Basic S-N curves

- summary of UD and MD CA@R=-1, 0.1 and 10 -

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Change record

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Introduction

This document presents the OB CA S-N data on the standard geometry that were listed in OptiDAT before the meeting in Patras (June 21st-23rd, 2004). From these data, a selection had to be made as to which data can be presented as 'valid'. A procedure is outlined for selecting these data, and the data selection that resulted was compared to the S-N curves that were given in the General Test Specification [1]. Also, an overview of the progress (basic S-N curves on standard OB specimens only) is given.

Raw S-N data

The raw S-N data were obtained by filtering OptiDAT d.d. june 11th, 2004.

The S-N curves were constructed from initial strain vs life to failure (columns 'e_max' and 'No. of cycles to failure' in OptiDAT). In the first phase of the project, it hasn't been standard procedure to list maximum strain when submitting data to the database. Therefore, for the points that lacked e_max data, an estimate was made on the basis of Young's Modulus, or on the basis of similar tests done in the same lab.
It would also have been possible to simply leave these tests out, but the authors are confident that reasonable estimates of the initial strain have been made.

Data from the preliminary programme (plates 204, 205, etc.) were excluded from the analysis.

Extraction of 'valid' data

The 'raw' S-N diagrams, which were produced in the manner described above, entered an assessment procedure yielding the points that could be described as the most valid data points. It was found in the course of the project, that testing frequency is of significant influence on the lifetime. Tests that were carried with a frequency that was above the prescribed frequency usually resulted in inferior lifetime performance.
In the current selection, an initial filtering was done using frequency. Then, from the remaining data, the data were discarded if they were below a given tolerance bound. Step-by-step, data were selected in the following manner:

1. A factor *x* is chosen, such that all specimens tested at a frequency higher than *x* times the prescribed frequency are considered invalid. For instance, an *x* of 1.1 means, that if the frequency is more than 10% higher than the prescribed frequency, the datapoint is discarded. The prescribed frequency was taken from Table I, which is in turn derived from [1].
2. A best fit is constructed using the remaining data, of the form e_max=A*log(N)+B
3. The residuals N_i-$N_{\text{best fit}}$ are calculated. Their mean is 0 and their standard deviation $\sigma_{\text{best fit}}$ is calculated.
4. With the number of points, a tolerance bound is found as:

   $$T_{n,\, c,\, p,\, \text{standard}}=N_{\text{best fit}}-K_{n,\, c,\, p,\, \text{standard}}*\sigma_{\text{best fit}}$$

   where $K_{n,\, c,\, p,\, \text{standard}}$ is a tabulated value, taken from different standards. This factor is dependent on the number of residual data, and on the desired confidence level *c*, and percentile *p*. In the current analysis, only the tolerance bounds for c=95 and p=95 or 90 were investigated.

5. All original data are evaluated and checked for their position relative to this lower tolerance bound. If they are above the tolerance bound, they are considered VALID (even if their frequency is too high!). If below the current tolerance bound, they are discarded.
6. A new fit is made through the valid data, which can be compared to the test specification.

Table I: A and B for F=A*N^B

		R		
		-1	**0.1**	**10**
MD	**A**	1217	6626	6151
	B	-1.9791	-2.0037	-2.0035
UD	**A**	1244	4198	4198*
	B	-1.9919	-1.9945	-1.9945*

*NB the values for R=0.1 were used here for lack of test specifications

The decisions that need to be taken in the course of this process are

A. Allowable frequency in step 1 (through the factor *x*);
B. Tolerance bound characteristics and relevant standard in step 4.

Apparently, the frequency can be of rather important influence on the lifetime. This is once more apparent from figure 1, where the number of points that is discarded is plotted versus *x* of step 1, for one R-ratio. This graph is fairly steep for small *x*'s. So, allowing higher frequencies will result in less data being discarded, which in the subsequent process will lead to increased scatter in the S-N diagram, and vice versa.

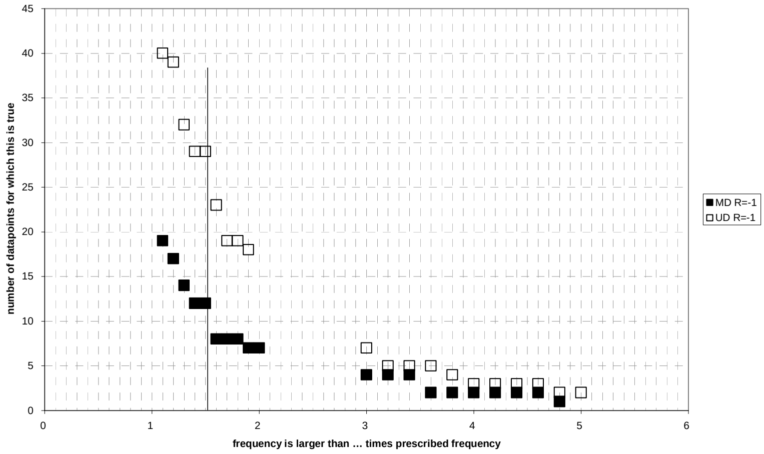


Figure 1: x vs number of points discarded in step 1

A complete treatment of tolerance bounds is far beyond the scope of this document. An attempt to a somewhat comprehensive description is given in [2]. This document compares tables of K-factors as used in step 4. Several sources have published rather different tables of these values. In general, the GL standard [3] yields non-conservative values, because this standard is meant for static data rather than fatigue data and therefore assumes a small coefficient of variation. Other standards are more conservative [4-6].
In the results presented in this document, the 95/95-tolerance bounds were used for step 4, the necessary $K_{n, c, p}$ -values were taken from the DIN-standard [5].

NB: It was assumed, that the residuals were Normal distributed. In the cases investigated, the R^2-value from a Normal probability plot varies between 0.6 and 0.95 roughly, in most cases the assumption of Normal distributed data seems reasonable, justifying the use of the abovementioned methods.

Rationale of the method

The advantage of this seemingly elaborate procedure, is that it results in an intuitively correct filtering of the S-N data. When using the frequency as an exclusive criterion, data that are actually very close to the test specification might be discarded because they were done at too high a frequency. This is especially true for the long running tests, where frequency-influence seemed of smaller severity than for the higher load levels. Also, data that were tested at or close to the correct frequency, but nevertheless did not come close to the expected lifetime would not be discarded

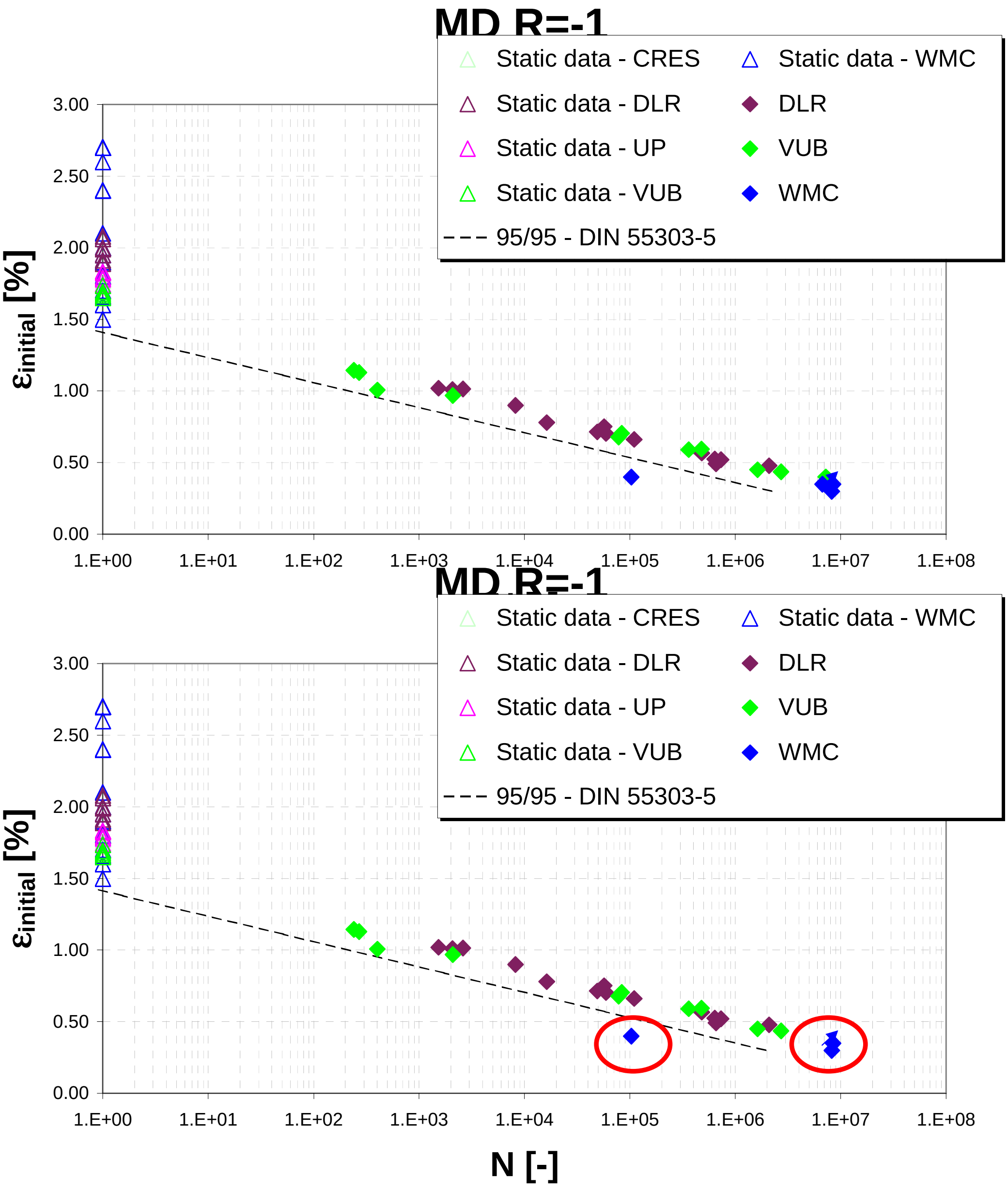


Figure 2a (top) and b, corresponding to an *x* of 1.2 and 1.1, respectively. The left red circle shows the datapoint that is counterintuitively retained (the frequency was close to prescribed, but without apparent reason, the lifetime was inferior).
The right circle shows the location of two WMC and VUB datapoints that were discarded, although they were virtually on the S-N line.
The dotted line shows the 95/95 tolerance bound according to DIN 55303-5 that was generated using the data shown. Clearly, using this tolerance bound as a lower ‘validity’boundary would result in the left WMC point to be discarded and the two missing points to being reinstalled.

when looking at frequency only, whereas, intuitively, they seem incorrect to include in the graphs.

An example of such data (counterintuitively discarded or counterintuitively retained) is given in figures 2a and b for MD R=-1 data.

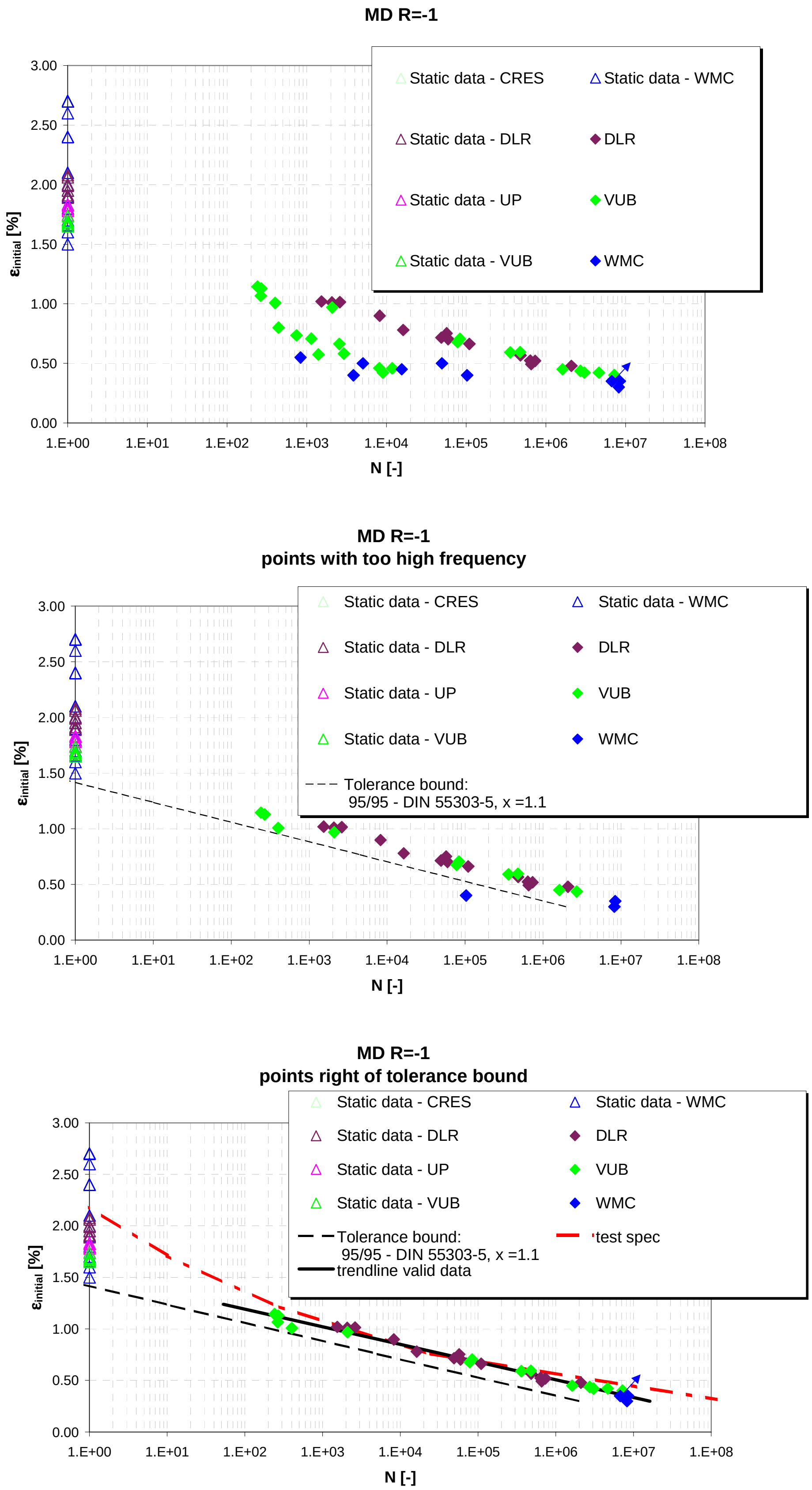
Results

The results of the selection are presented in figures 3-10.

Figures 3 show the raw data, the results of step 1 and finally, the results of step 4 for MD R=-1.

Figures 4-8 show the results for step 4 for the other R-ratios and for UD. Note, that for UD, R=10, there was no test specification available for this case at the time of writing. The tolerance bound was determined using the frequency vs F information of R=0.1 (these A and Bs were very similar for MD, it was assumed that this was the case for UD as well).
In most cases, the general test specification [1] was closely matched by the results. For MD R=0.1, the lifetimes were generally higher than as per the specification.
The data seem to follow a lin-log trend in some cases, rather than the log-log trend as was suggested in the specification. This especially has consequences for tests done at level 1, where the target number of tests is higher than the results show. Not being able to meet the target number of cycles has been a problem in phase 1 for level 1.
It is interesting to note, that in this strain-based representation, the lifetimes that can be expected from UD specimens closely match those of MD specimens.

Finally, the progress is shown per R-ratio and laminate for the different labs, see figures 9-11.
Clearly especially WMC and to some extent CCLRC and VUB are behind schedule.


MD R=-1

MD R=-1
points with too high frequency

MD R=-1
points right of tolerance bound

Figure 3a, b, c (top, middle, bottom): Raw MD=-1 data; data after extraction of the points with factor x (step 1); data after extraction of points left of the tolerance bound that resulted from step 1. The red line in c) gives the test specification, the thick black line gives the S-N data from the ultimately selected data.

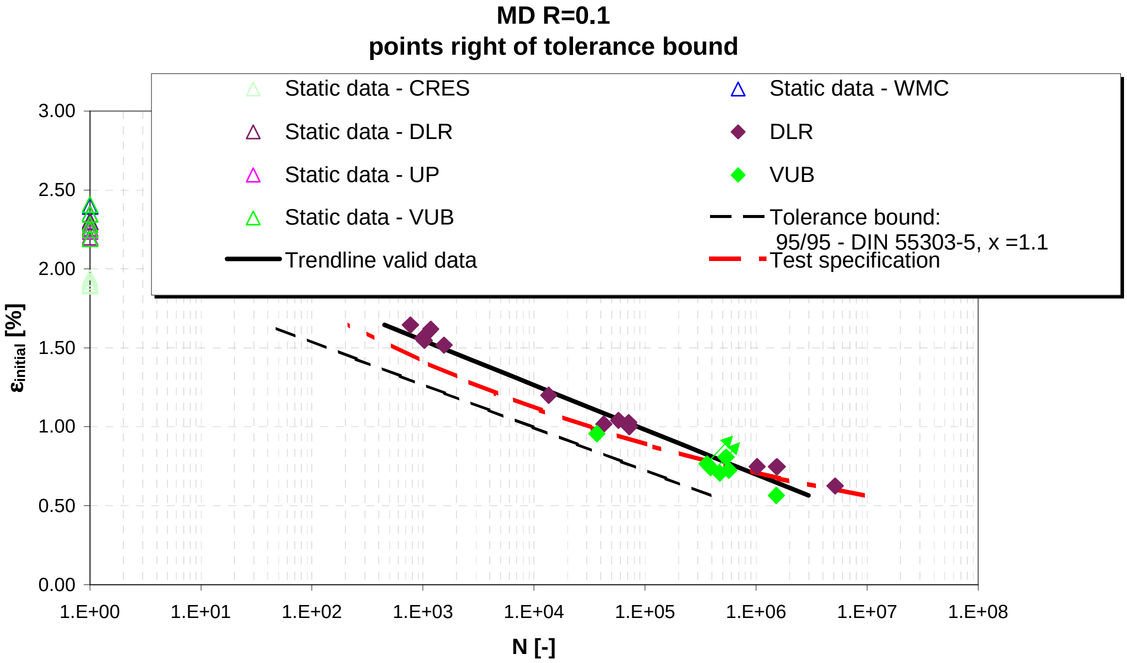


Figure 4

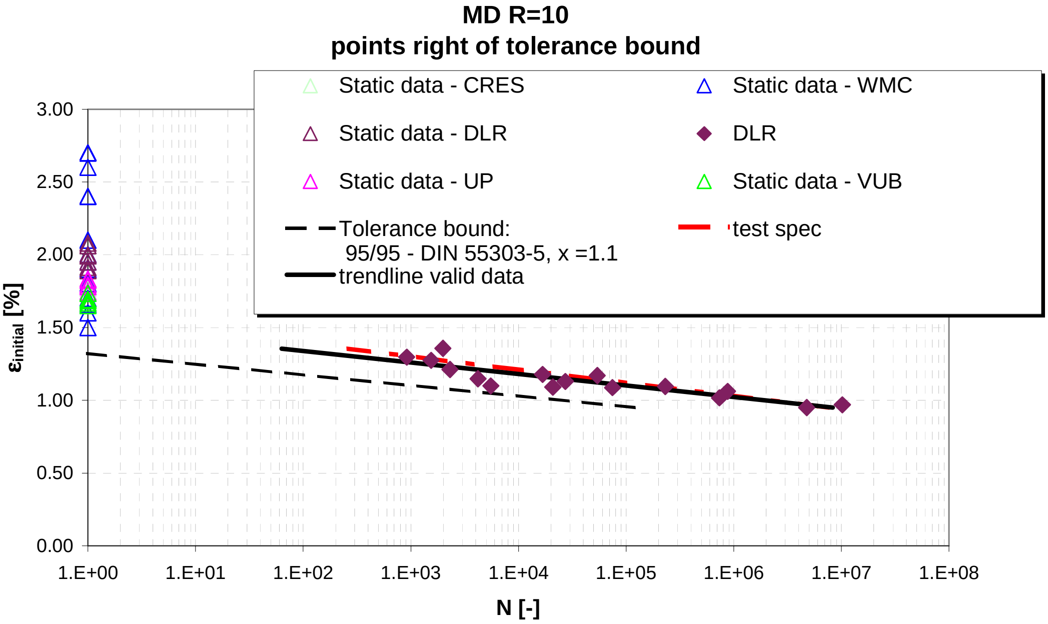


Figure 5

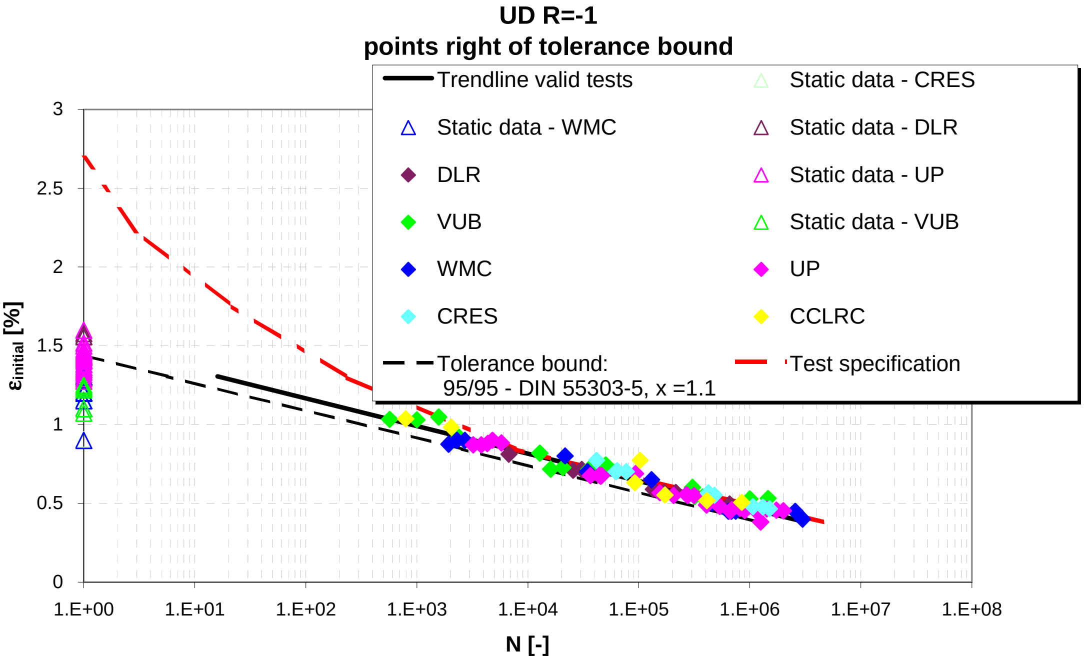


Figure 6

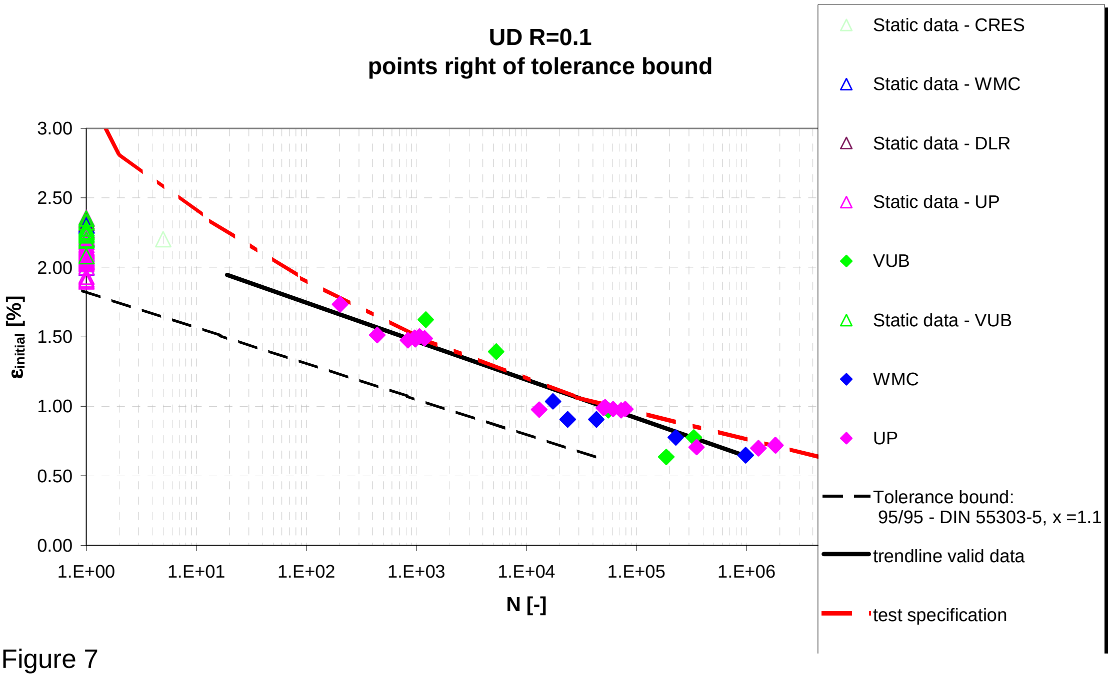


Figure 7

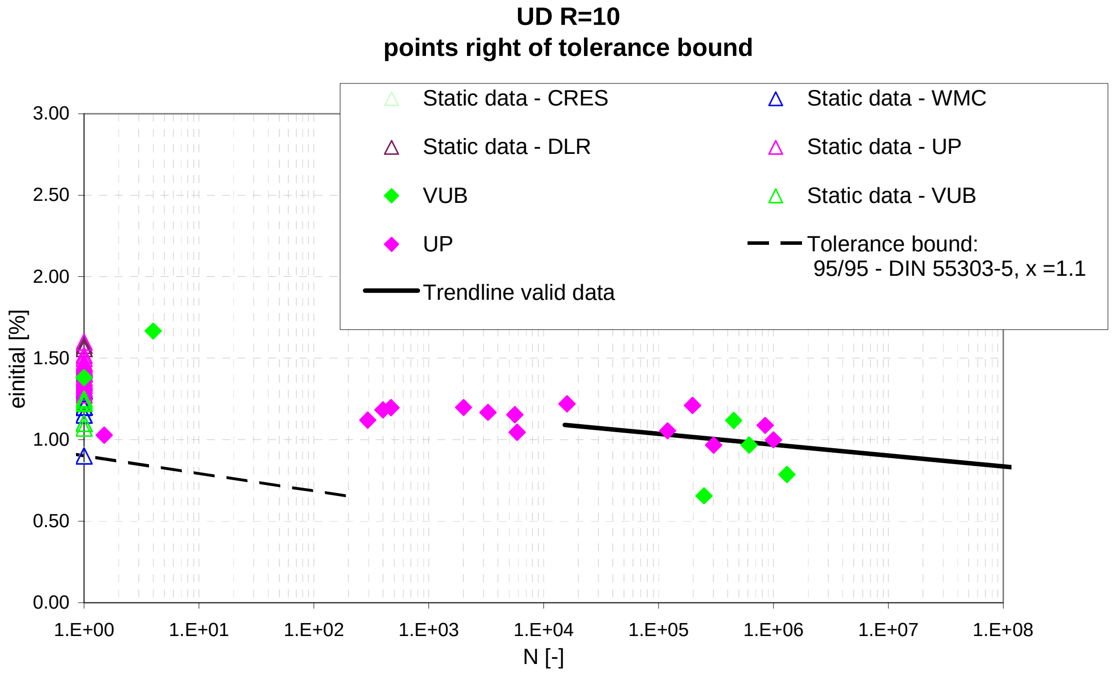

UD R=10
points right of tolerance bound
Static data - CRES
Static data - WMC
Static data - DLR
Static data - UP
VUB
Static data - VUB
UP
Tolerance bound:
95/95 - DIN 55303-5, x =1.1
Trendline valid data
3.00
2.50
2.00
1.50
1.00
0.50
0.00
einitial [%]
1.E+00
1.E+01
1.E+02
1.E+03
1.E+04
1.E+05
1.E+06
1.E+07
1.E+08
N [-]

Figure 8

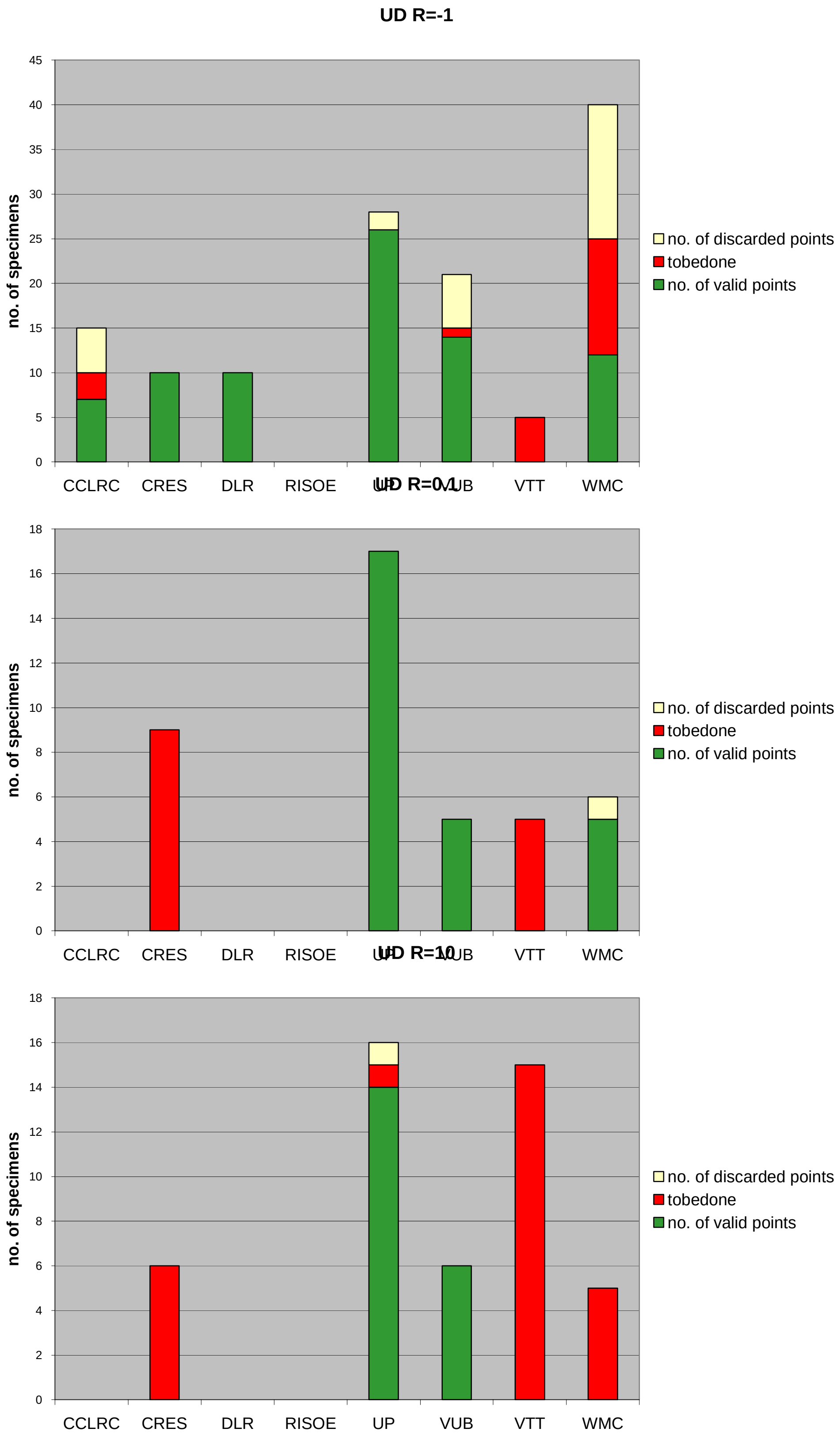

UD R=-1
no. of specimens
0
5
10
15
20
25
30
35
40
45
CCLRC
CRES
DLR
RISOE
UP
VUB
VTT
WMC
no. of discarded points
tobedone
no. of valid points
UD R=0.1
no. of specimens
0
2
4
6
8
10
12
14
16
18
CCLRC
CRES
DLR
RISOE
UP
VUB
VTT
WMC
no. of discarded points
tobedone
no. of valid points
UD R=10
no. of specimens
0
2
4
6
8
10
12
14
16
18
CCLRC
CRES
DLR
RISOE
UP
VUB
VTT
WMC
no. of discarded points
tobedone
no. of valid points

Figure 9

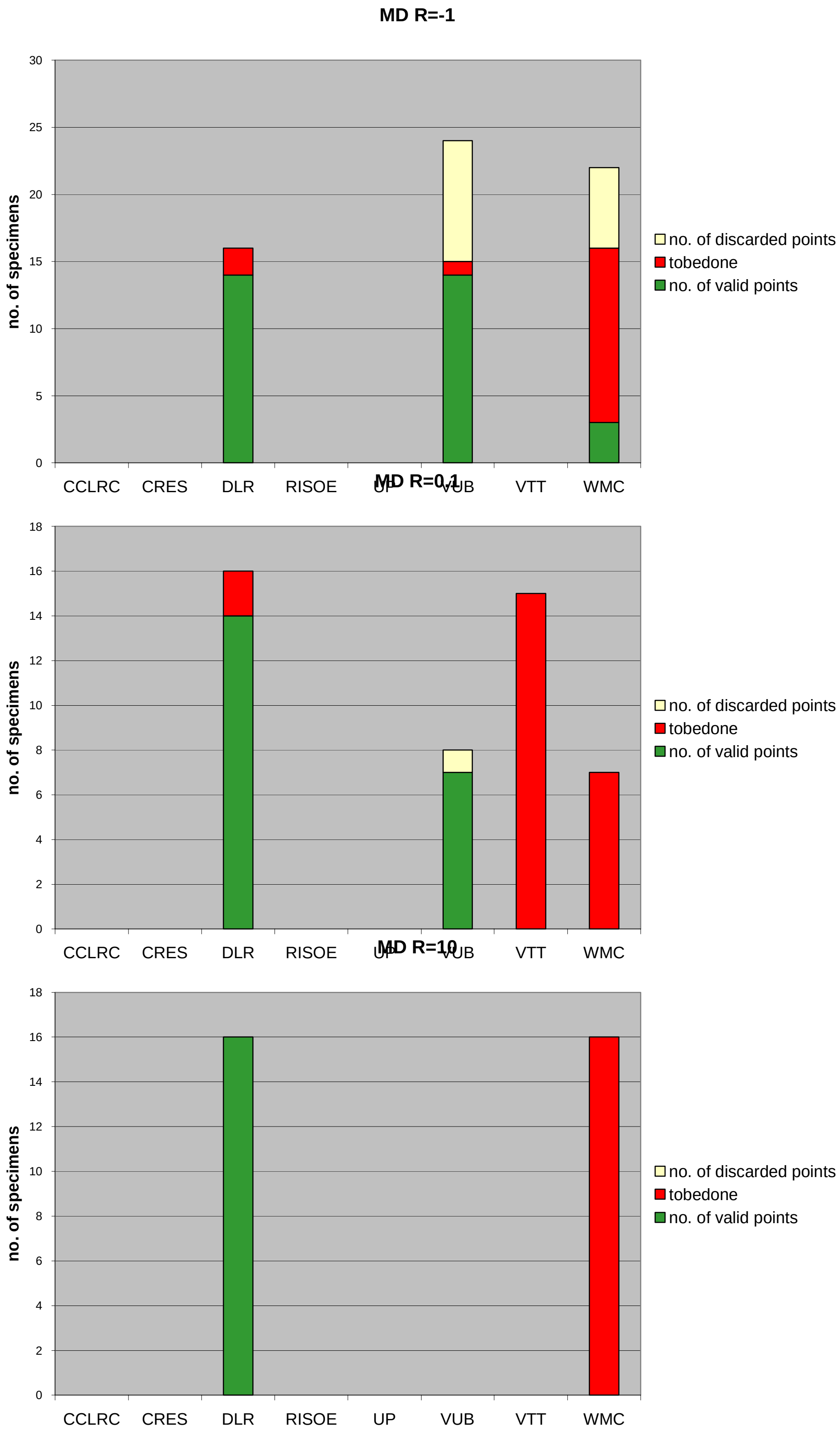
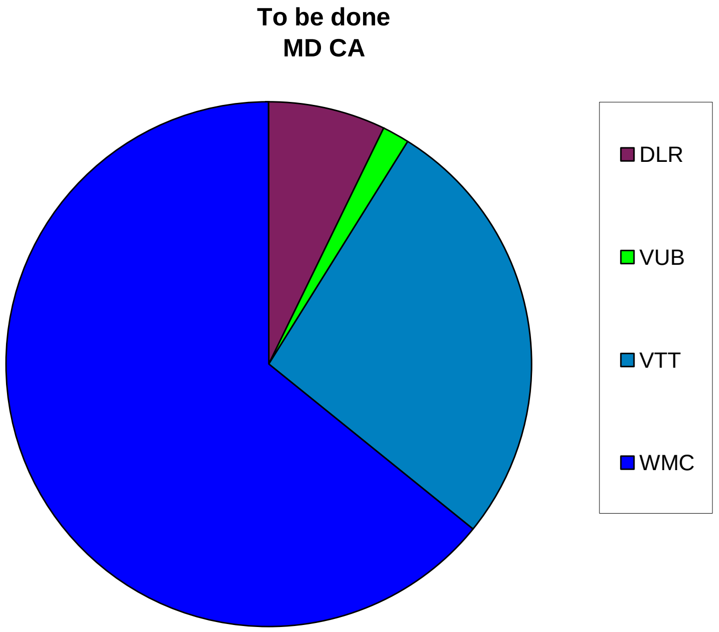

MD R=-1
no. of specimens
0
5
10
15
20
25
30
CCLRC
CRES
DLR
RISOE
UP
VUB
VTT
WMC
□ no. of discarded points
🟥 tobedone
🟩 no. of valid points
MD R=0.1
no. of specimens
0
2
4
6
8
10
12
14
16
18
CCLRC
CRES
DLR
RISOE
UP
VUB
VTT
WMC
□ no. of discarded points
🟥 tobedone
🟩 no. of valid points
MD R=10
no. of specimens
0
2
4
6
8
10
12
14
16
18
CCLRC
CRES
DLR
RISOE
UP
VUB
VTT
WMC
□ no. of discarded points
🟥 tobedone
🟩 no. of valid points

Figure 10


To be done
MD CA
DLR
VUB
VTT
WMC

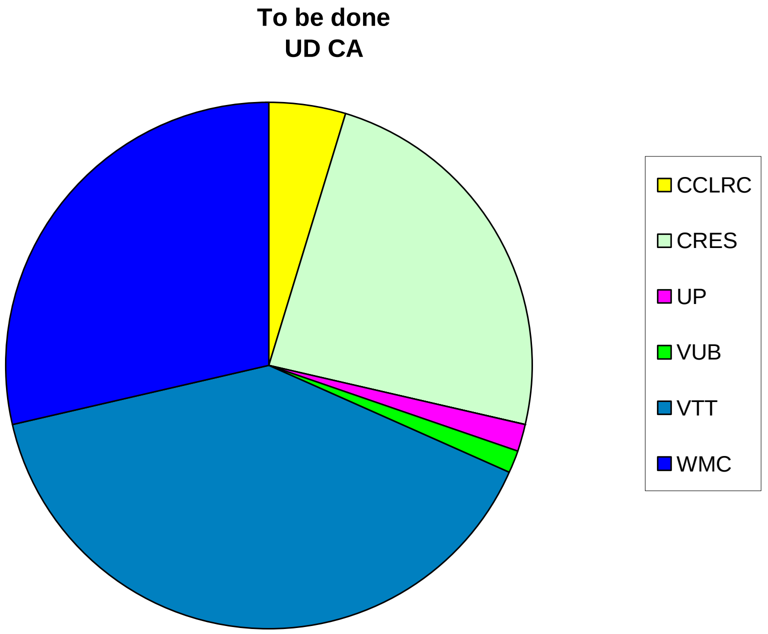

To be done
UD CA
CCLRC
CRES
UP
VUB
VTT
WMC

Figure 11

References

1. O. Krause, Th. Philippidis, *'General Test specification'*, OB_TC_R014 rev002, March 2004
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4. '*Polymer matrix composites – Department of defense handbook MIL-HDBK-17-1E working draft'*, Volume 1-Guidelines for characterization of structural materials, Chapter 8, U.S. Department of Defense, 23 January 1997
5. '*Statistische Auswertung von Daten – Bestimmung eines statistischen Anteilsbereiches'*, DIN 55-303, Teil 5, Beuth Verlag GmbH, Berlin, February 1987
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