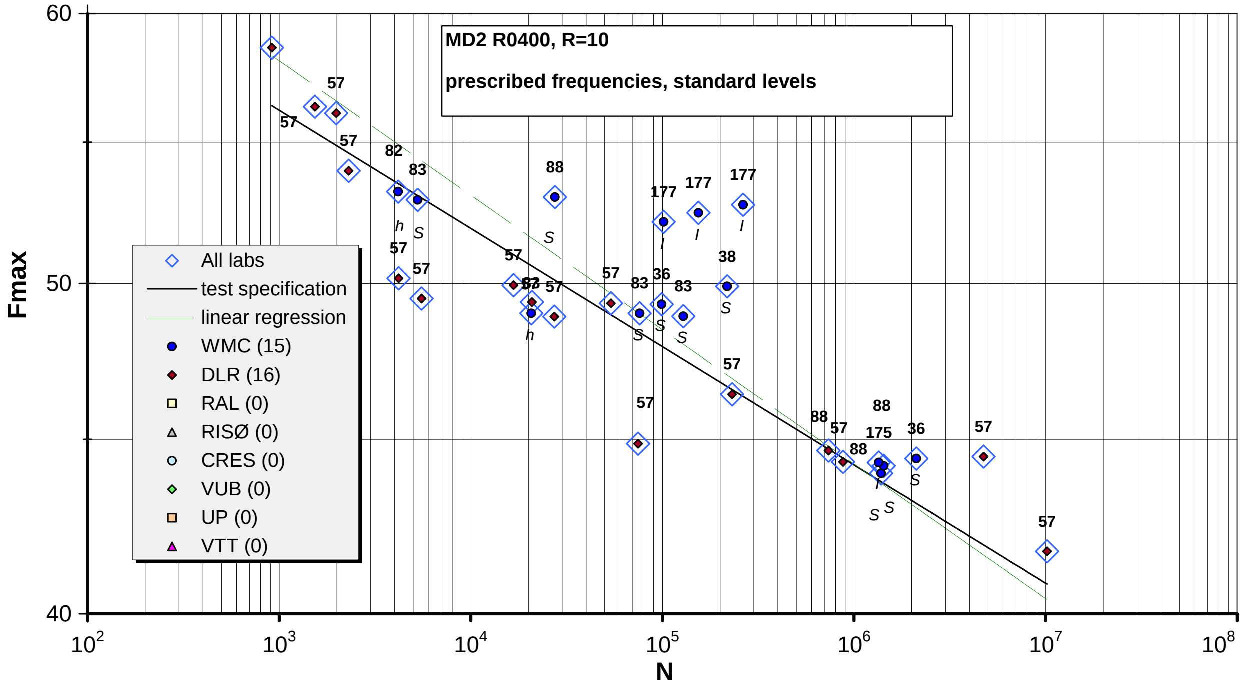


Fig. 18: MD2 R0400 R=10 S-N curve

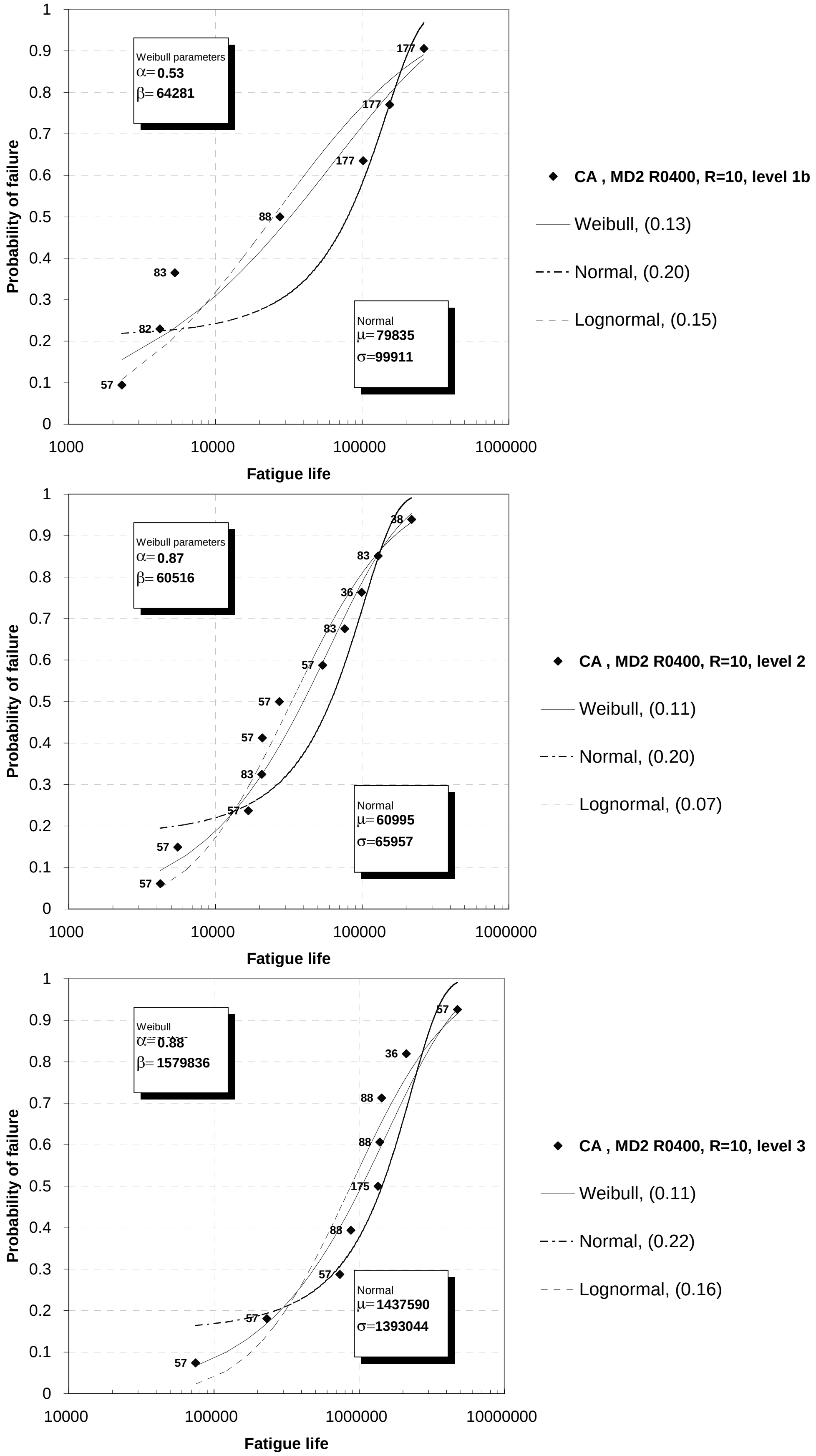


Fig. 19: MD2 R0400 R=10 level 1b-3 probability plots

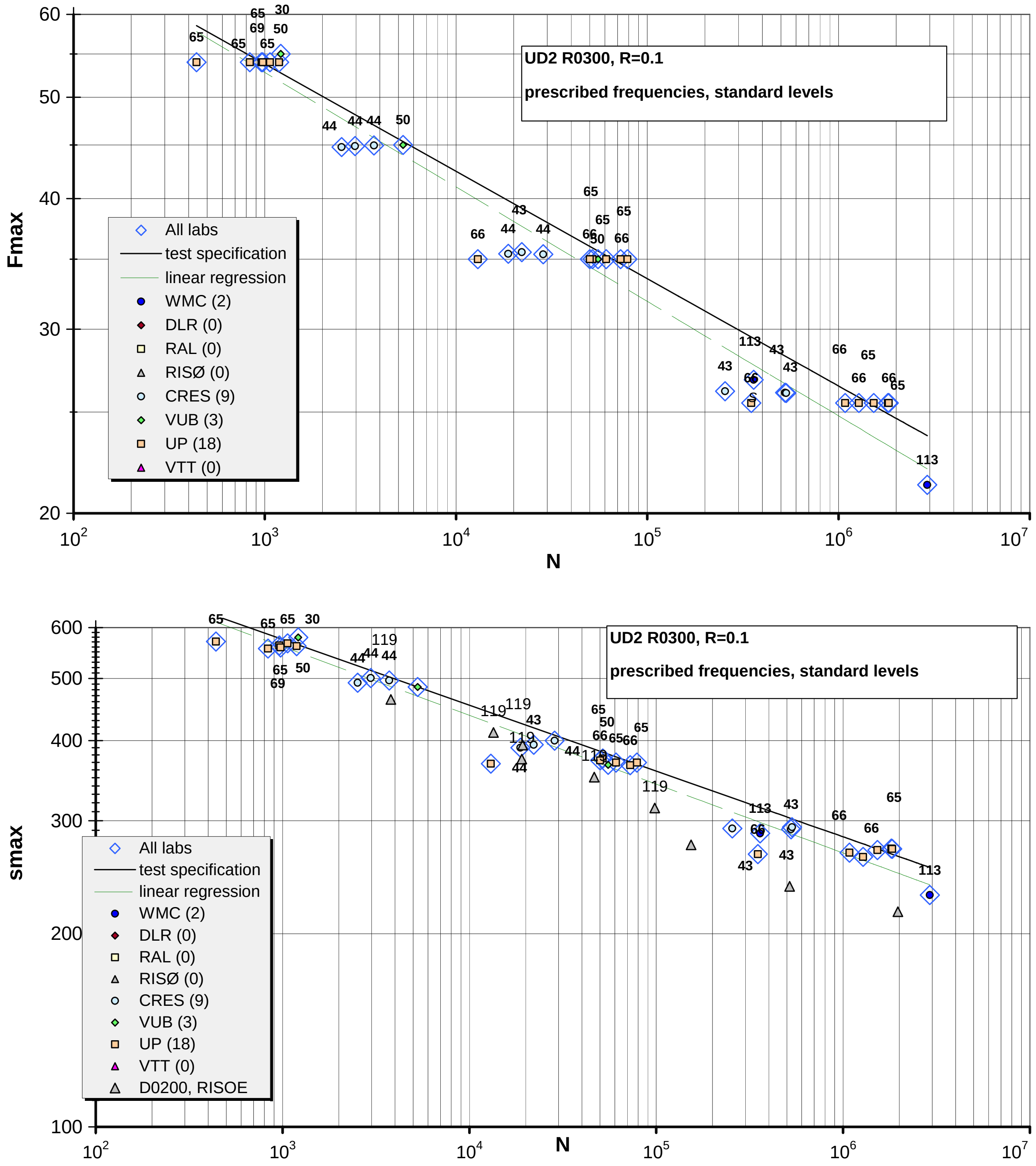


Fig. 20: UD2 R0300 R=0.1 S-N curves (lower including dog-bone D0200 geometry (grey triangles))

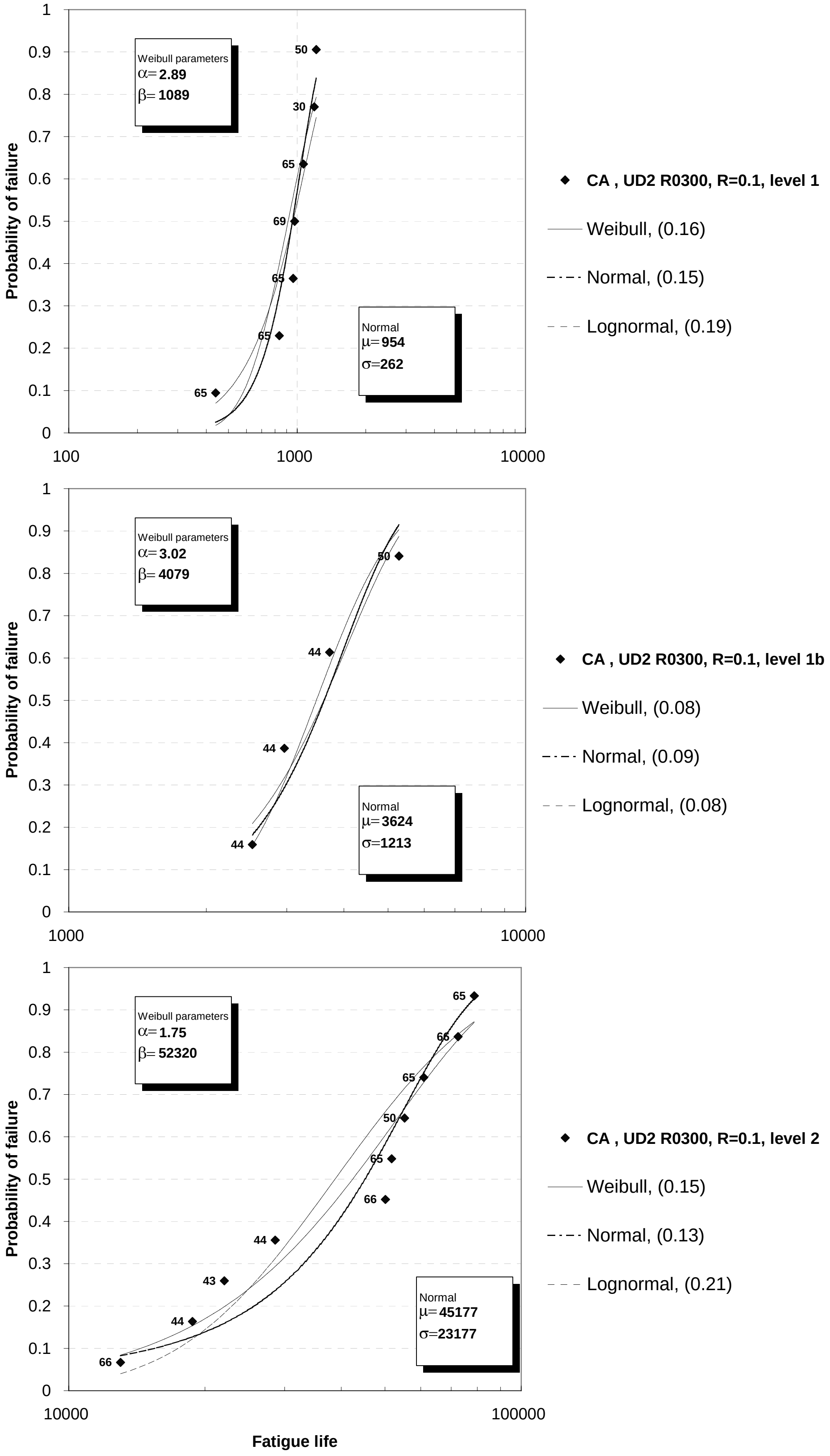


Fig. 21: UD2 R0300 R=0.1 level 1-2 probability plots

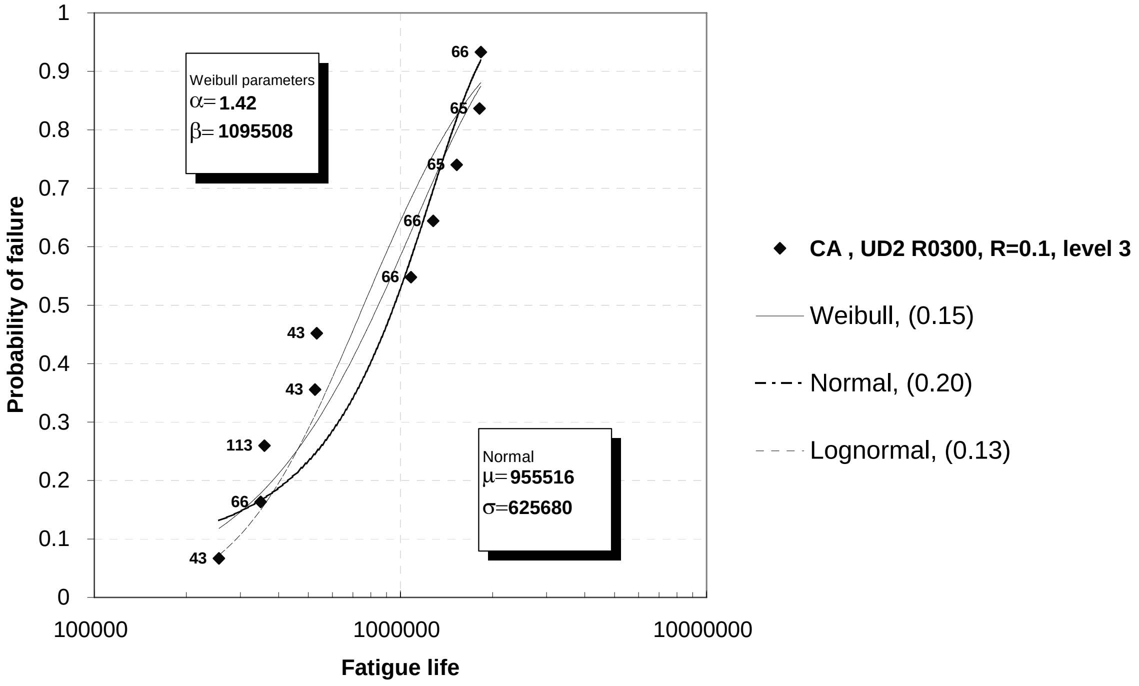


Fig. 22: UD2 R0300 R=0.1 level 3 probability plot

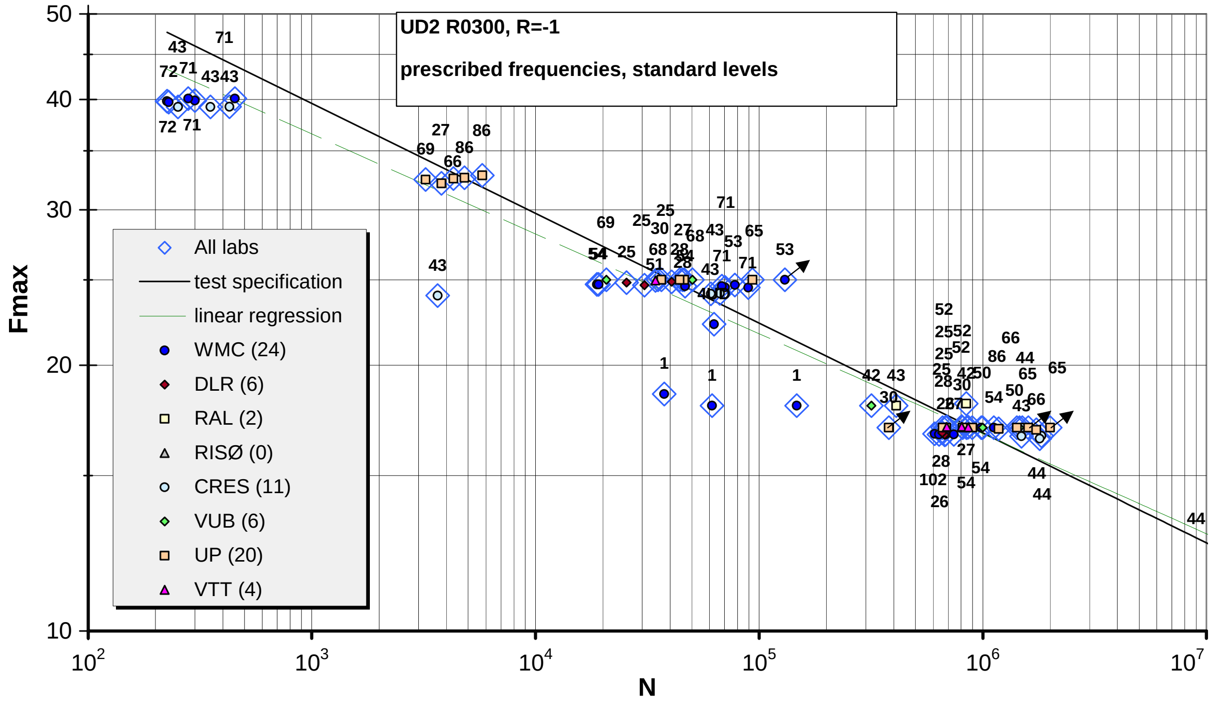


Fig. 23: UD2 R0300 R=-1 S-N curve

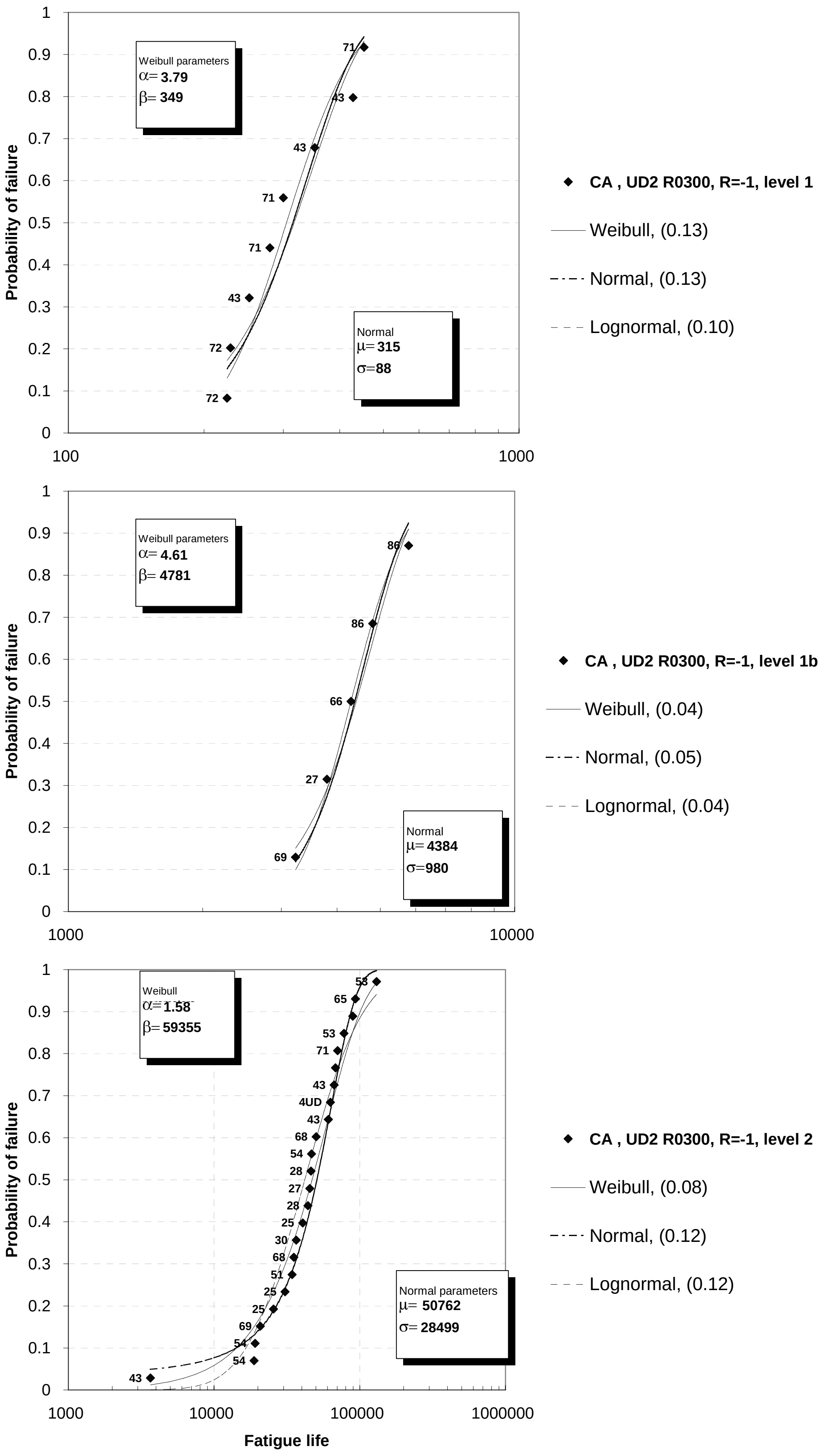


Fig. 24: UD2 R0300 R=-1 level 1-2 probability plots

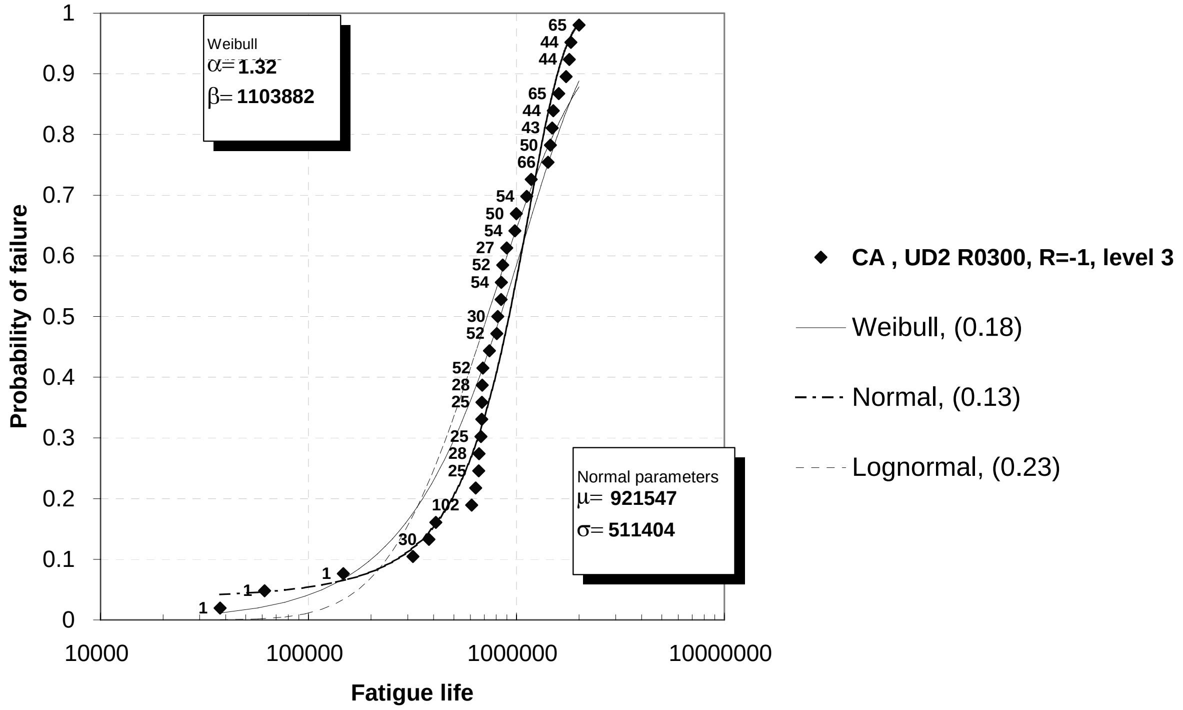


Fig. 25: UD2 R0300 R=-1 level 3 probability plot

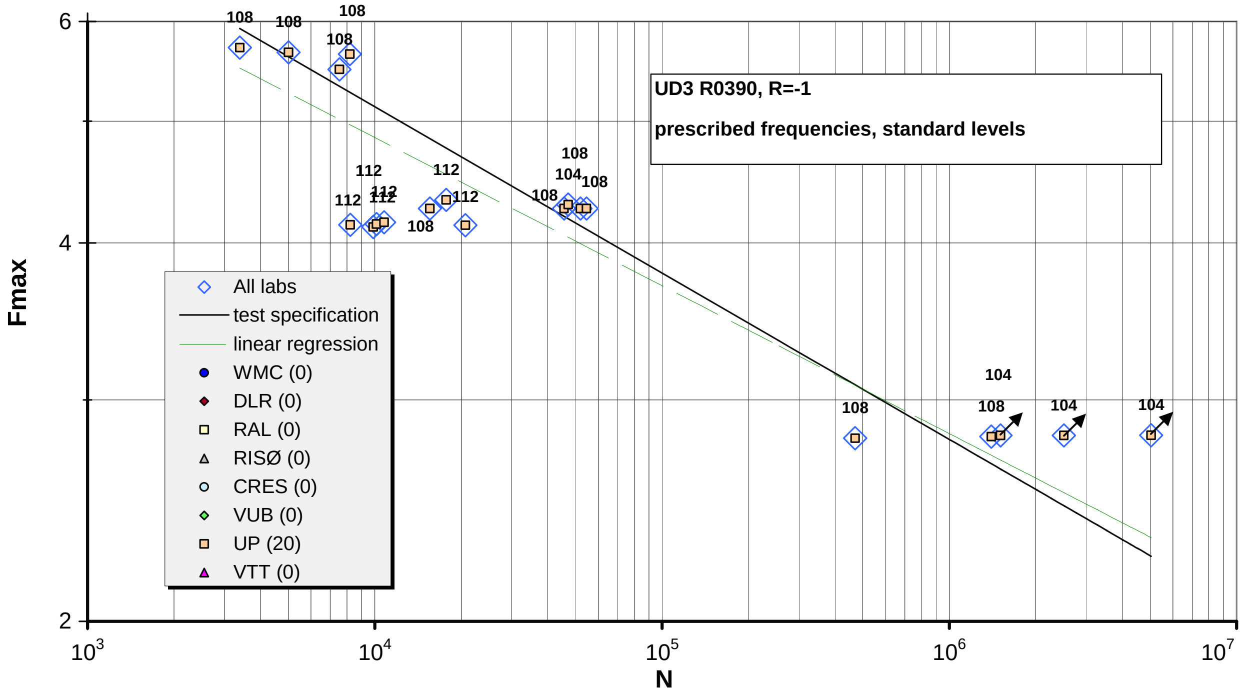


Fig. 26: UD3 R0390 R=-1 S-N curve

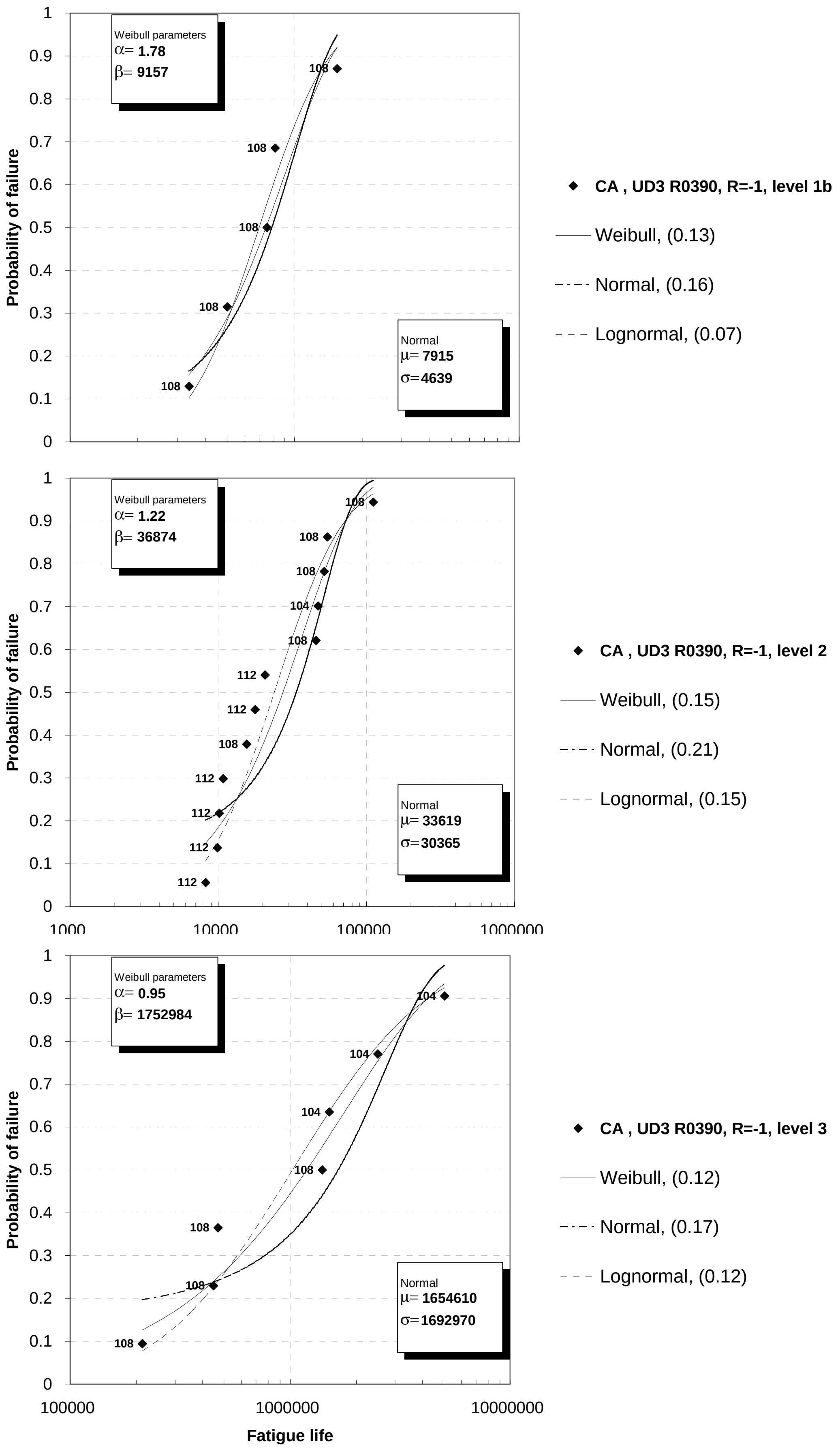


Fig. 27: UD3 R0390 R=-1 level 1b-3 probability plots

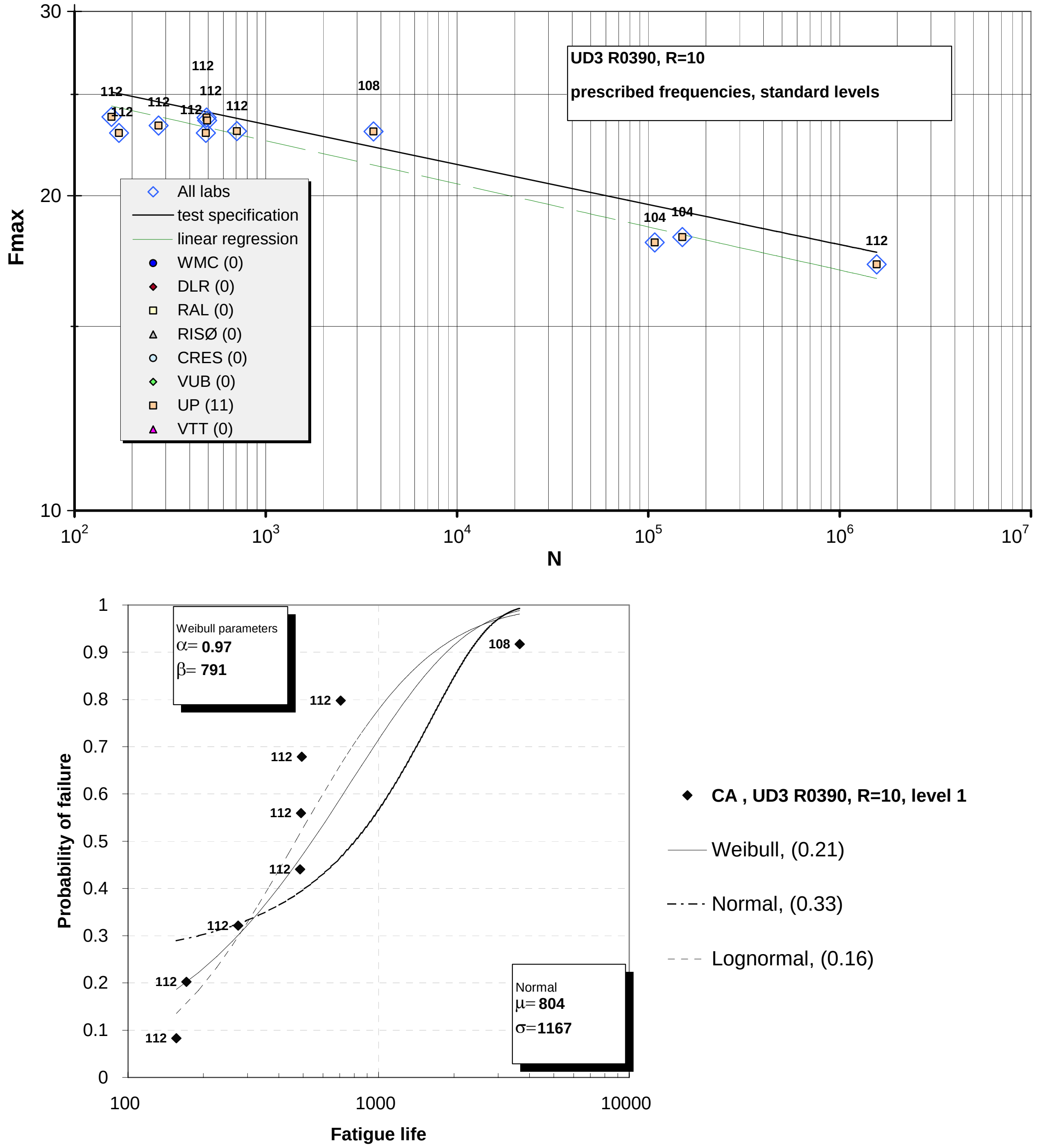


Fig. 28: UD3 R0390 R=10 S-N curve and level 1b probability plot

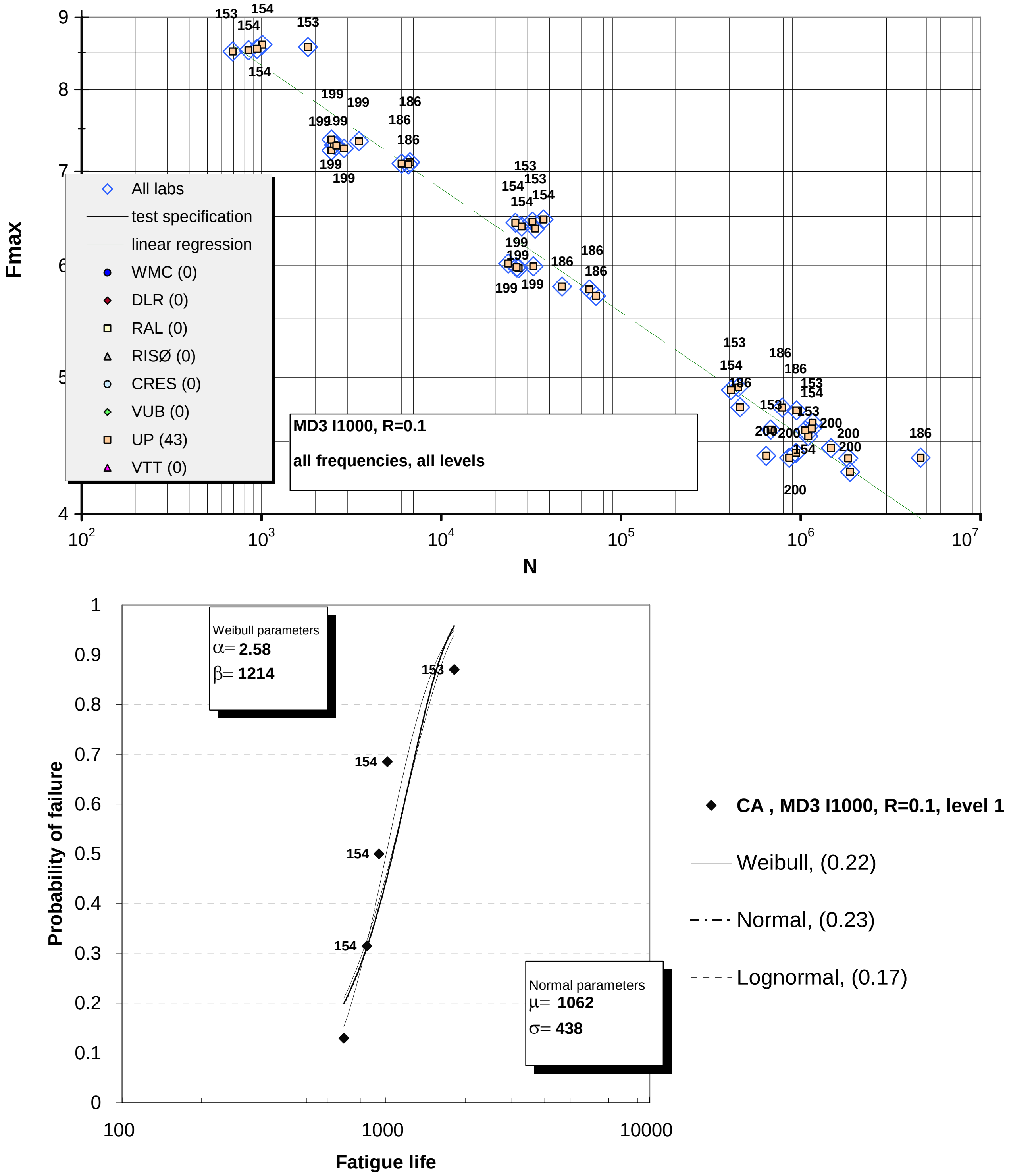


Fig. 29: MD3 I1000 R=0.1 S-N curve and level 1 probability plot

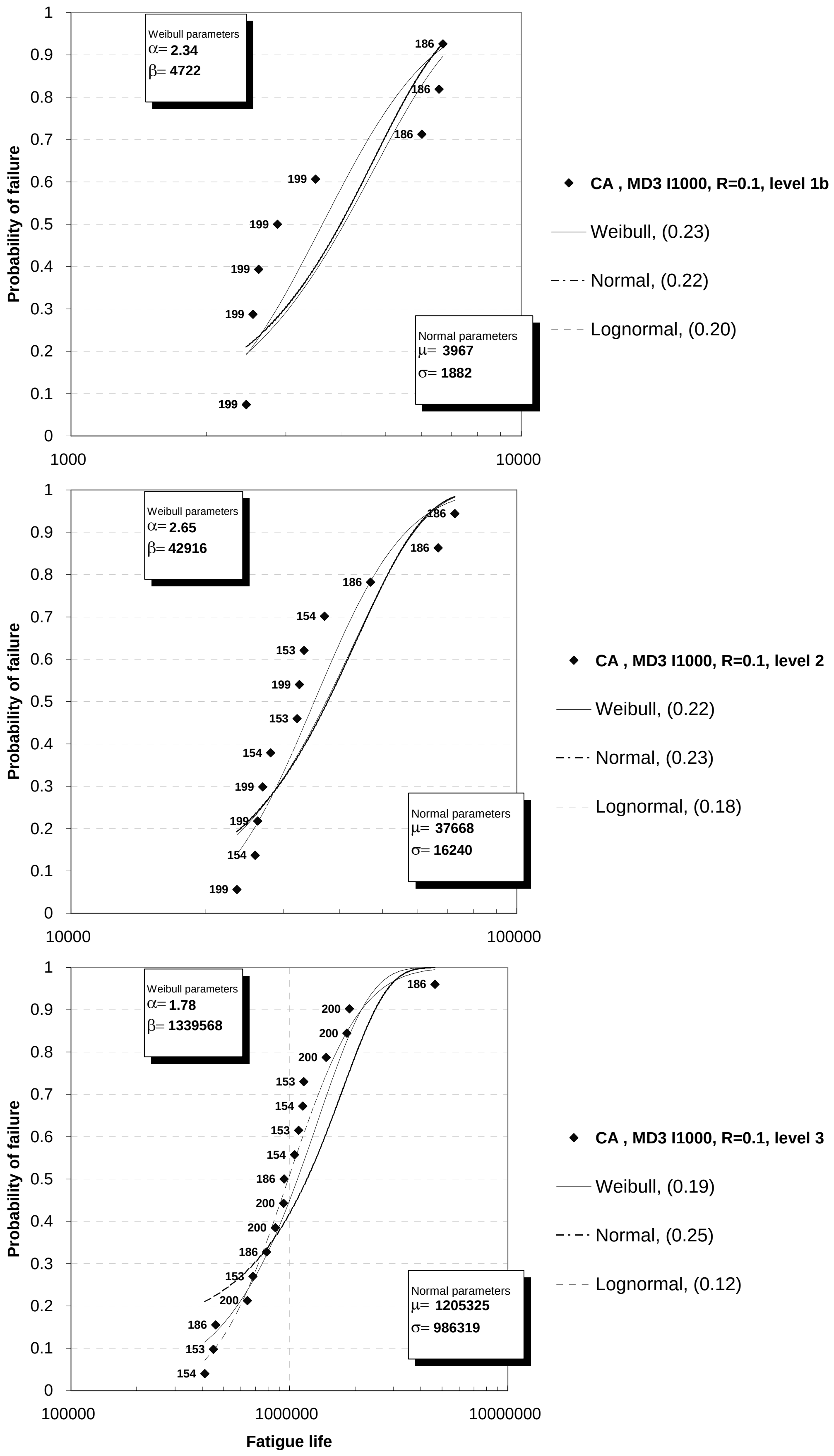


Fig. 30: MD3 I1000 R=0.1 level 1b-3 probability plots

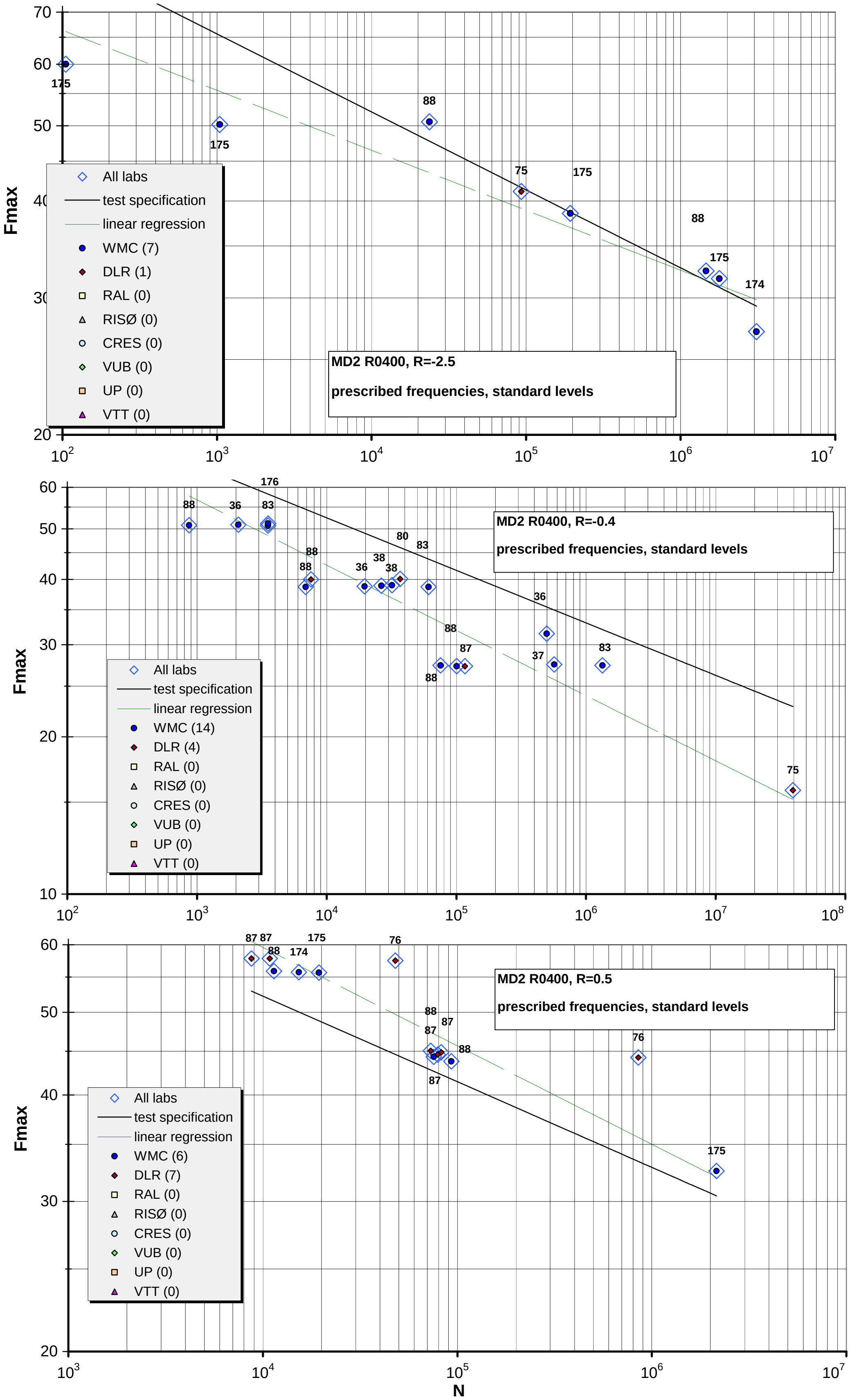


Fig. 31: MD2 R0400 other R-value S-N curves

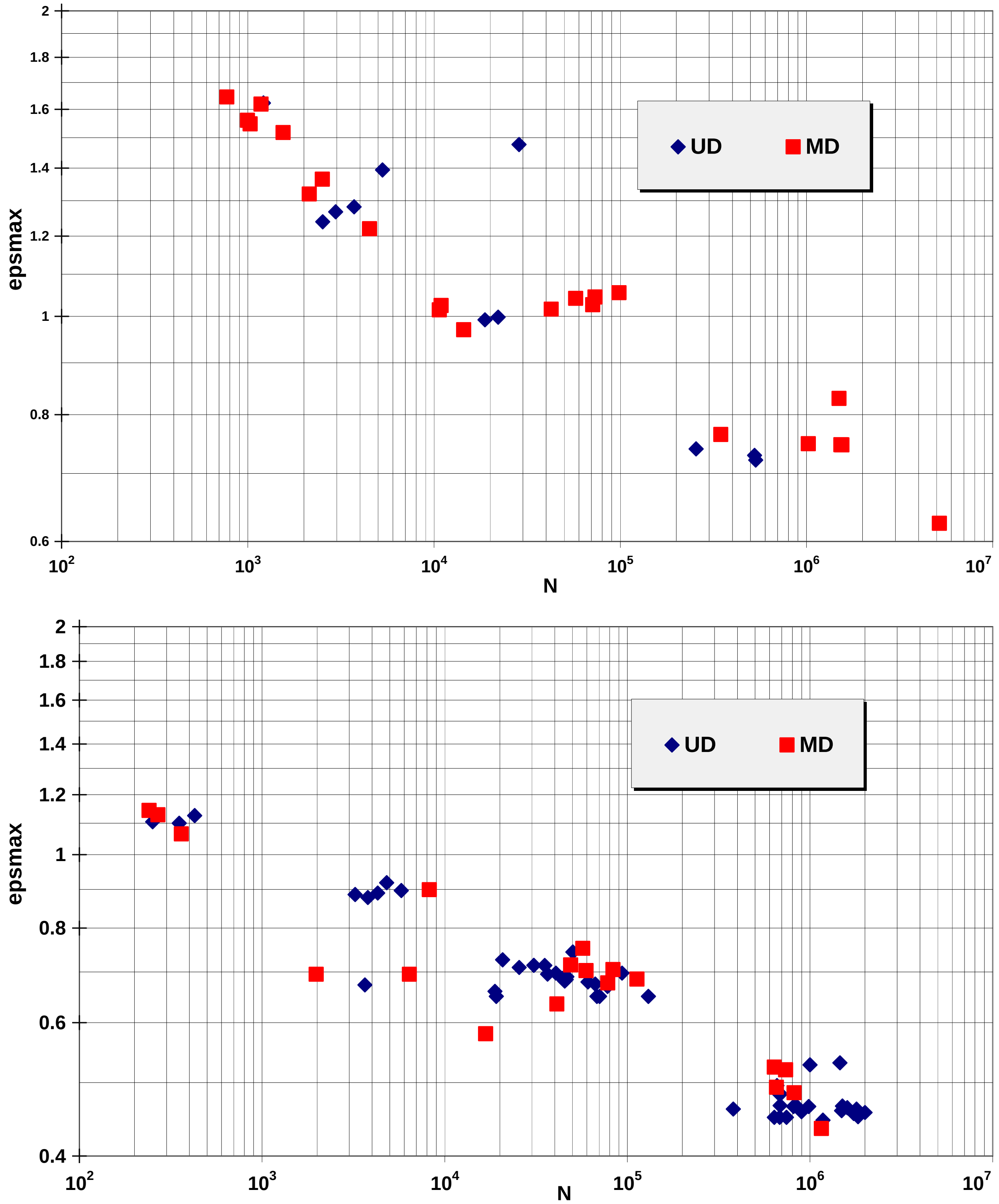


Fig. 32: Strain based R=-1 S-N curves for UD2 and MD2

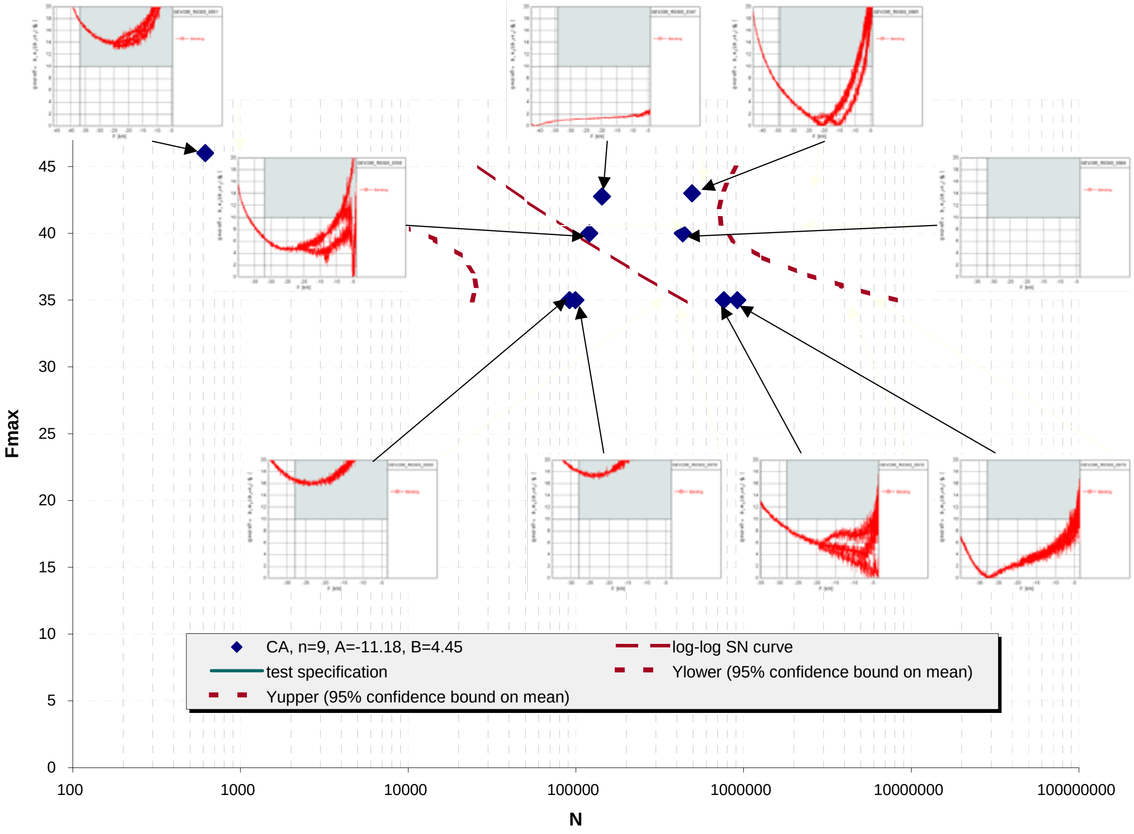


Fig. 33: UD R0300 at R=10. The inserts show bending during the first cycle, the bottom of the grey area represents 10% bending

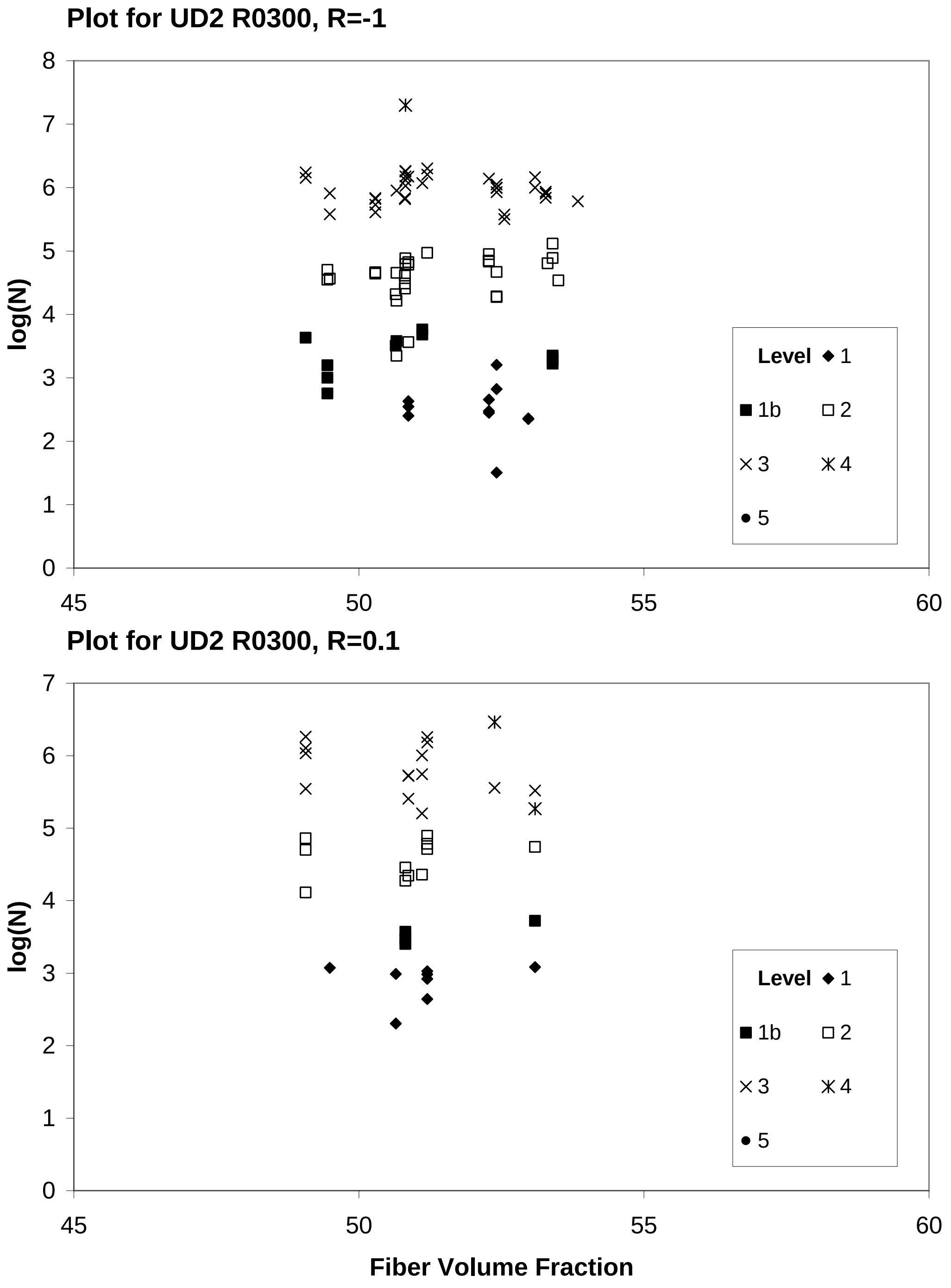


Fig. 34: Fatigue life vs Fibre Volume Fraction for UD2 at R=-1 and R=0.1

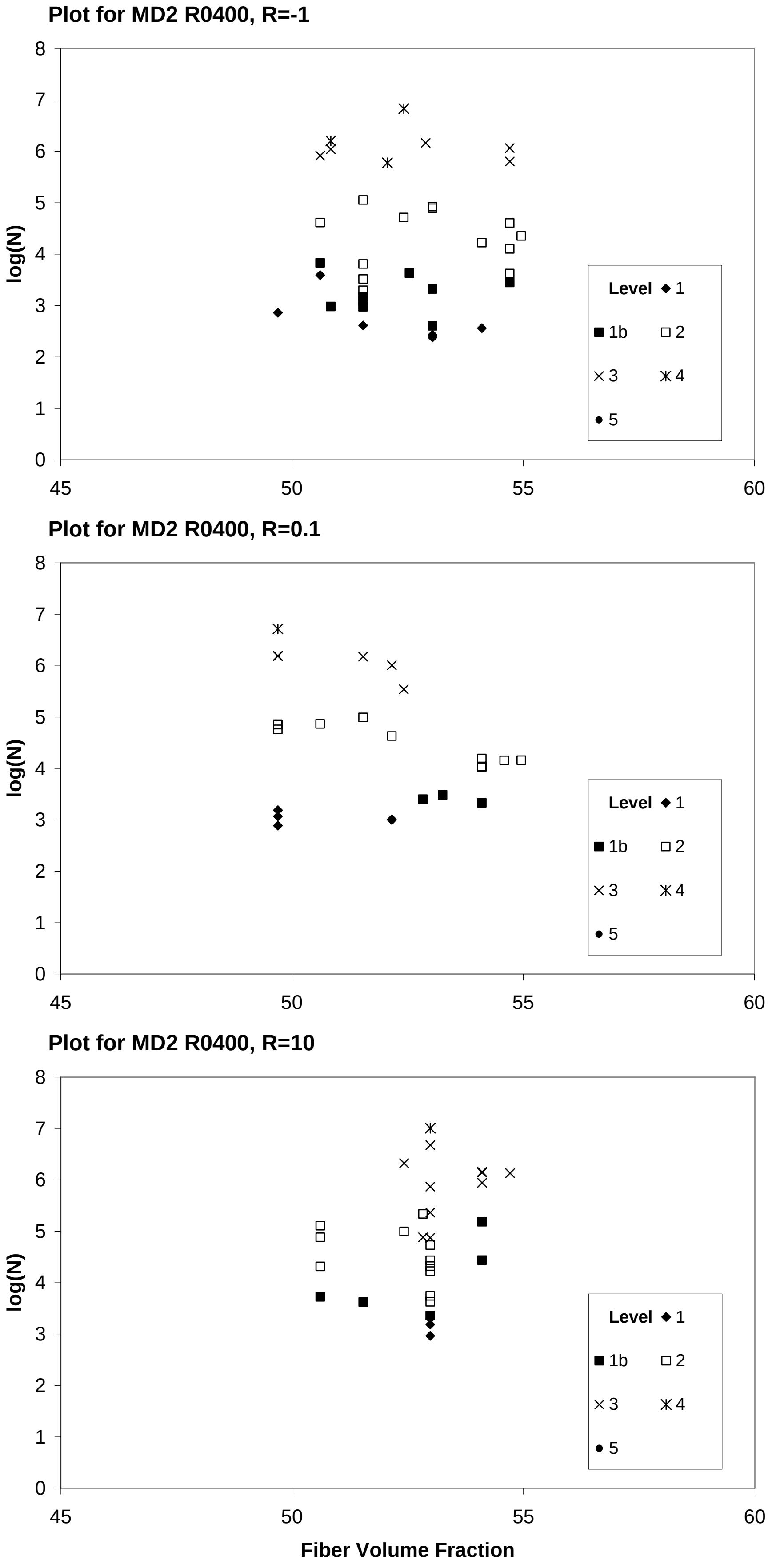


Fig. 35: Fatigue life vs Fibre Volume Fraction for MD2 at R=-1, 0.1, and 10

6. Fatigue of the alternative (phase II) material

The S-N curves for the alternative material are shown in Fig. 36 and Fig. 37(with a different resin: LM-E6 instead of the phase I Prime 20 from SP systems). The alternative material has slightly longer fatigue lives than the Phase I material for the cases investigated.

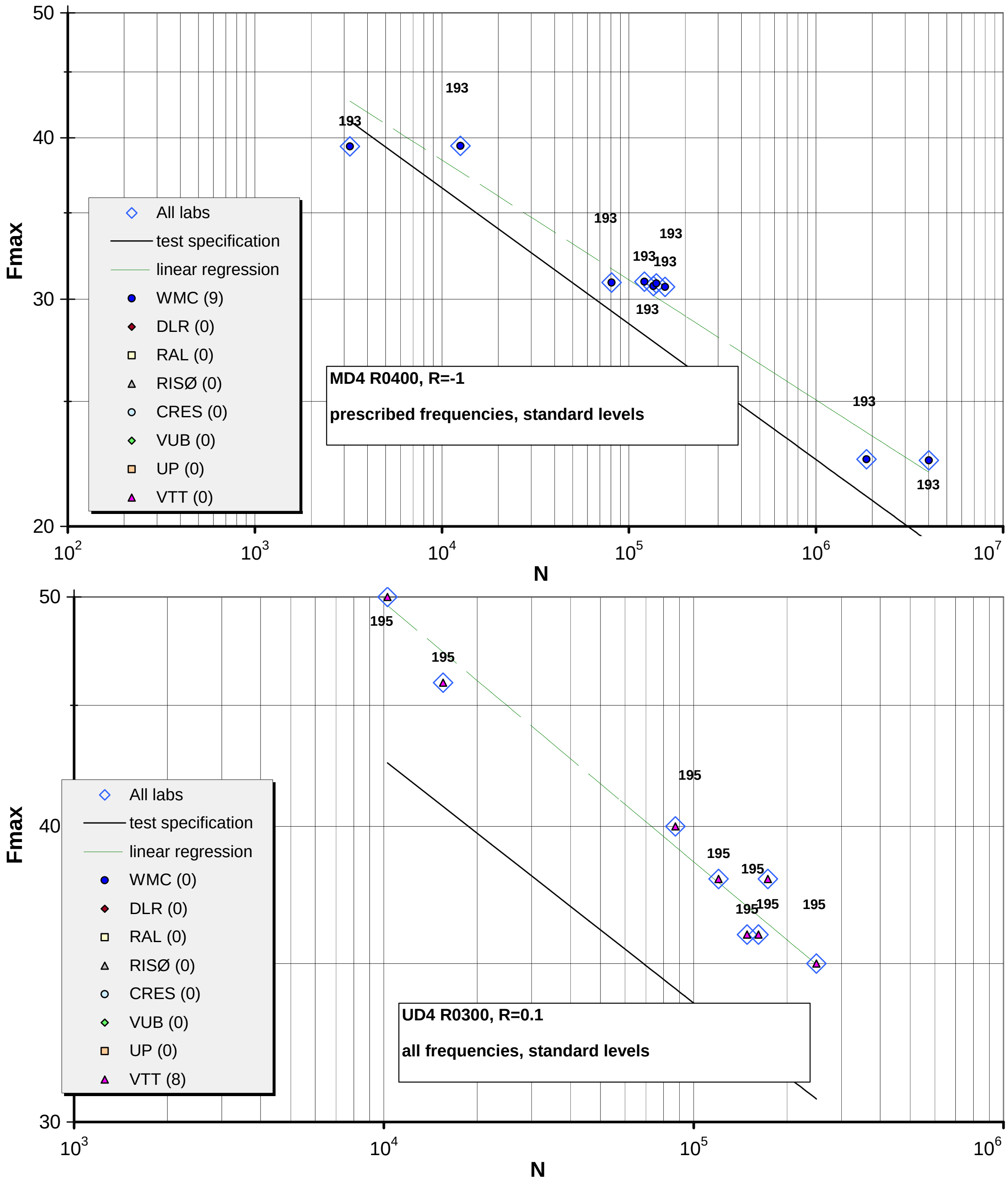


Fig. 36: S-N curves for MD4 R=-1 and UD4 R=0.1

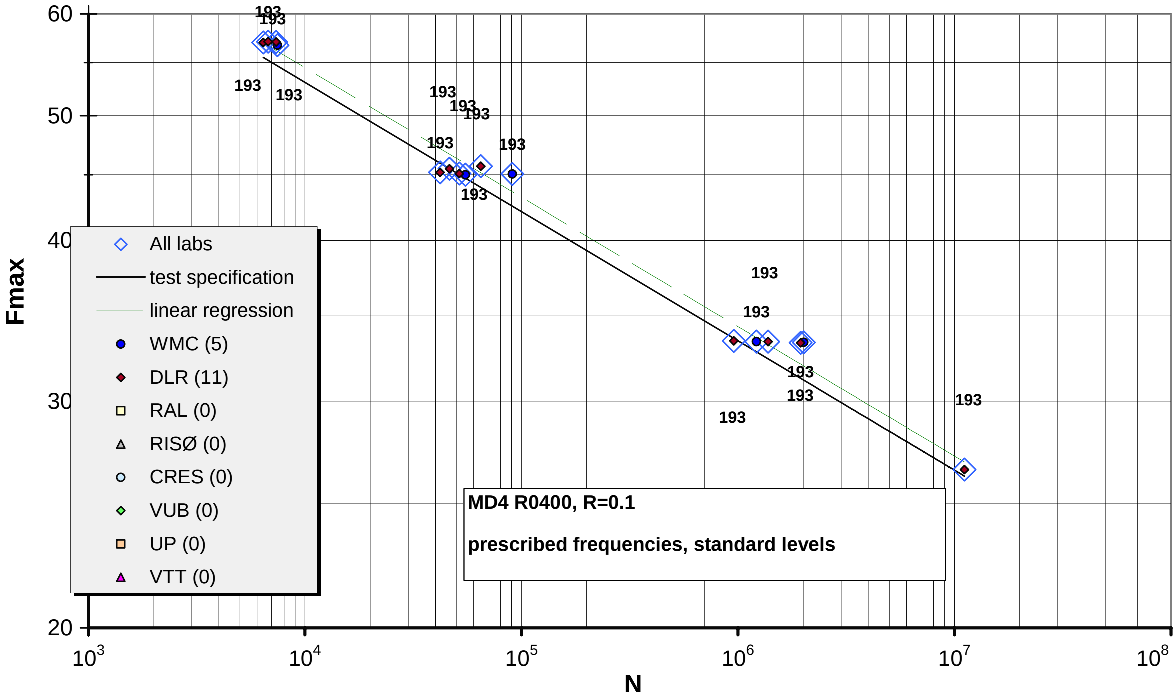


Fig. 37: MD4 R=0.1 S-N curve

7. Concluding Remarks

For the static data:

- A large static dataset is available from OptiDAT for the standard specimens, an extensive summary of which is described in this document
- There is no evidence, that either of the investigated distribution functions (Weibull, Normal, or Lognormal) describes static data best
- Scatter, in terms of the standard deviation of the Normal distribution σ/μ, is 5% of the mean strength for data per material, for batches of different plates. For nominally identical plates, cf. STT on MD3, the standard deviation can be as small as 2% of the mean.
- From a rudimentary variability analysis:
  - Plate-to-plate variations are generally smaller than machine-to-machine variations for UD2 and MD2
  - UD2 is more sensitive to machine-to-machine variations than MD2, especially in compression
  - Plate-to-plate variation can partly be explained by variations in fiber volume fraction.

For the fatigue data:

- The data generally follow the general test specification in terms of slope, indicating that:
  - For an acceptable determination of the slope of an S-N curve 6-10 specimens suffice
- Scatter is in the order of magnitude of 1 decade for most tests, and can be characterised by:
  - a σ/μ of 30% (on life) for both UD2 and MD2 at R=0.1, and for UD2 at R=-1
  - a σ/μ of 50-100% (on life) in other cases (standard OB specimens)
- On strain basis, the S-N curves for UD and MD are essentially identical
  - This is due to the fact that both laminates are fibre dominated
- There is no evidence, that either of the investigated distribution functions (Weibull, Normal, or Lognormal) describes static data best per standard level
- Lab-to-lab variations seem to be larger than plate-to-plate
  - Plate-to-plate variations are difficult to quantify due to the set-up of the test programme
  - No sigificant influence of Fibre volume fraction on life was found
  - It does not seem feasible to correct mean life estimates based on plate number.

Furthermore, it is recommended that the following aspects of the test results are subjected to further research (using e.g. multiple non-linear regression analysis):

- plate-to-plate variation
- lab-to-lab variation

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