

# Residual Strength Tests - data and analysis -

OB\_TG5\_R007 rev. 003 (final)  
doc. no. 10285

June 19<sup>th</sup>, 2006



*TG 5*

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Change record

Issue/revision	date	pages	Summary of changes
draft version 000	June 14th, 2005	38	
revision 1	December 11 <sup>th</sup> , 2005	53	revised figures and graphs. Added level 4 graphs and other lay-ups, RS probability plots. Included more text on stiffness degradation.
revision 2	February 8 <sup>th</sup> , 2006	5459	updated RSTT, R=0.1, UD2, level 2; added RST for transverse UD at R=10
revision 3 (final)	June 19 <sup>th</sup> , 2006	59	revised/updated all graphs with new data from OptiDAT



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## 1. Introduction

Strength and stiffness are potentially useful parameters in life estimation for composites in fatigue. They are material characteristics, which have been extensively modeled (see e.g. the review by Philippidis and Passipoularidis [1]), but for which experimental data are limited. Within TG5 an attempt was made to describe strength degradation after fatigue as extensively as was feasible within the project constraints.

This document describes the residual strength tests performed in phase I. Most of the tests ultimately reported in OptiDAT are discussed here, including test methodology, general data trends, and possible analysis method.

## 2. Description of test set-up and procedure

### 2.1. Baseline Tests

Prior to the residual strength tests, some baseline tests were performed to describe the fatigue behaviour at different R-ratios, and the static strengths. The relevant test results were recorded in OptiDAT [2]. A summary of static strengths and fatigue lives according to the test specification and actual data is given in [3].

### 2.2. Residual Strength Tests

The residual strength test consists of a (series of) slow cycle(s), followed by a constant amplitude fatigue section, acoustic emission measurements (RAL and UP)), another (series of) slow cycle(s), and it is finalised by a static test. See Figure 1 and [4].

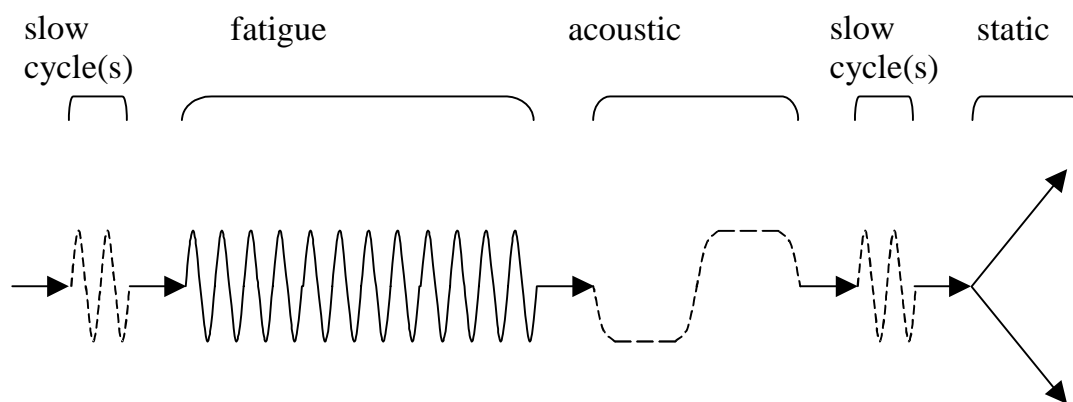


Figure 1: Schematic of residual strength test procedure

The slow cycle(s) enable measurement of both the tensile and compressive modulus and/or initial maximum strain. The constant amplitude section is expected to introduce some fatigue damage into the specimen. This section is specified at load levels and frequencies which comply with the constant amplitude tests done for the determination of the S-N curves. The final acoustic emission measurement, slow cycle(s) and static test serve to evaluate the influence of prior fatigue on remaining strength and stiffness of the coupon. Acoustic emission was measured by UP and RAL, see e.g. [5].



Although the utmost consistency was strived for, there were some inevitable differences between the laboratories in the methodology of testing for residual strength. By this is meant the inherent differences in testing machines, tested plates, slight differences in ambient conditions, etc. Additional potential sources of inconsistency were introduced by application of non-destructive testing in some laboratories. For example, WMC did not perform any intermittent acoustic measurements, contrary to UP and RAL. At UP, application of the necessary equipment did necessitate taking the specimen out of the machine prior to the final static test. At WMC, for the long-life fatigue tests (level 4), this was also necessary. The transfer of the specimen between test frames might introduce a small misalignment of the coupon, which might be reflected in the residual strength. The effect of misalignment is likely to be R-ratio dependent, and to depend on the sign of the residual strength test.

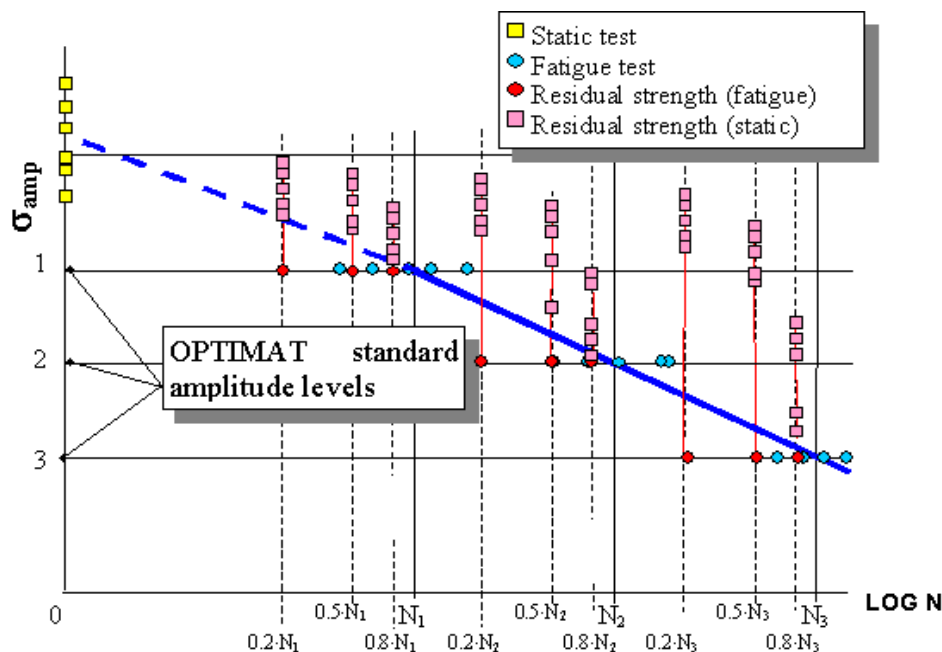


Figure 2: Overview of tests per R-value

Moreover, the number of slow cycles prior to, and after fatigue, varied. In some cases, the slow cycle after fatigue was omitted; Young's modulus was measured from the static test. Sometimes, the slow cycle was performed at identical load amplitude and R-ratio as fatigue test, in other cases it was done at a small load amplitude (e.g. 10 kN) for measurement of Young's modulus in both compression and tension, under the assumption that this did not influence fatigue life significantly. Using a low-amplitude  $R=-1$  slow cycle for modulus measurement might influence the residual strength because of the introduction of an 'odd' fatigue cycle. This influence is likely to be largest for fatigue with  $R \neq -1$ . On the other hand, using a small cycle with the same load characteristics as the fatigue cycles does not allow for measurement of compressive modulus in strictly tensile fatigue, or tensile modulus in compressive fatigue. In those cases, half the tests enable measurement of both compressive and tensile final moduli, depending on the sign of the static test. However, these can then not be compared to the initial moduli. Despite procedural differences, the data are reported here as if they were generated in essentially identical circumstances.

According to Figure 2, residual strength tests were carried out at the three standard OB load levels, at three life fractions per load level (20%, 50%, and 80% of nominal average life), with a minimum of 4 tension tests and 4 compression tests per load level.

In the course of the project, it turned out that in some cases an excessive amount of premature failures occurred in some of the test matrix cells. The main reason for excessive premature failures was, that the life fraction number of cycles to residual strength testing was based on nominal lifetime, rather than measured average lifetime, see [3]. In terms of testing time, the consequences can be detrimental; the coupons that are most likely to fail prematurely are the specimens at the highest target life fraction. These tests by definition take the most time.

Because of buckling problems, the highest load level (level 1, nominal life 1000 cycles), was lowered to a nominal life of 5000 cycles (level '1b'). The tests that were already done at level 1 (MD R=0.1) were not repeated for level 1b.

Two measures were taken to ensure feasible testing times and sufficient data points to reasonably analyse:

- The smallest life fractions were prioritised
- The 0.8 life fraction was in some cases changed to 0.35 life, or even 0.10 or 0.15 fraction

Additional data were generated, especially for the long-life tests of standard MD2 and UD2 specimens:

- R=-1 tests with nominal life of 10 million cycles
- R=0.1 tests with nominal life of 10 million cycles

### 3. Results and discussion

The results are plotted in a 'Strength Degradation Plot'. A schematic of such a plot is shown in Figure 3. It shows strength of the laminate as a function of constant amplitude fatigue lifetime. There are three regions. At  $n/N=0$ , the strength is interpreted as the static strength of coupons submitted to static tests (STT or STC in the test-type column in OptiDAT). These data are plotted as dots in

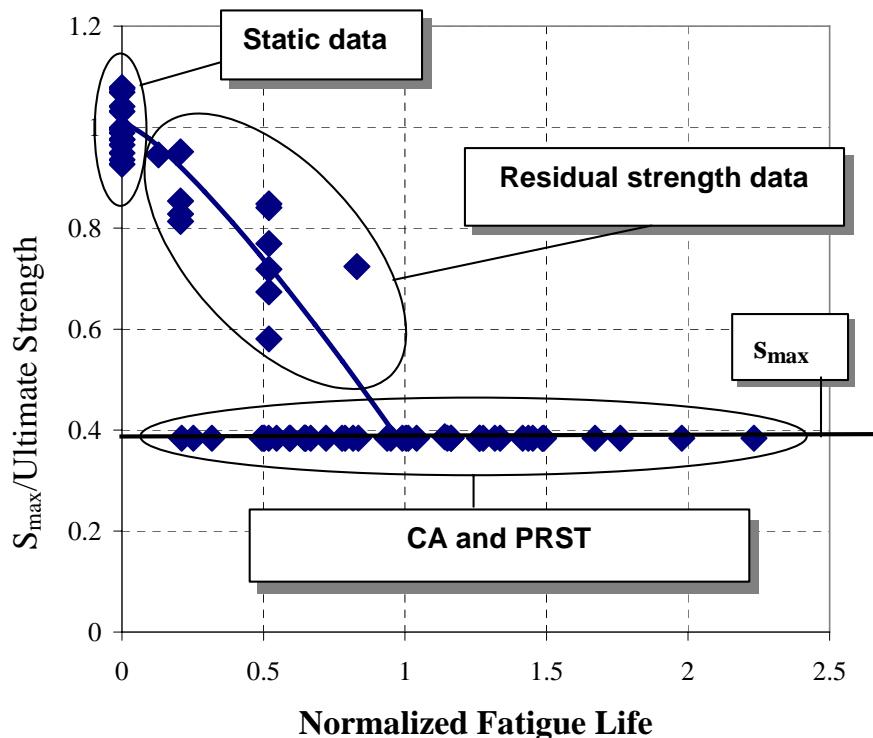


Figure 3: Schematic of Strength Degradation plot



Figure 4-Figure 31. At  $n/N_{\text{average}}$  equal to one of the main life fractions in the test matrix (viz. 0.2, 0.35, 0.5, and 0.8), the residual strength found in the final static test after fatigue is plotted, as squares. Residual strength tests (RST) are abbreviated as (RST, C or T, and the life fraction in percent, e.g. RSTC50 for a residual compressive test after 50% of the mean fatigue life). In a horizontal band at  $S_{\text{max}}/US$ , the constant amplitude data (CA) are plotted as diamonds, and the premature failures as crosses. Premature failures are specimens that were intended for a residual strength test of a predetermined sign and life fraction, but did not reach the intended number of cycles. These are marked with a 'P' preceding test type, and include intended life fraction in OptiDAT, i.e. PRSTC20, PRSTT80, etc.

All data are colour-coded for the relevant test lab, and for all tests but the static tests the plate number is indicated next to the data points. For the plate numbers of static tests, refer to [3].

Residual strength is normalised using the static strength with the same sign as the residual strength test, i.e. residual tensile strength is normalised with tensile strength etc.

In the case of constant amplitude tests (CA), the number of cycles is normalised by the average lifetime, and the static strength at failure is taken equal to the maximum stress in the fatigue test.

Fatigue life can be normalised using either:

- test specification [6]
- linear regression of all relevant CA data on all load levels
- CA data for single load level

In case of normalisation by test specification, the nominal lives are used that are linked to the standard OB levels. This means, that the life fractions are 20%, 50%, and 80%, by definition. Due to the fact that the test specification has been formulated in an early stage of the test programme, the actual average fatigue lives may differ from the specification. To allow for a more accurate description of the strength degradation, the life should be normalised by the actual mean fatigue life at each load level for the complete population of CA data. The CA data obtained at the single load level are the preferred data for normalisation of life. However, in some cases it is possible that the data obtained at a single load level do not reflect accurately the mean fatigue life of the population at this stress level, e.g. because the number of coupons is too small, the fatigue tests on the relevant level were subject to severe plate-to-plate, lab-to-lab, or machine-to-machine variations. If this is suspected, normalisation using the regression line through all data (obtained at standard load-levels and frequencies) is preferred. An example where the latter method could be implemented is for the long-life residual strength tests ( $10^7$  cycles), where realisation of sufficient CA data was not feasible within the allocated test time.

For each strength degradation plot, the number of cycles that was used for normalising is displayed below the legend. The values of mean fatigue life, used for normalising fatigue lives are given in [3], and the values in the strength degradation plots correspond exactly to the values presented in [3]. These are from CA data for single standard load levels (10% deviation from the test specification [6] was allowed in load and frequency). Run-outs are included, records marked 'Invalid' were excluded.

Also the method of normalisation is indicated in brackets ('level' for normalisation with the single level data; 'all CA' for normalisation using linear regression of all valid data, and 'test spec.' for normalisation using the nominal number of cycles. Furthermore, the value for the ultimate strength is indicated.

Since strengths were normalised with the level-average values, and some plate-to-plate and machine-to-machine variation was identified in [3], the strength degradation plots might be slightly





corrected, to account for these identified effects. For instance, UD tensile tests involving plate 113 may be corrected for the above-average initial strengths found for these plates (Figure 4-Figure 5-Figure 8-Figure 9). On the other hand, compressive residual strength results for UD2 should be shifted slightly upward, for data generated by VUB or WMC on the same machine on which the slightly lower STC-results were obtained [3] (for WMC this is not the case). As was pointed out in [3], it is not feasible to suggest implications for the fatigue lives of the residual strength tests for the standard coupons.

It is interesting to know the statistical distribution of residual strength. However, with the limited number of data available, some of which 'obscured' by plate-to-plate/machine-to-machine variations, it is not possible to analyse scatter in residual strength properly for the standard specimens. For the ISO specimens, however, many specimens were tested in tension for each life fraction. The probability functions are shown per life fraction for each level (Figure 22-Figure 24). Clearly, the strength degradation is visible, and the scatter is seen to increase from 2% (static), to 5%, to ~8% for the 80% life fraction. This is valid for all levels.

Scatter is relatively high for the transverse UD tests. Also, this part of the test programme was plagued by a high number of premature failures, see e.g. Figure 28.

### 3.1. Plate-to-plate and lab-to-lab variation

In the analysis, the data might be treated as if static tests, residual strength tests, and constant amplitude fatigue tests were done on identical coupons under identical circumstances. In practice, as is evident from Figure 4-Figure 31, this is not the case. As a result, the actual strength degradation may be obscured by plate-to-plate variation and lab-to-lab variation. These two parameters can be a combination of other factors, such as variation of results between test frames, and differences in procedure, such as transferral of the coupon from one machine to another, meanwhile equipping it with additional measurement instruments. Below, some examples of possible plate-to-plate variation and lab-to-lab variations from the results are discussed.

The UD  $R=0.1$  and  $R=-1$  tensile strengths apparently show an increase in strength in early life at the high stress level, and specimens tested at RAL show lower residual tensile strengths than those tested at VUB. Both effects could be a lab-to-lab or a plate-to-plate variation. From Figure 6, the specimens tested by RAL come from different plates to those tested by VUB (plate 93 vs 113). In this case, and in the case of the  $R=-1$  residual tensile strengths measured at WMC, no static tests were done using specimens from the same plate. Also, static residual strength was normalised using the average static strength as calculated in [3], i.e. from *all* specimens tested in almost all laboratories. However, the residual strength tests were carried out in a few laboratories only. Theoretically, the residual strengths should be normalised by the static strength values obtained in the same laboratory and identical plate as the residual strength tests were done. An example is the compressive strength of standard UD specimens after tensile fatigue (Figure 6, level 1 and level 2). The values from RAL are systematically higher than those from VUB, but this is true for both the initial static as the residual static strengths. Normalising the data per lab would severely mitigate scatter in these plots.

Where multiple results are available per life fraction, from identical plates, laboratories, test machines, e.g. tensile residual strength after  $R=-1$  fatigue of MD specimens (Figure 16), scatter seems to be similar to scatter in the static tests. In all available data, there is no evidence, that scatter on the strength coordinate differs significantly from initial strength scatter. However, the high-life fraction data might show less scatter because of premature failures (this is assuming that higher strengths lead to longer fatigue life and lower strength leads to shorter fatigue life).

On the horizontal co-ordinate, plate-to-plate or lab-to-lab variations may also occur. This is illustrated e.g. by the data in Figure 19: MD2 R0400  $R=10$  RSD plot level 1b-3 (tension). The



constant amplitude data provided by DLR have a lower mean fatigue life (and less scatter) than those provided by WMC. The specimens used by DLR were from plate 57, the specimens of WMC from other plates. The RS tests, in turn, were mostly done on other plates than were used for the CA tests.

In the light of lab-to-lab variations, the tests on  $\pm 45^\circ$  and UD  $90^\circ$ -material is interesting. All specimens came from slightly different numbered plates, but they were tested exclusively by UP. The strength degradation plots are shown in Figure 21-Figure 24. Comparison with other tensile strength data does not reveal that the scatter is significantly influenced by lab-to-lab variation.

Another interesting aspect of these strength degradation plots is, that the degradation of these matrix-dominated material resembles that of the fiber dominated lay-ups MD2 and UD2, i.e. tensile strength degrades linearly, and compressive strength seems unaffected by fatigue.

A separate note is dedicated to the premature failures, indicated by crosses in the figures. Although these specimens have only been subjected to constant amplitude loading, they can not be regarded as constant amplitude tests, since they were intended for a 'fatigue life' below  $N_{avg}$ , and if they were included in the determination of mean fatigue life, would bias fatigue life towards a lower  $N_{avg}$ . The occurrence of premature failures can have an impact on the data analysis, as will be discussed later on.

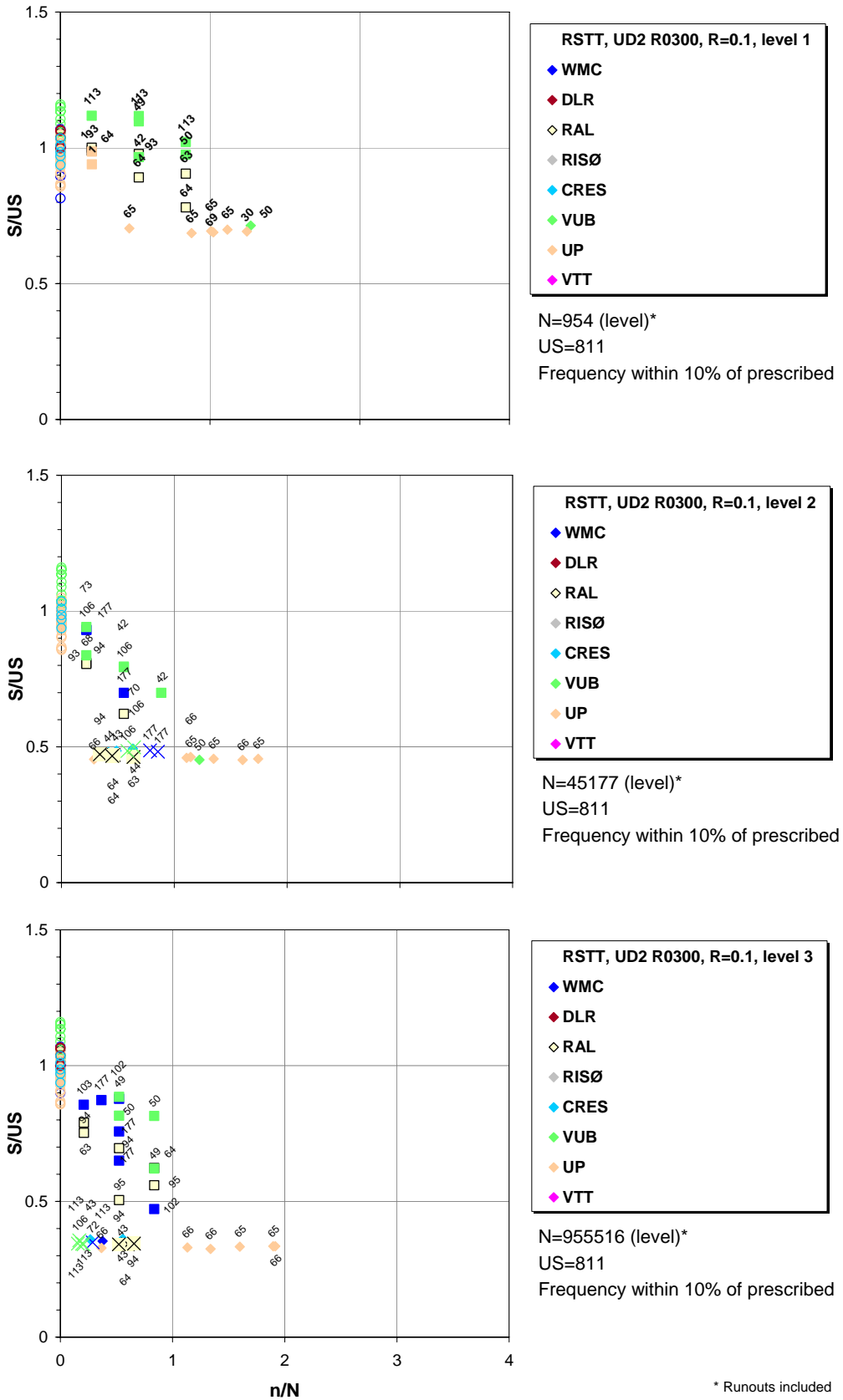


Figure 4: UD2 R0300 R=0.1 RSD plots level 1-3 (tension)

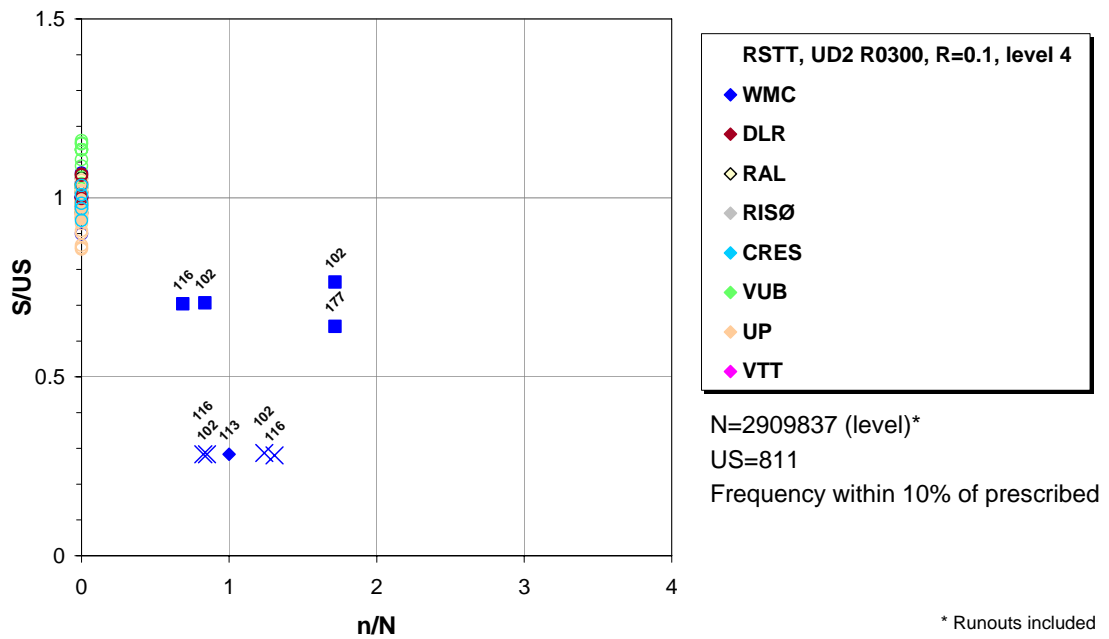


Figure 5: UD2 R0300 R=0.1 RSD plots level 4 (tension)

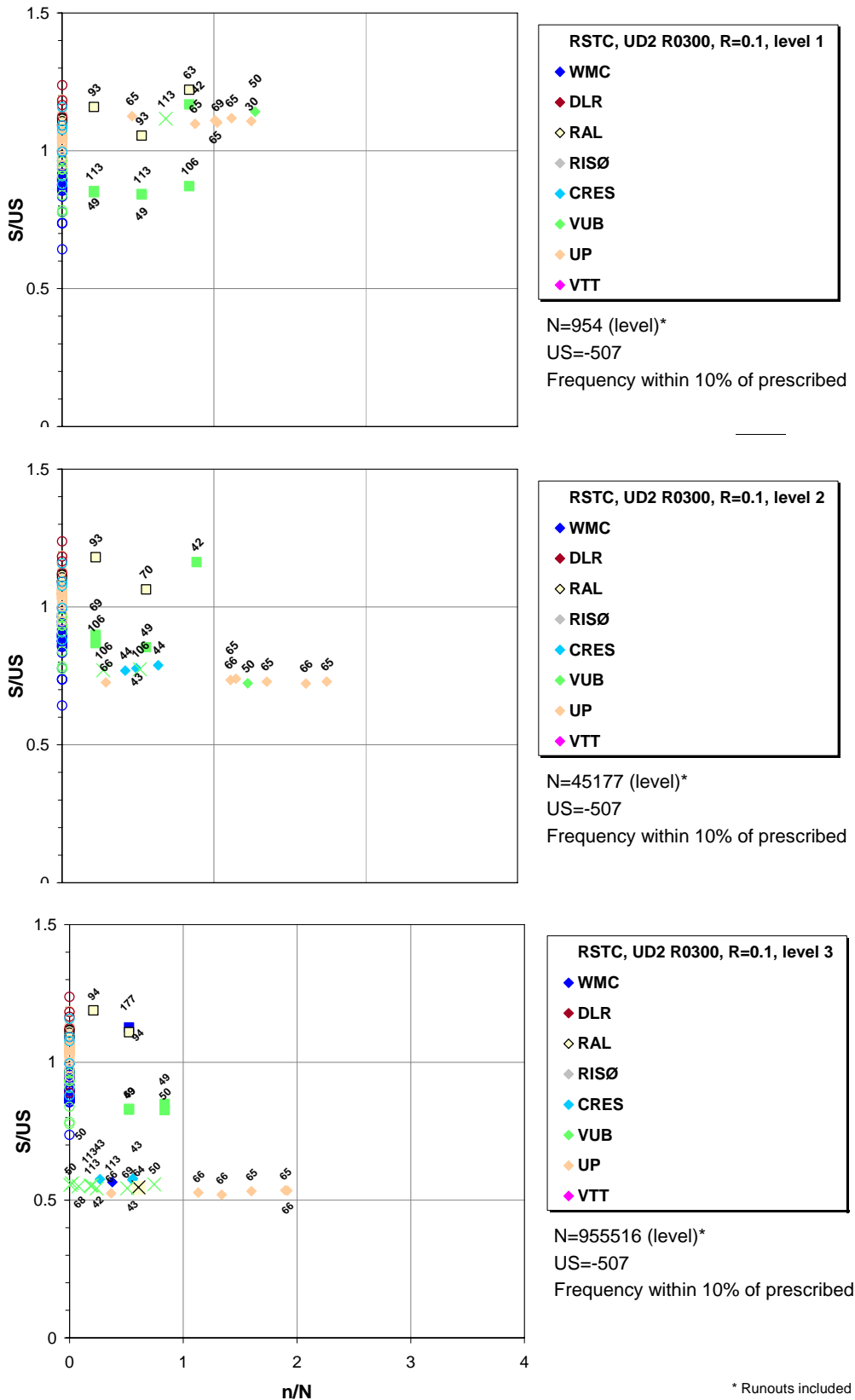


Figure 6: UD2 R0300 R=0.1 RSD plots level 1-3 (compression)

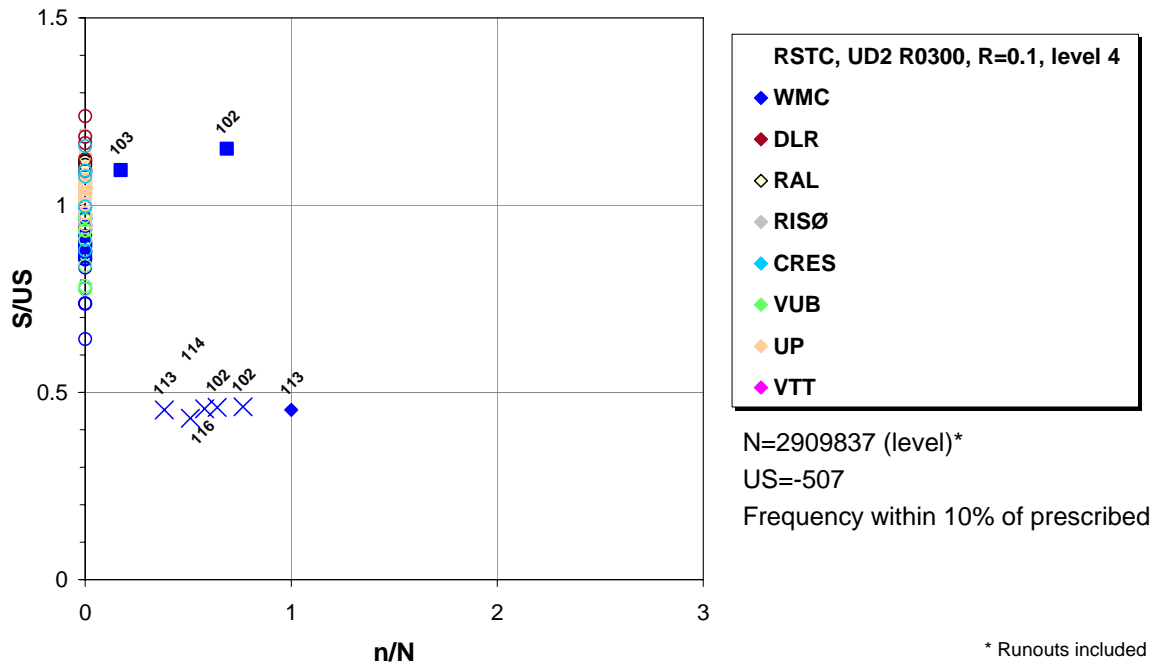


Figure 7: UD2 R0300 R=0.1 RSD plot level 4 (compression)

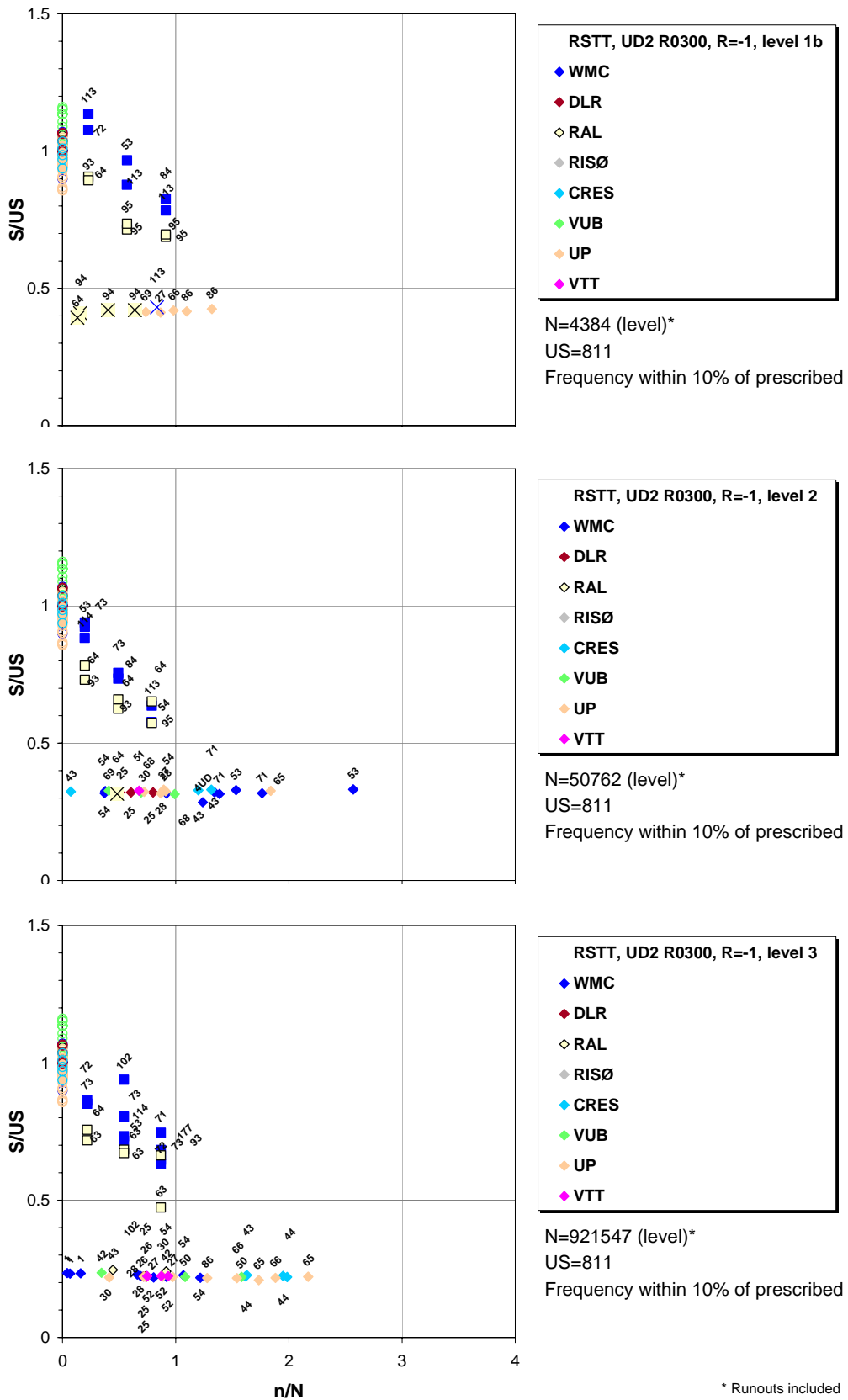


Figure 8: UD2 R0300 R=-1 RSD plots level 1b-3 (tension)





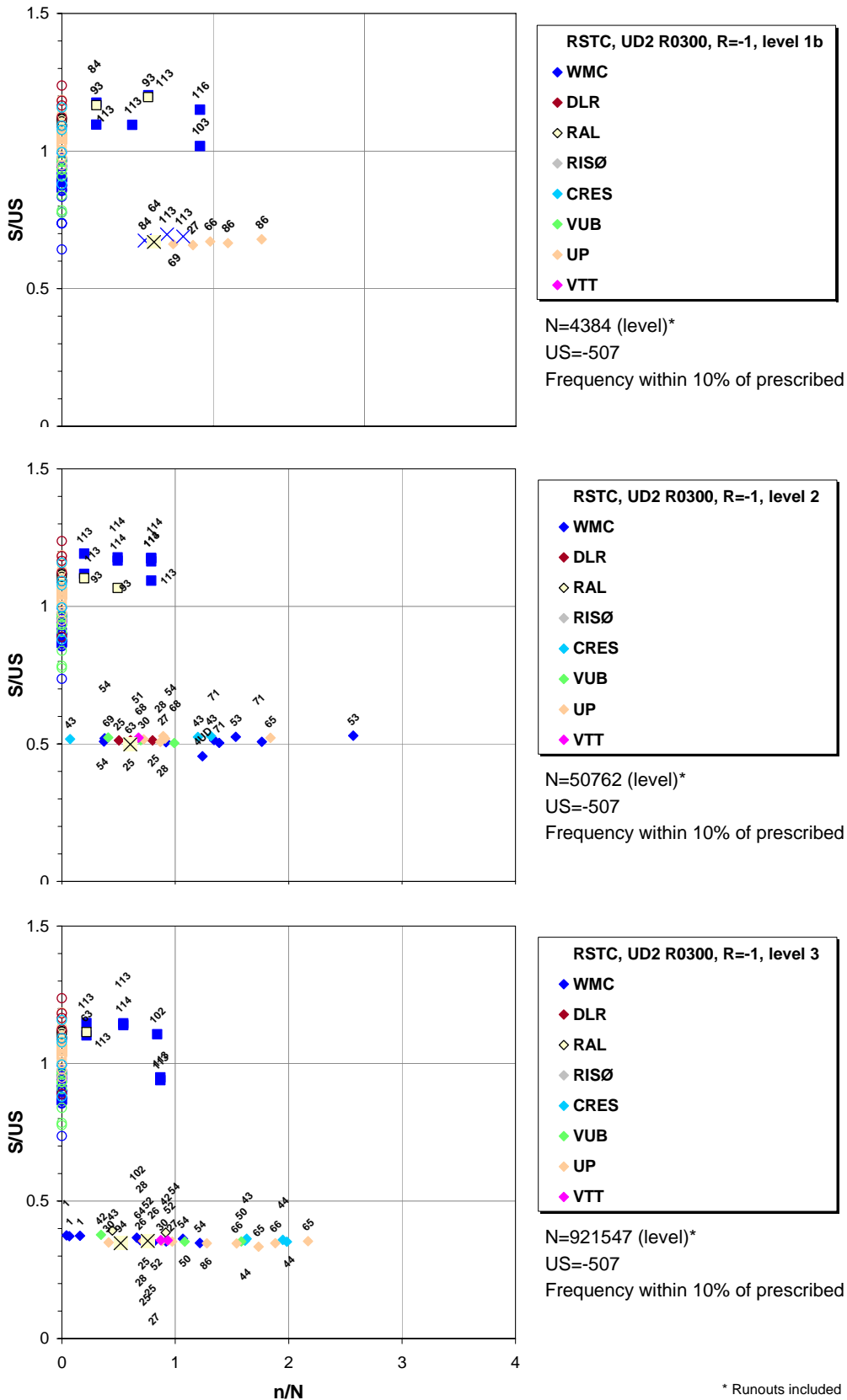


Figure 10: UD2 R0300 R=-1 RSD plots level 1b-3 (compression)

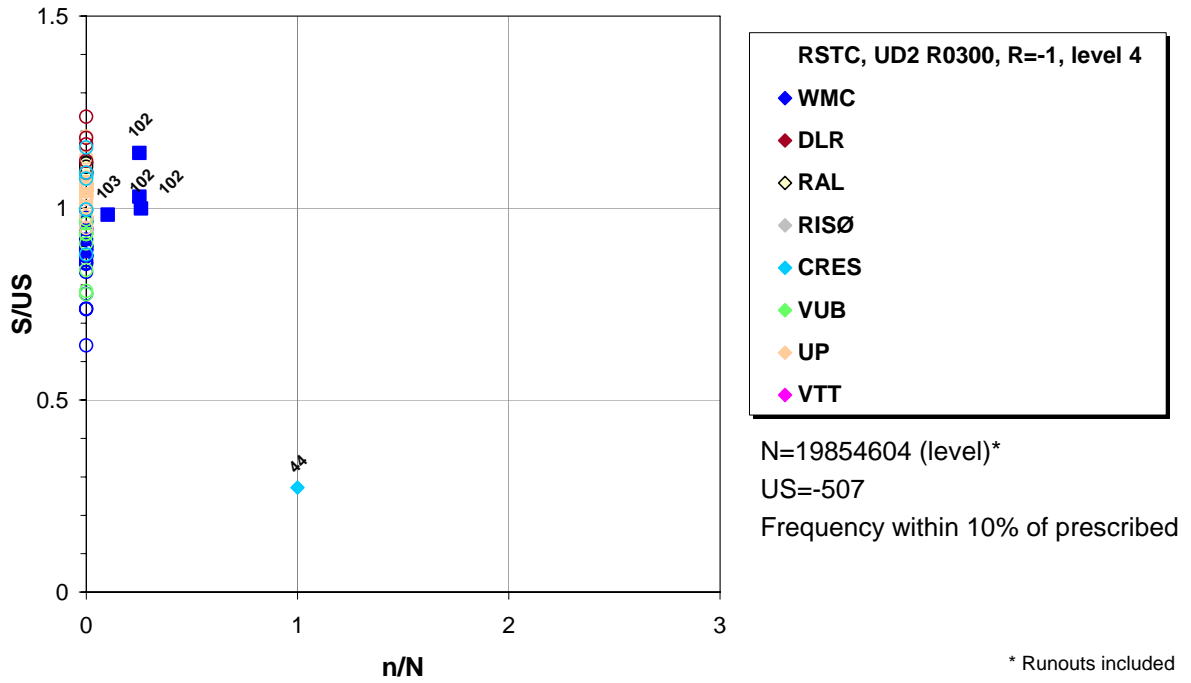


Figure 11: UD2 R0300 R=-1 RSD plot level 4 (compression)

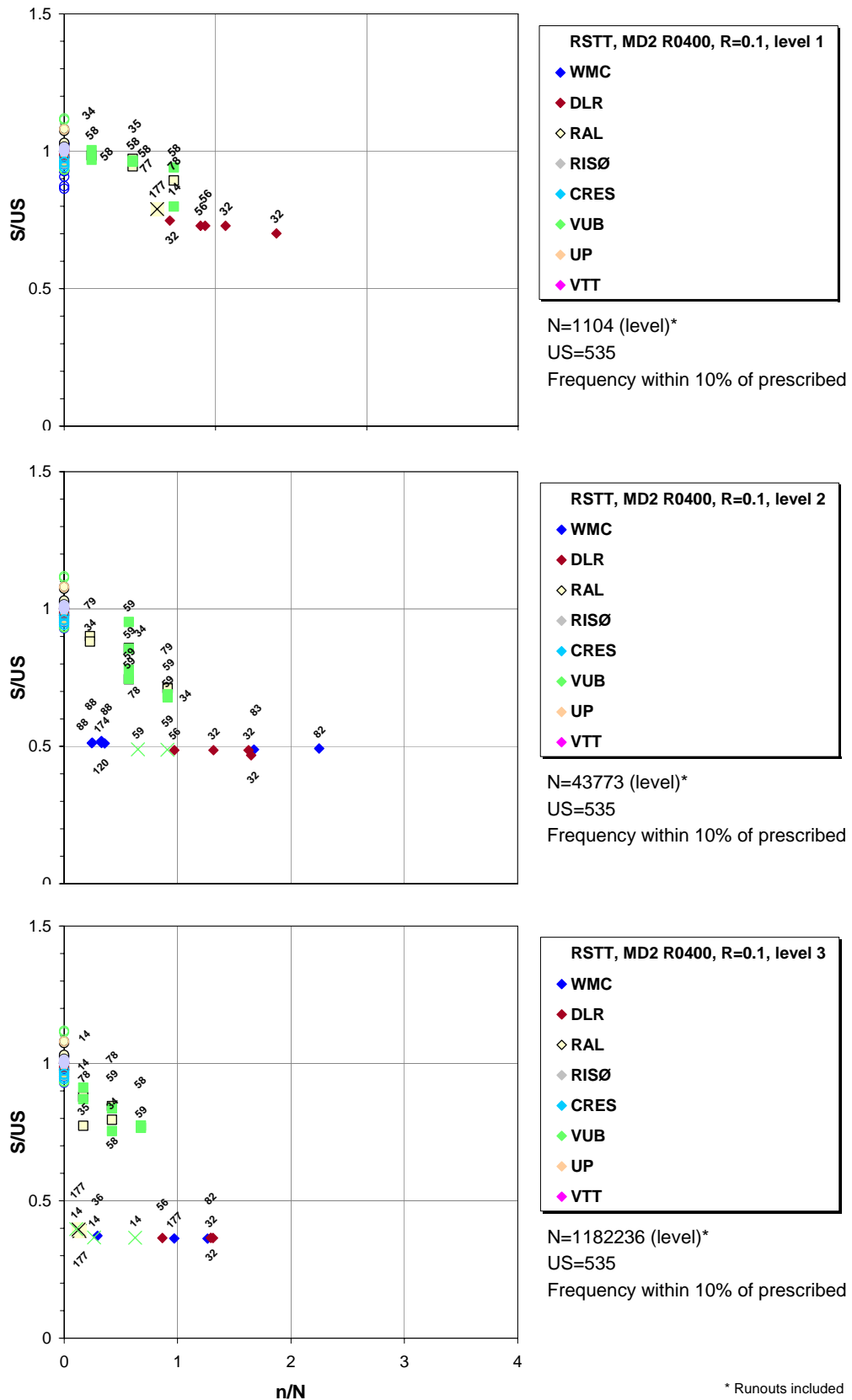


Figure 12: MD2 R0400 R=0.1 RSD plots level 1-3 (tension)



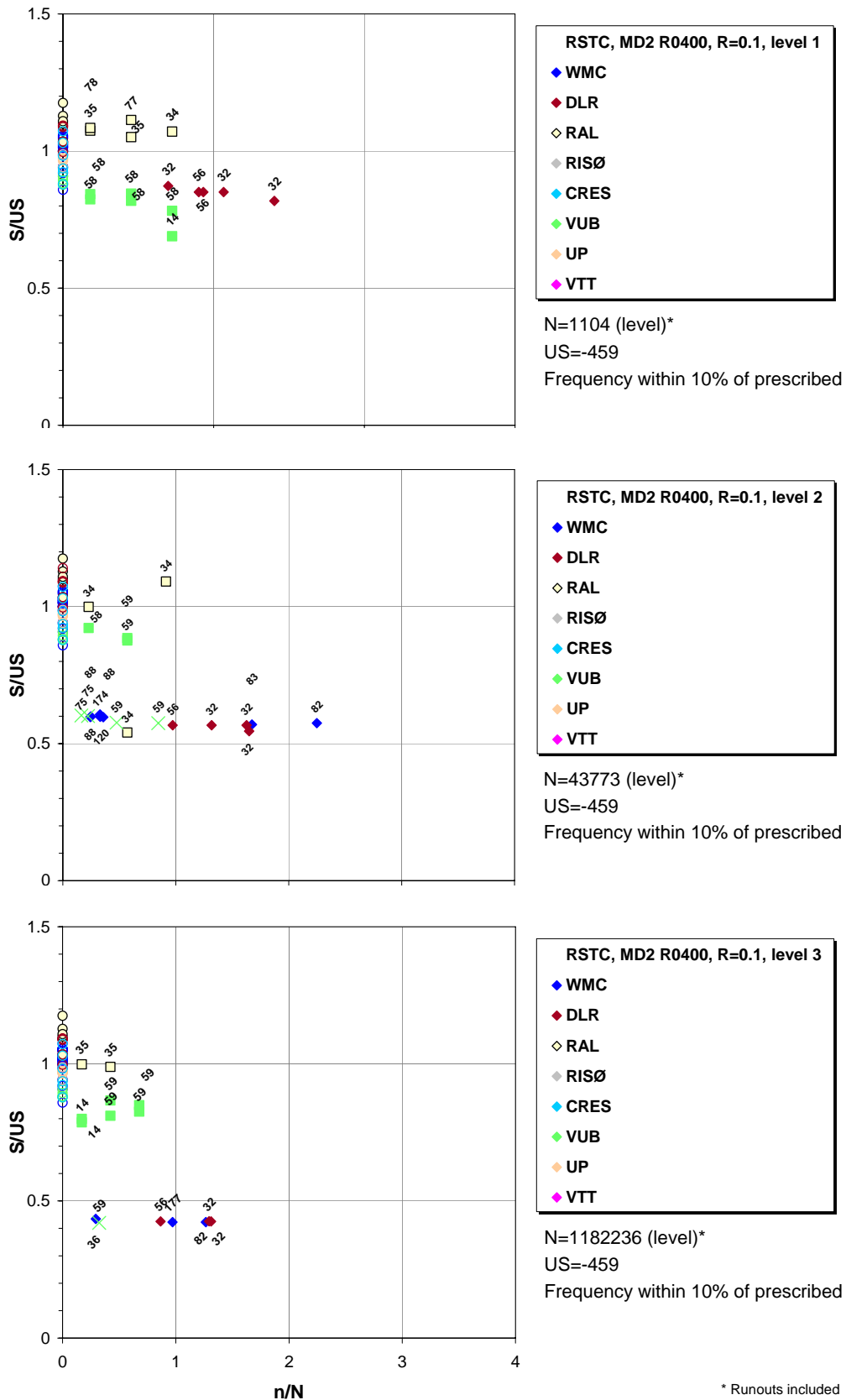


Figure 14: MD2 R0400 R=0.1 RSD plots level 1-3 (compression)

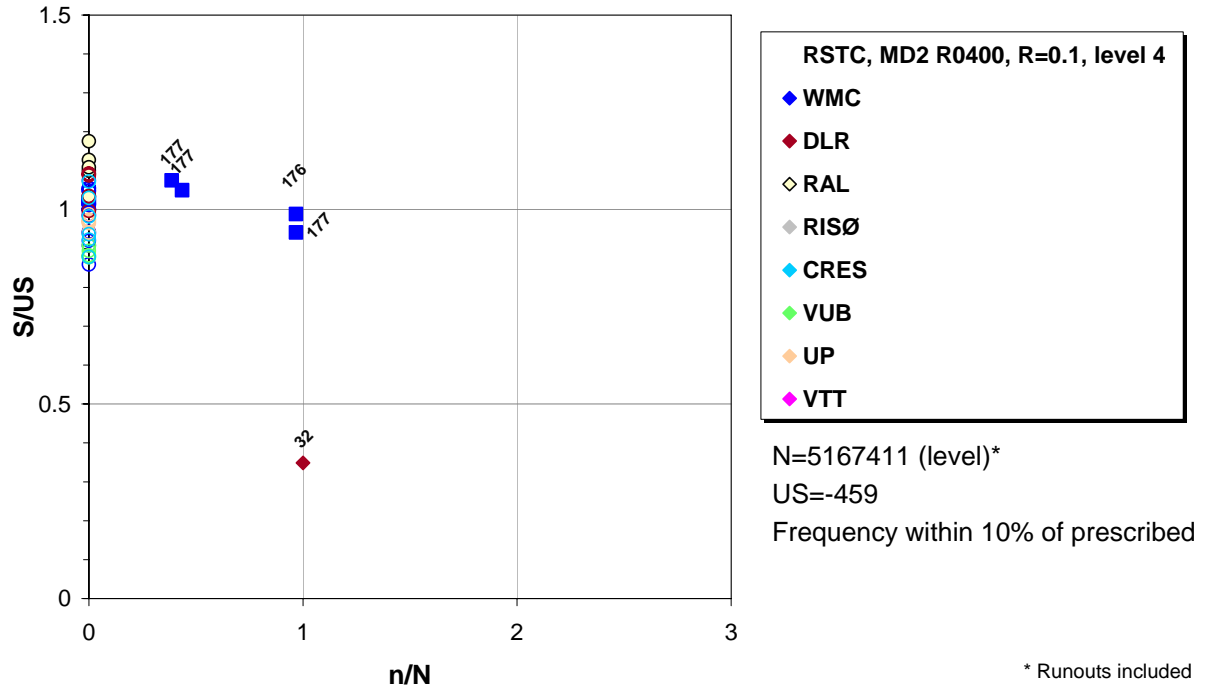


Figure 15: MD2 R0400 R=0.1 RSD plot level 4 (compression)

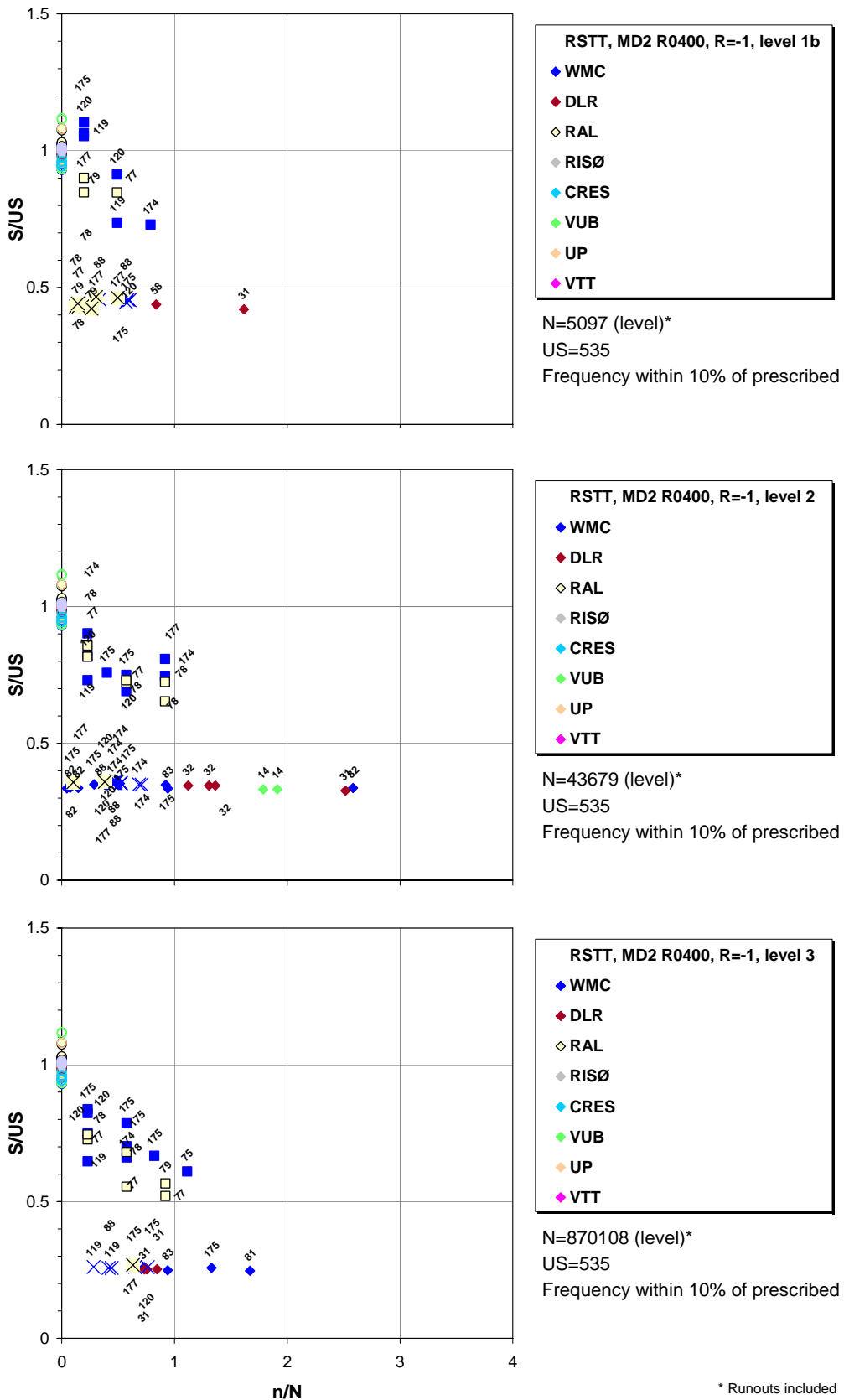


Figure 16: MD2 R0400 R=-1 RSD plots level 1b-3 (tension)

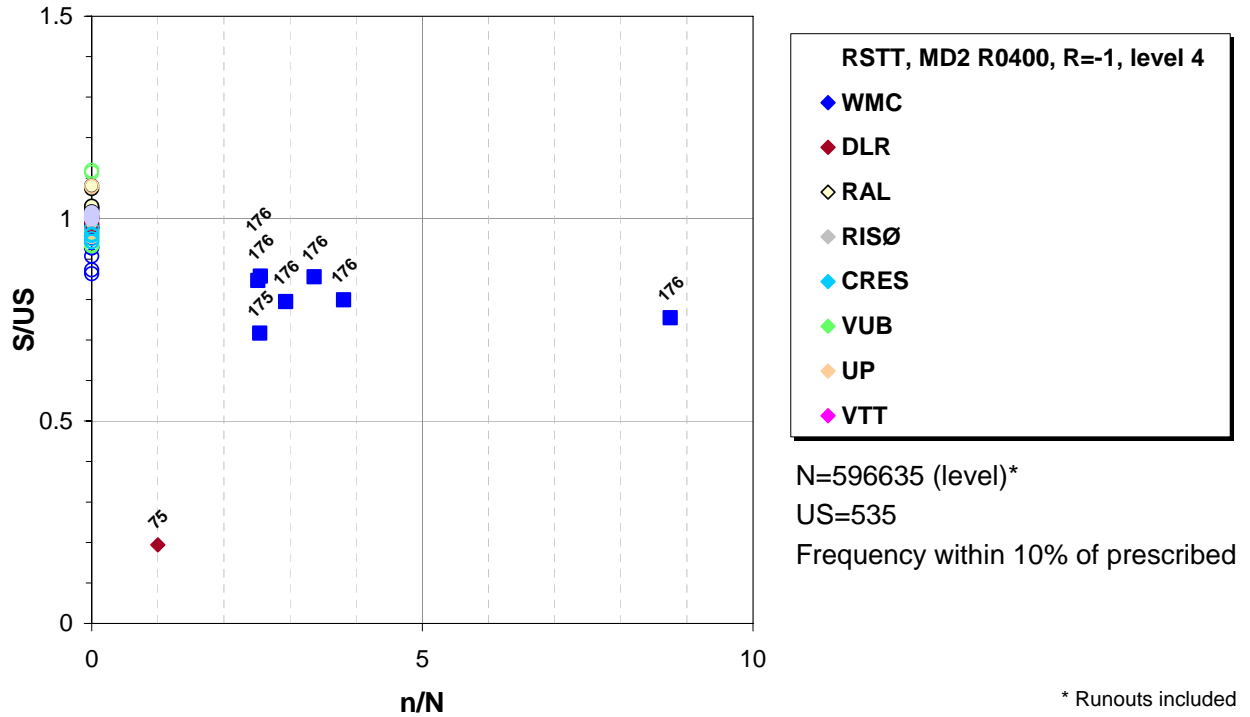


Figure 17: MD2 R0400 R=-1 RSD plot level 4 (tension)



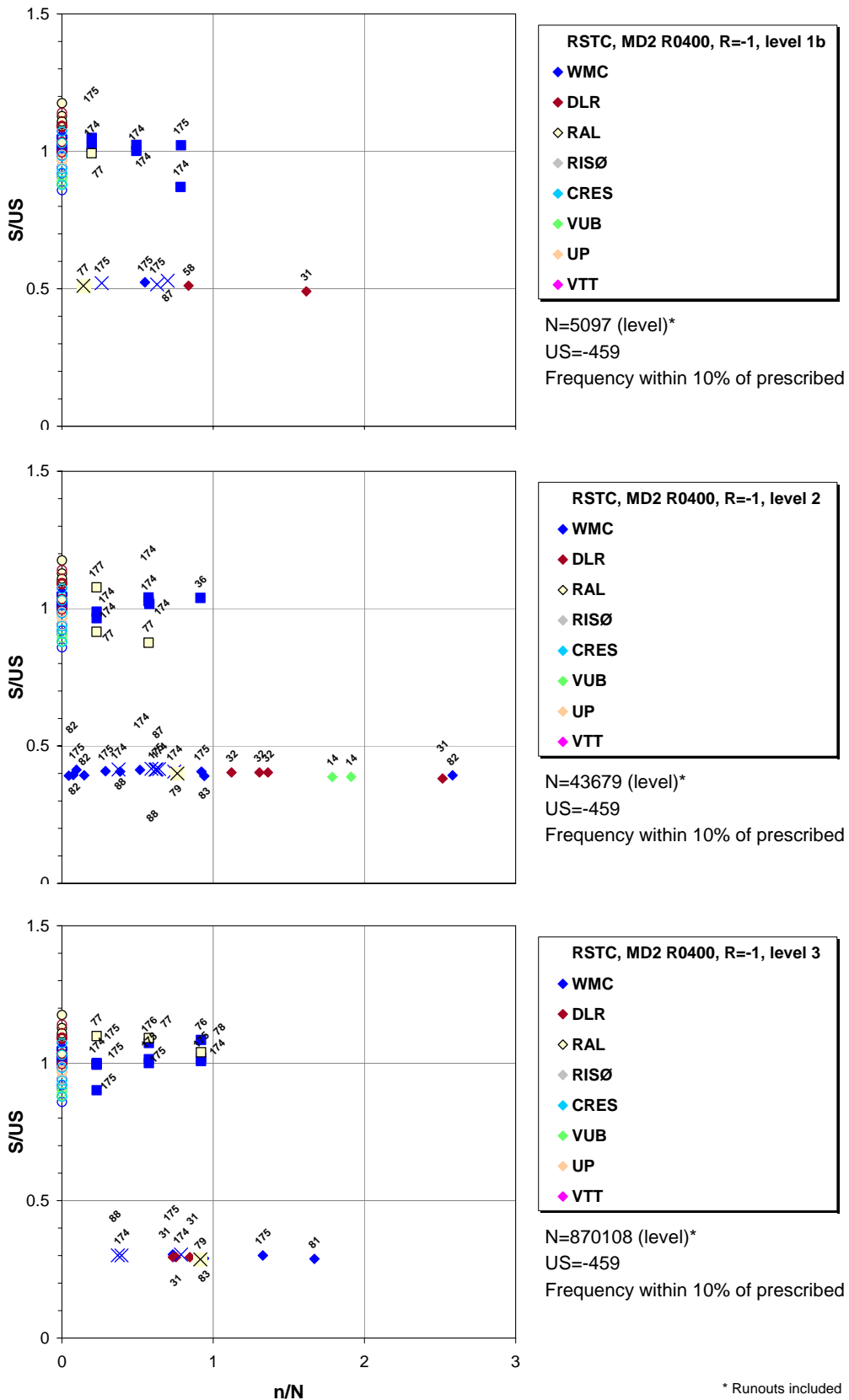


Figure 18: MD2 R0400 R=-1 RSD plots level 1b-3 (compression)

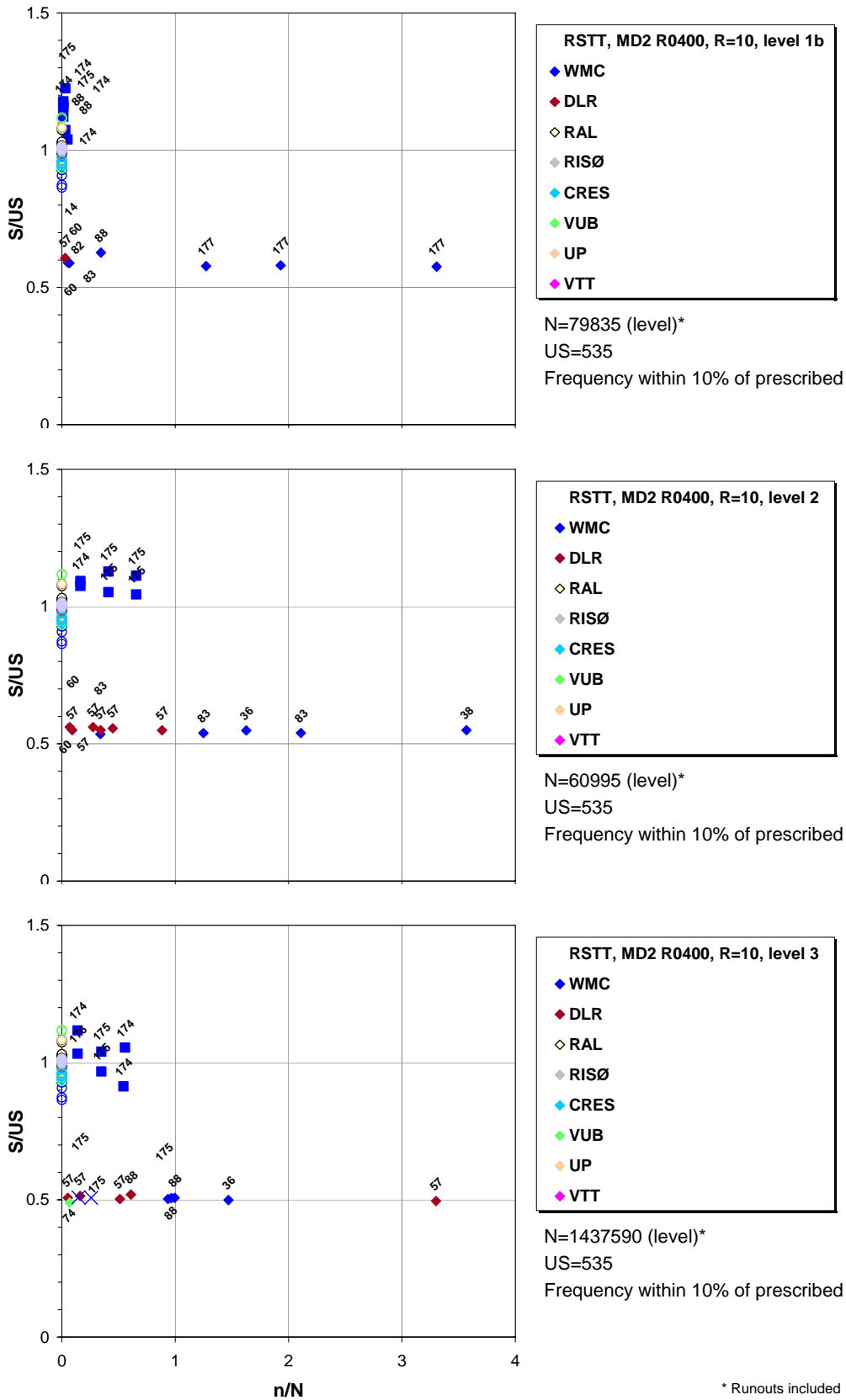


Figure 19: MD2 R0400 R=10 RSD plot level 1b-3 (tension)



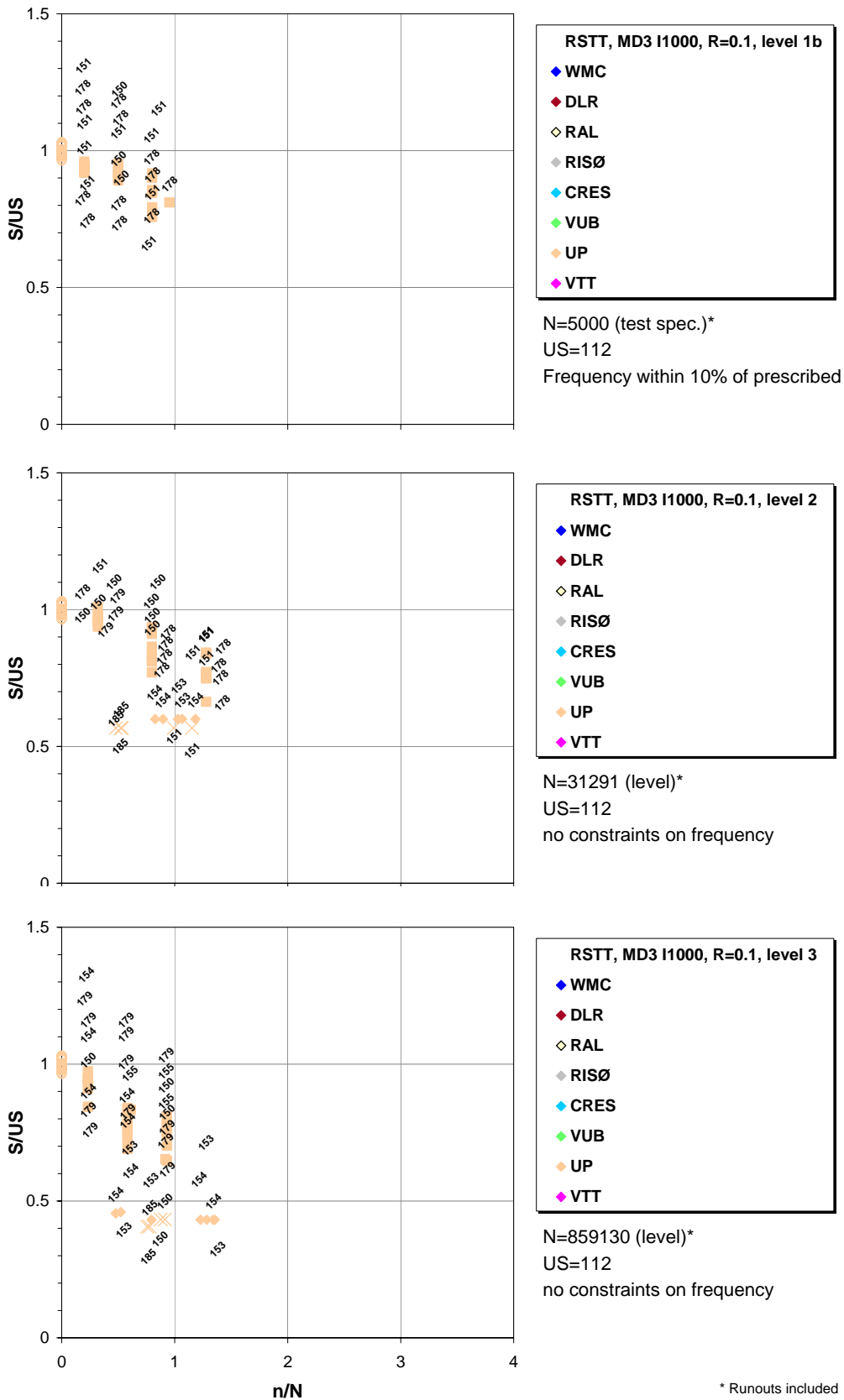


Figure 21: MD3 I1000 R=0.1 RSD plots level 1b-3 (tension)

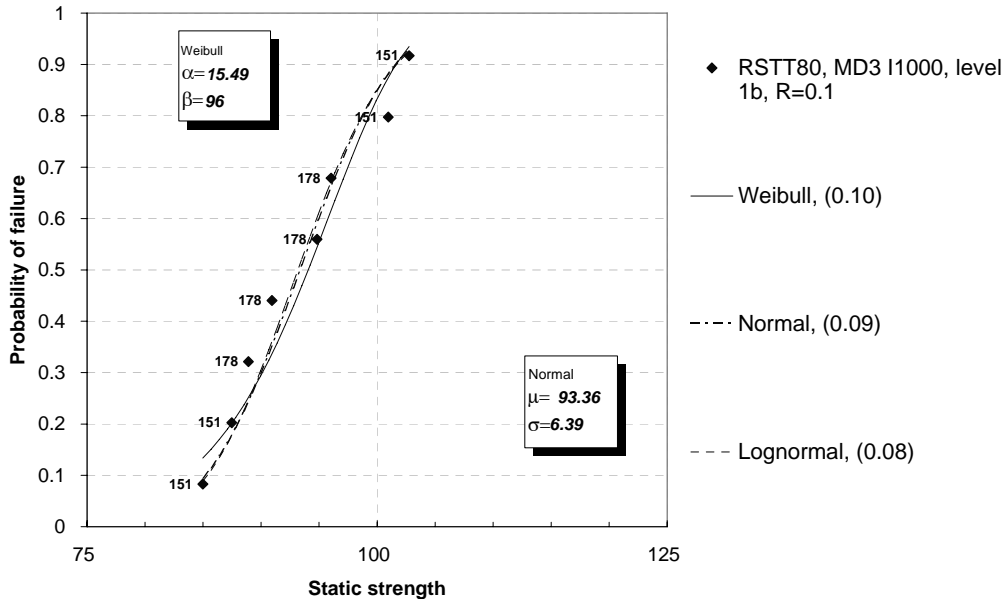
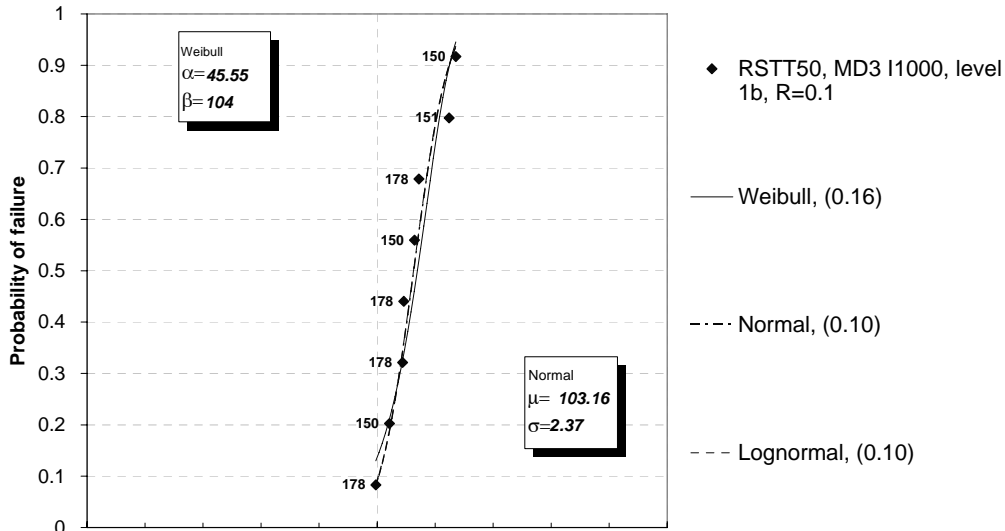
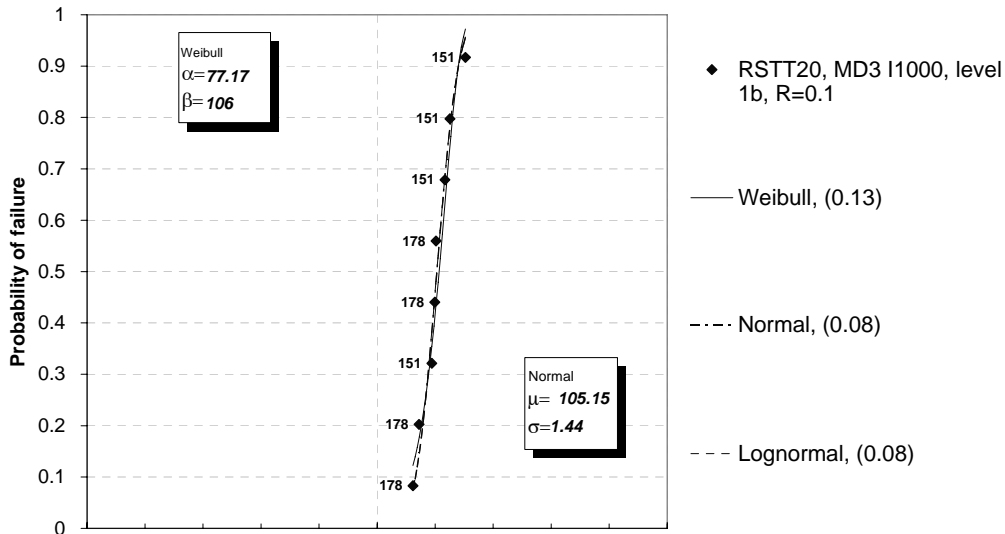


Figure 22: MD3 I1000 level 1b RS probability plots

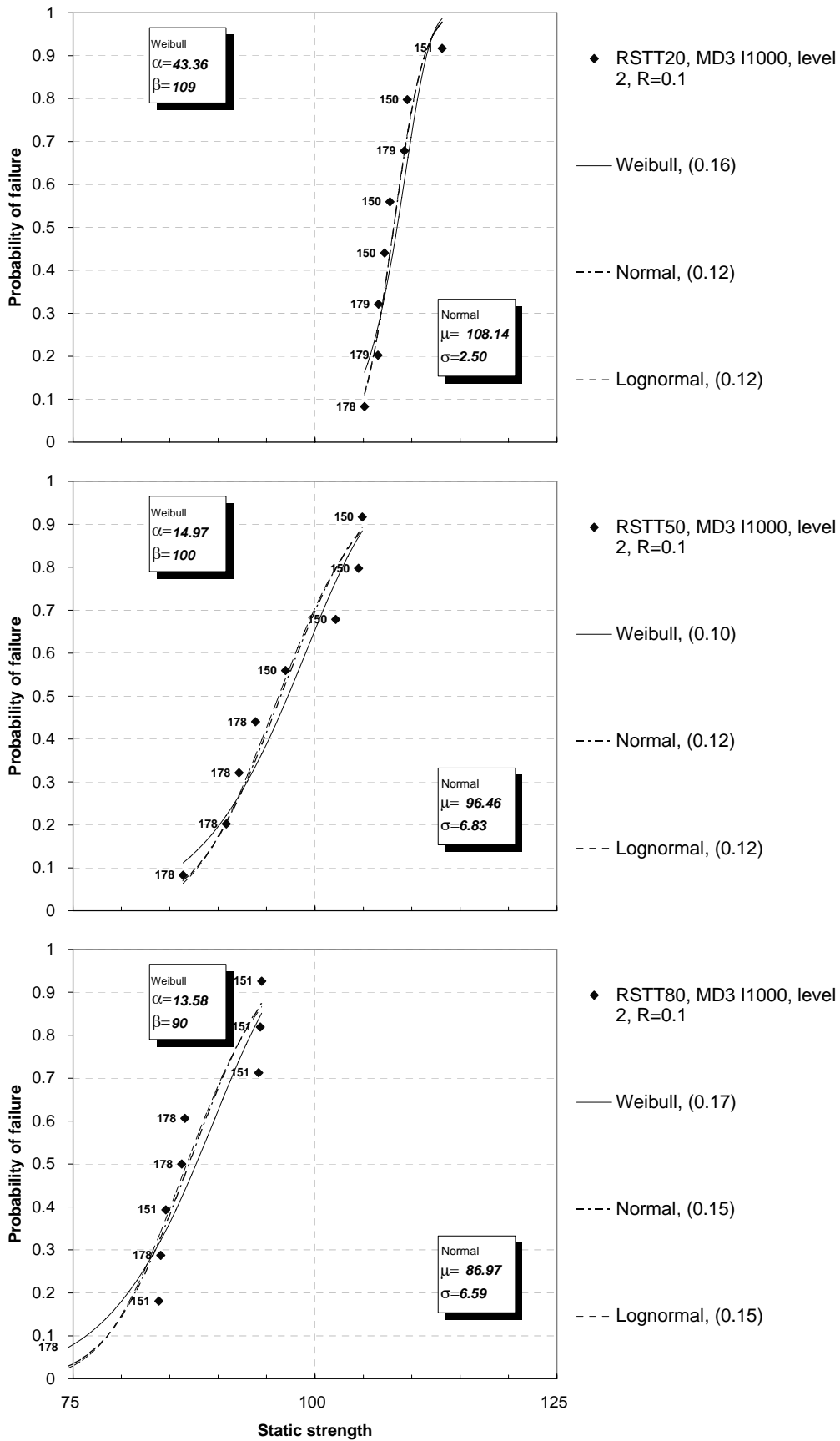


Figure 23: MD3 I1000 R=0.1 RSD probability plots level 2

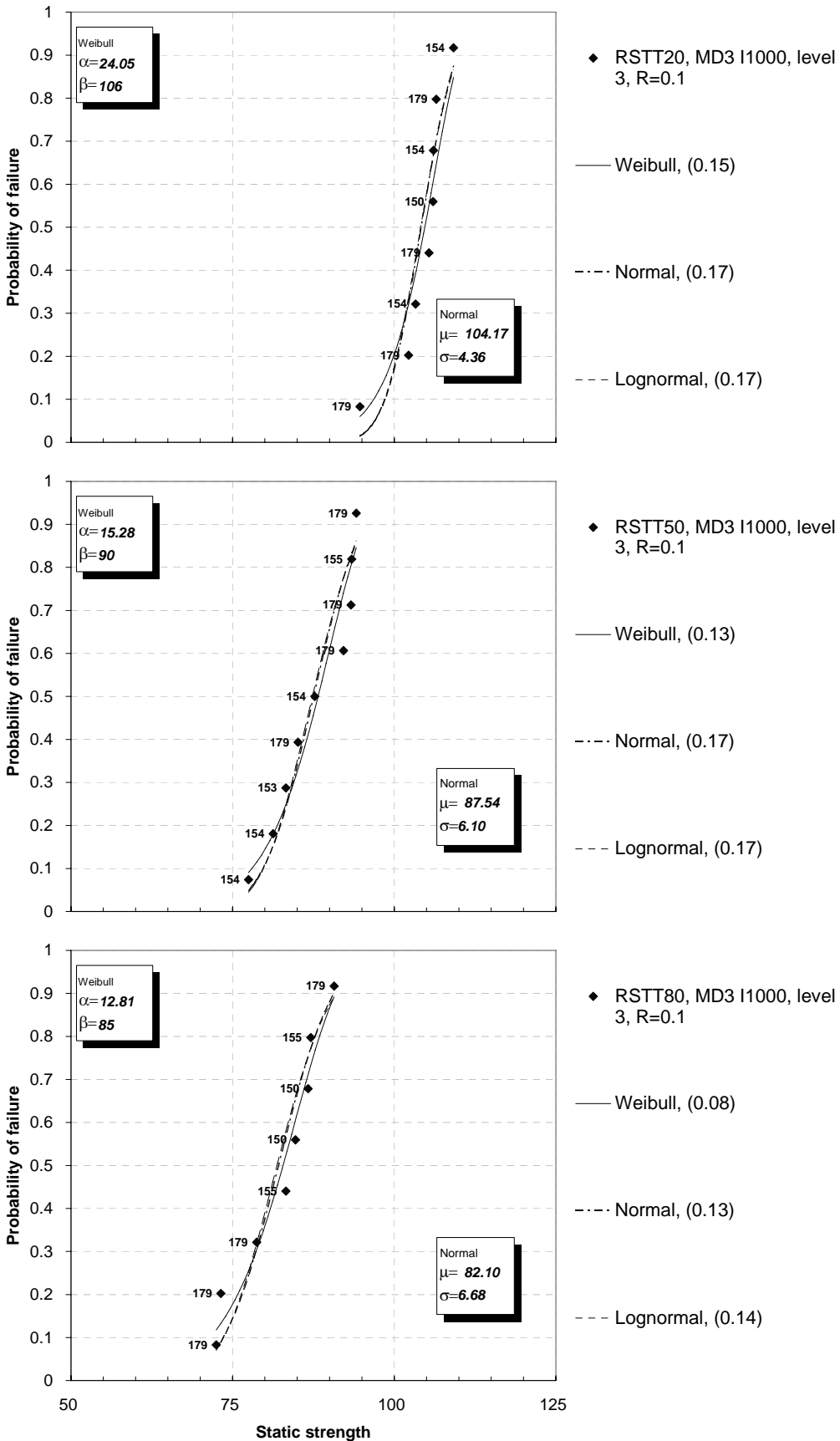


Figure 24: MD3 I1000 R=0.1 RSD probability plots level 3

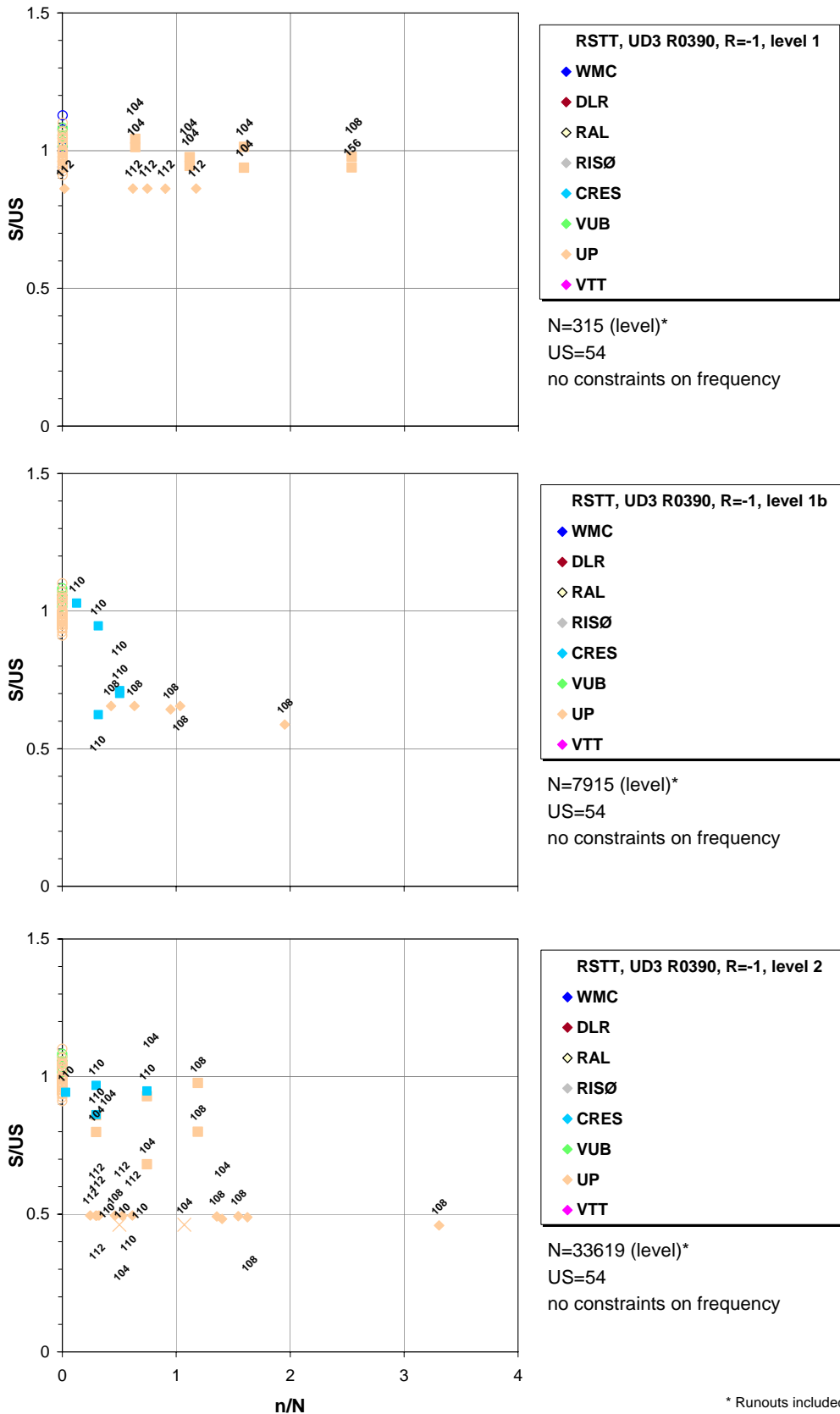


Figure 25: UD3 R0390 R=-1 RSD plots level 1-2 (tension)





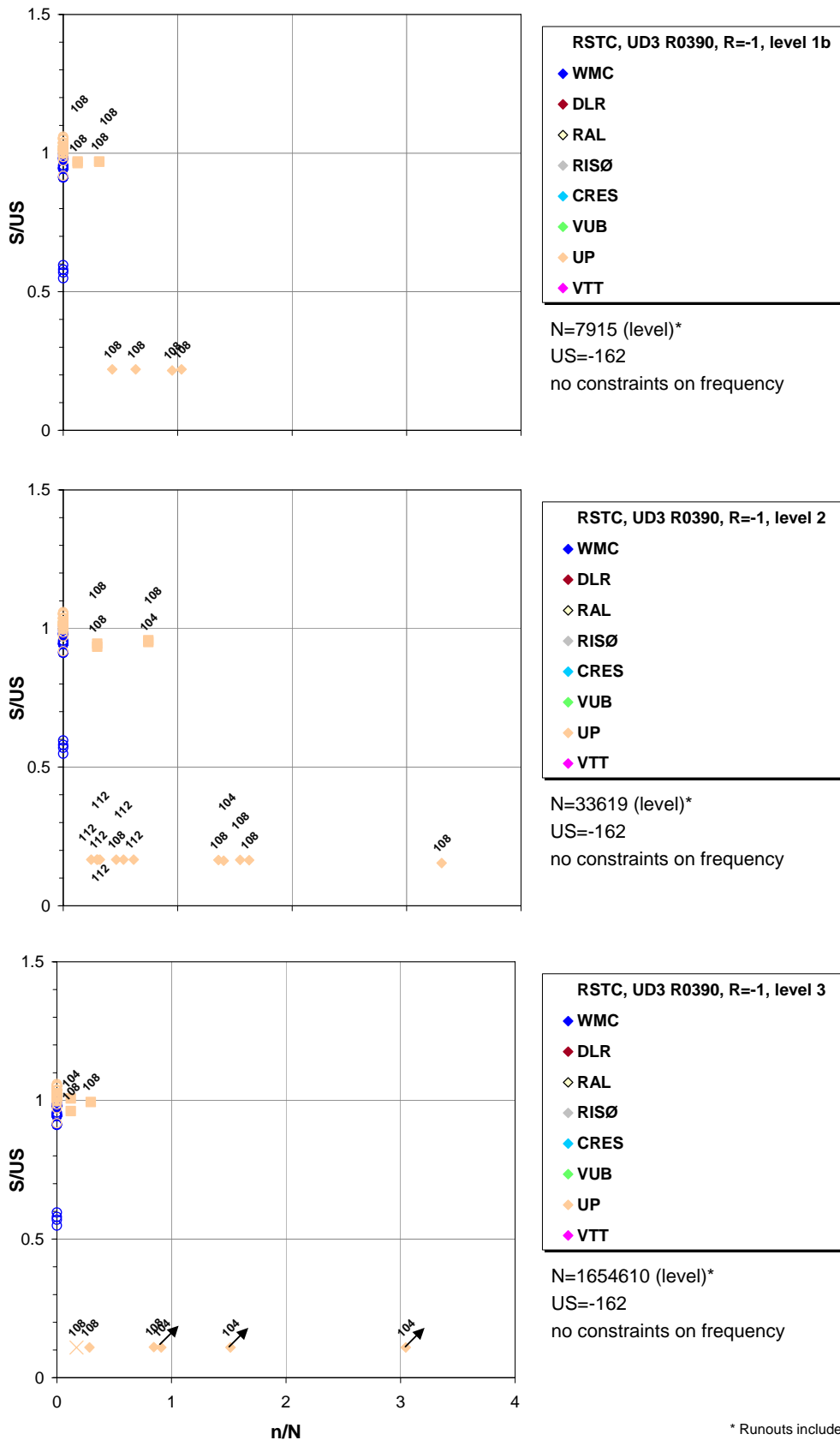


Figure 27: UD3 R0390 R=-1 RSD plot level 1b-3 (compression)

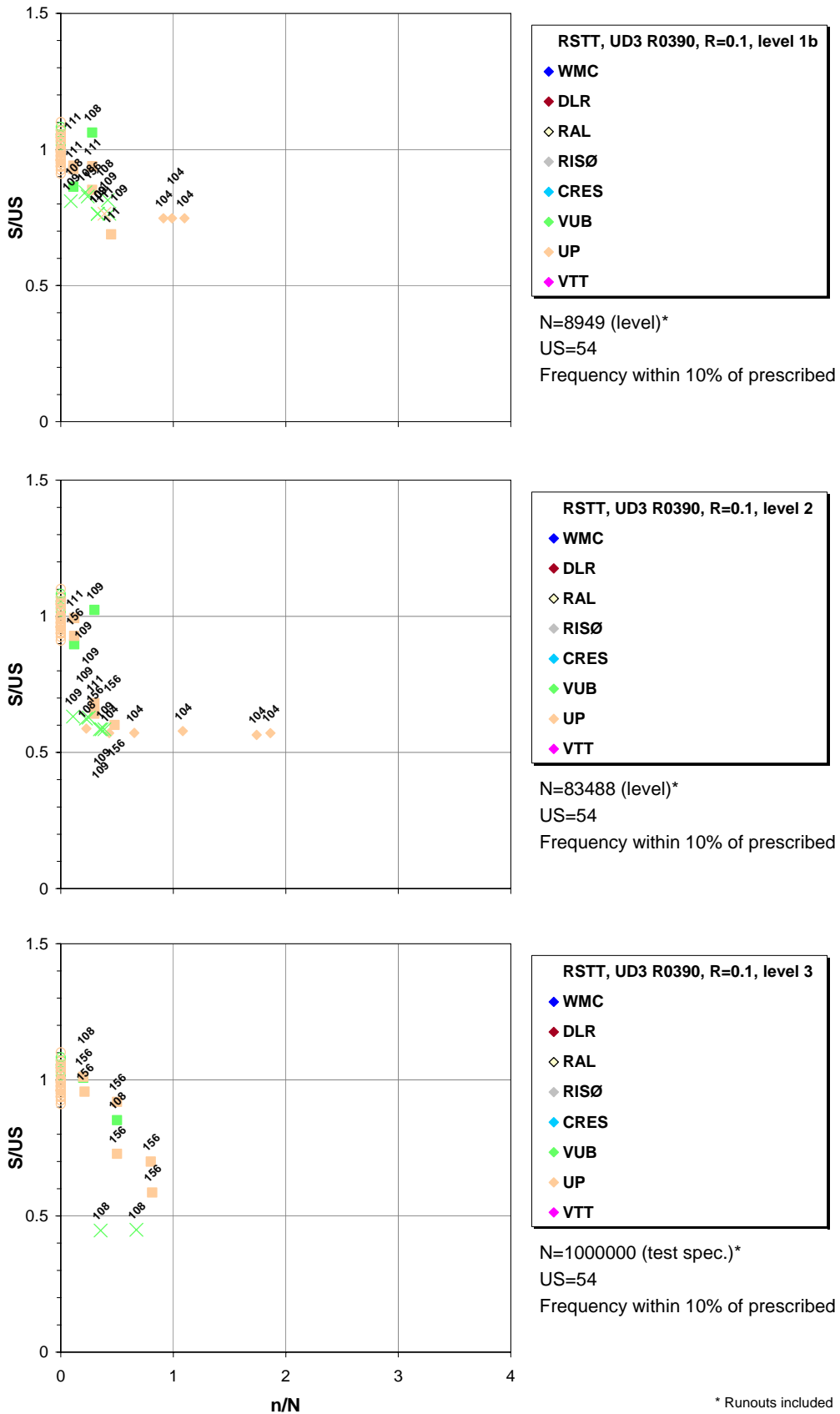


Figure 28: UD3 R0390 R=0.1 RSD plot level 1b-3 (tension)

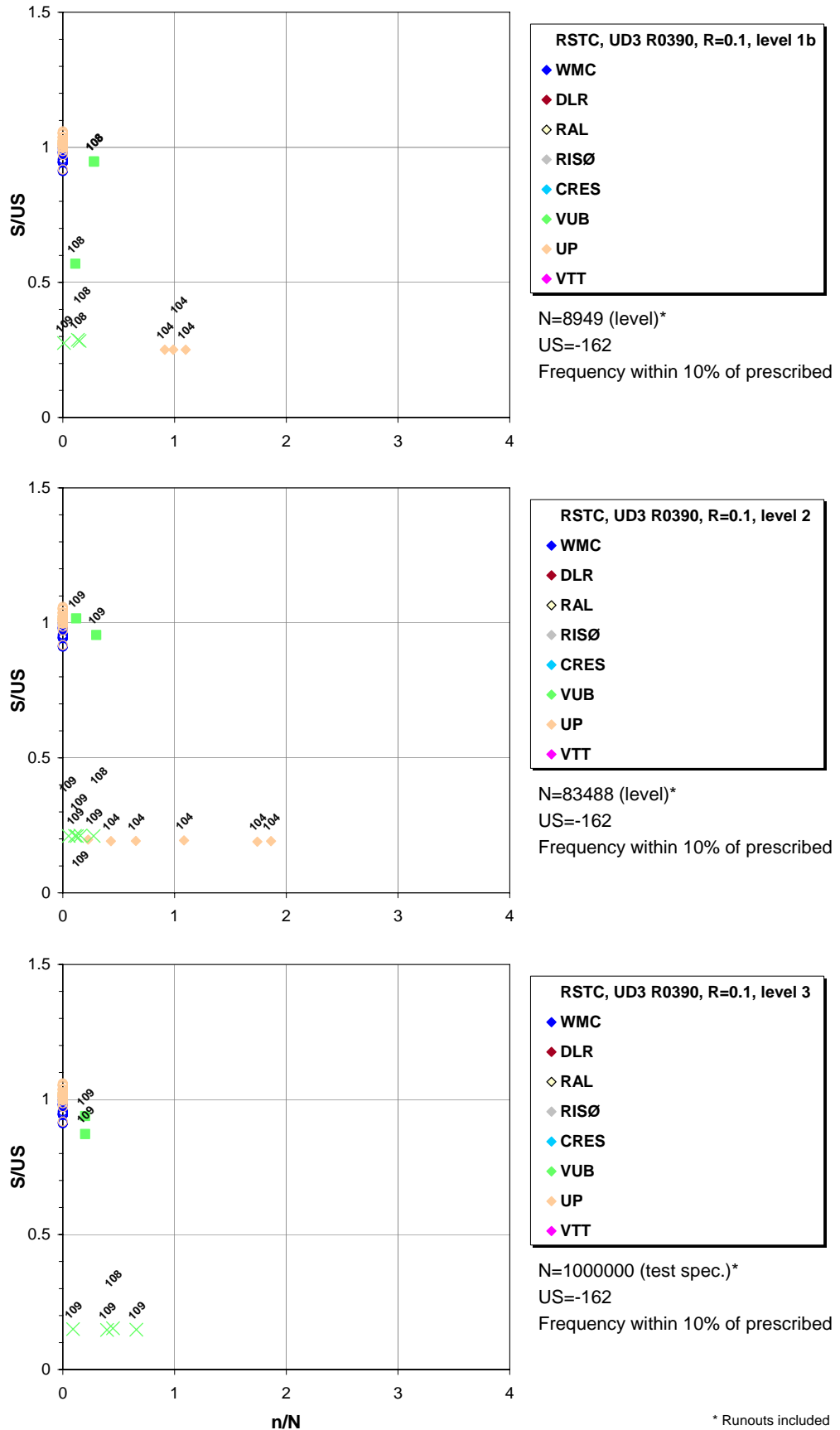
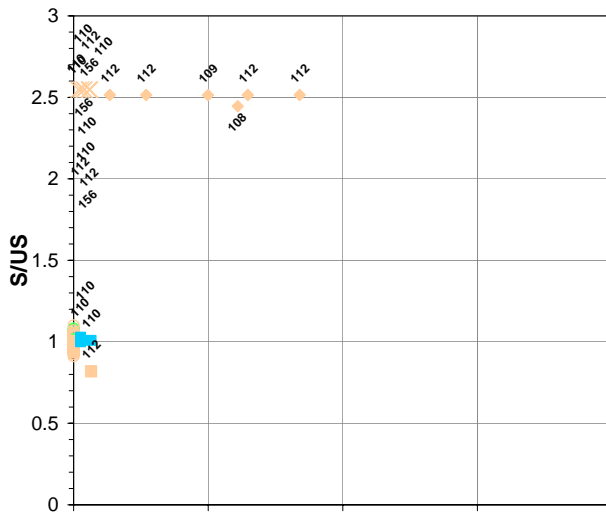


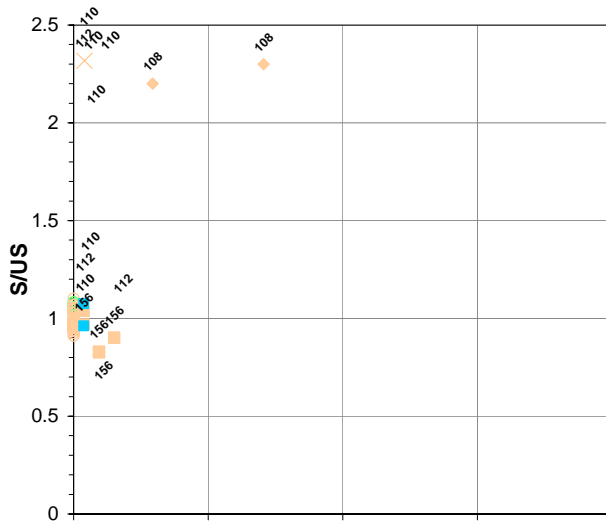
Figure 29: UD3 R0390 R=0.1 RSD plot level 1b-3 (compression)



RSTT, UD3 R0390, R=10, level 1b

- ◆ WMC
- ◆ DLR
- ◇ RAL
- ◆ RISØ
- ◆ CRES
- ◆ VUB
- ◆ UP
- ◆ VTT

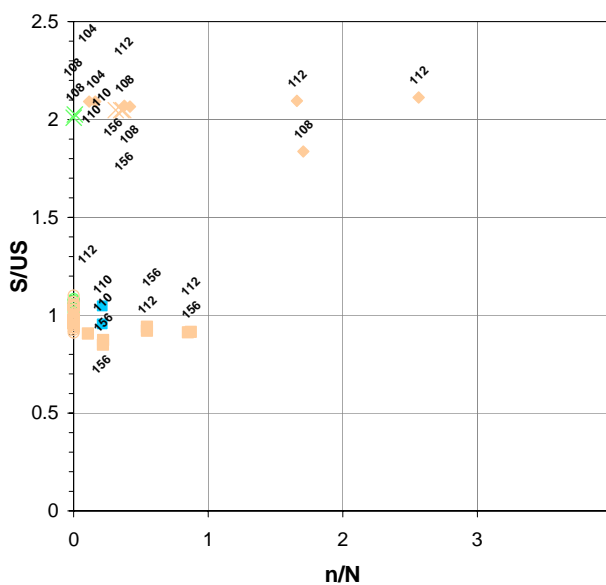
N=19293 (level)\*  
 US=54  
 no constraints on frequency



RSTT, UD3 R0390, R=10, level 2

- ◆ WMC
- ◆ DLR
- ◇ RAL
- ◆ RISØ
- ◆ CRES
- ◆ VUB
- ◆ UP
- ◆ VTT

N=132887 (level)\*  
 US=54  
 no constraints on frequency



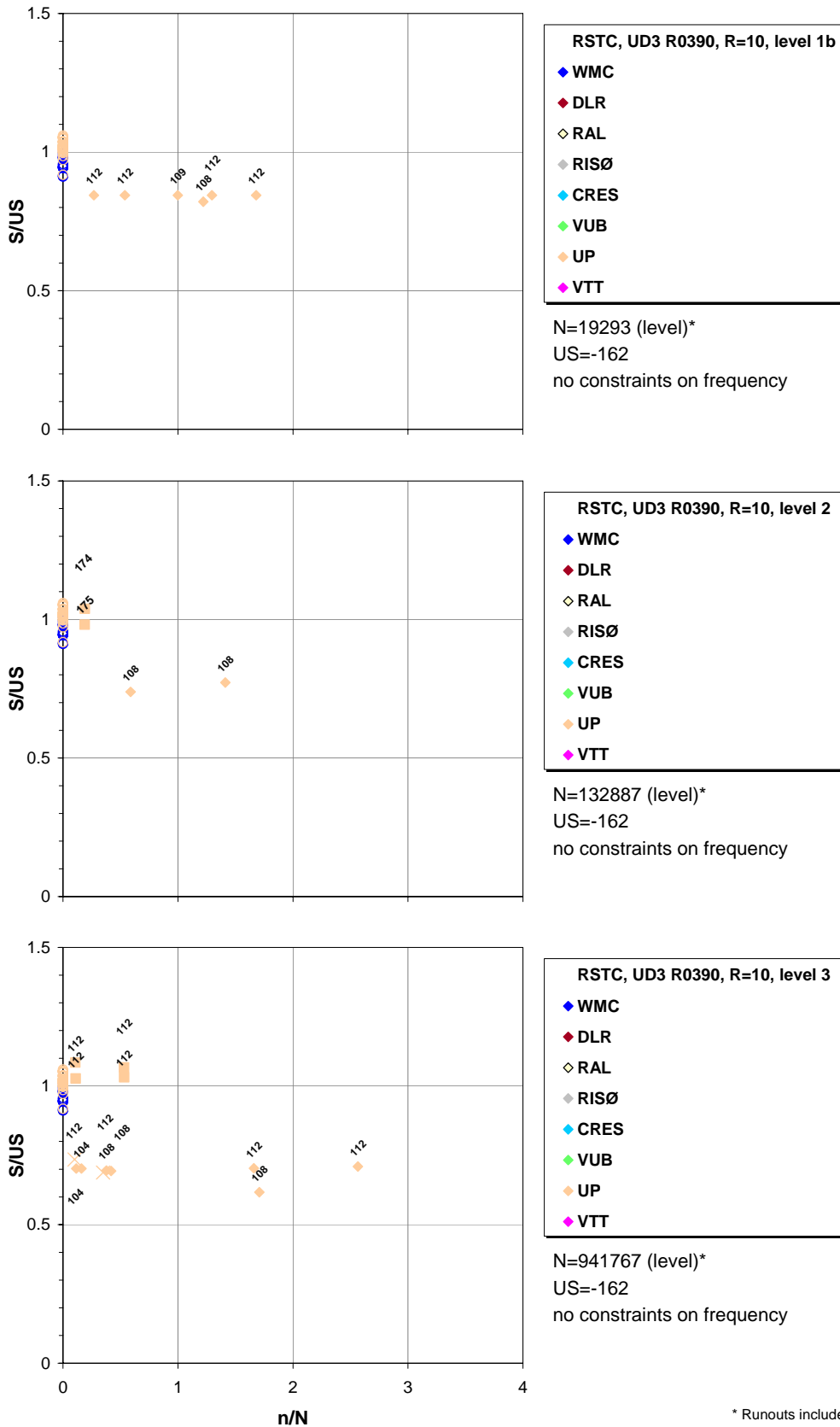


Figure 31: UD3 R0390 R=10 RSD plots level 1b-3 (compression)



### 3.2. Data trends

Difficulties are foreseen in quantifying exactly the residual strength degradation from the data. These will be discussed later. Now, the following qualitative remarks can be made from the results:

- Residual strength degradation roughly follows the patterns illustrated in Figure 32-Figure 34.
  - For R=0.1 and -1, strength degradation is similar for UD and MD material
    - Strength degradation is linear for tensile strength after R=-1 fatigue
    - For R=0.1 tensile strength, linear degradation seems to be the lower boundary for strength degradation
    - compressive strength after fatigue can not be proven to degrade after fatigue
    - For MD R=10, residual strength tests at higher life fractions for level 1b are necessary due to the discrepancy between test specification and actual mean fatigue life for the load levels
- From limited results available to date, residual strength of matrix dominated specimens, viz. the MD3 specimens and the thick transverse UD3 R0390 specimens, residual strength seems to follow similar patterns as in fiber dominated laminates UD2 and MD2. Scatter for the transverse UD case is very high.
- Scatter in residual strength seems to be comparable to that of the initial static strength. The data for MD3 I1000 are the only case, where more detailed statistical analysis is useful. There, the scatter in terms of  $\sigma/\mu$  (ratio of standard deviation and mean) is roughly

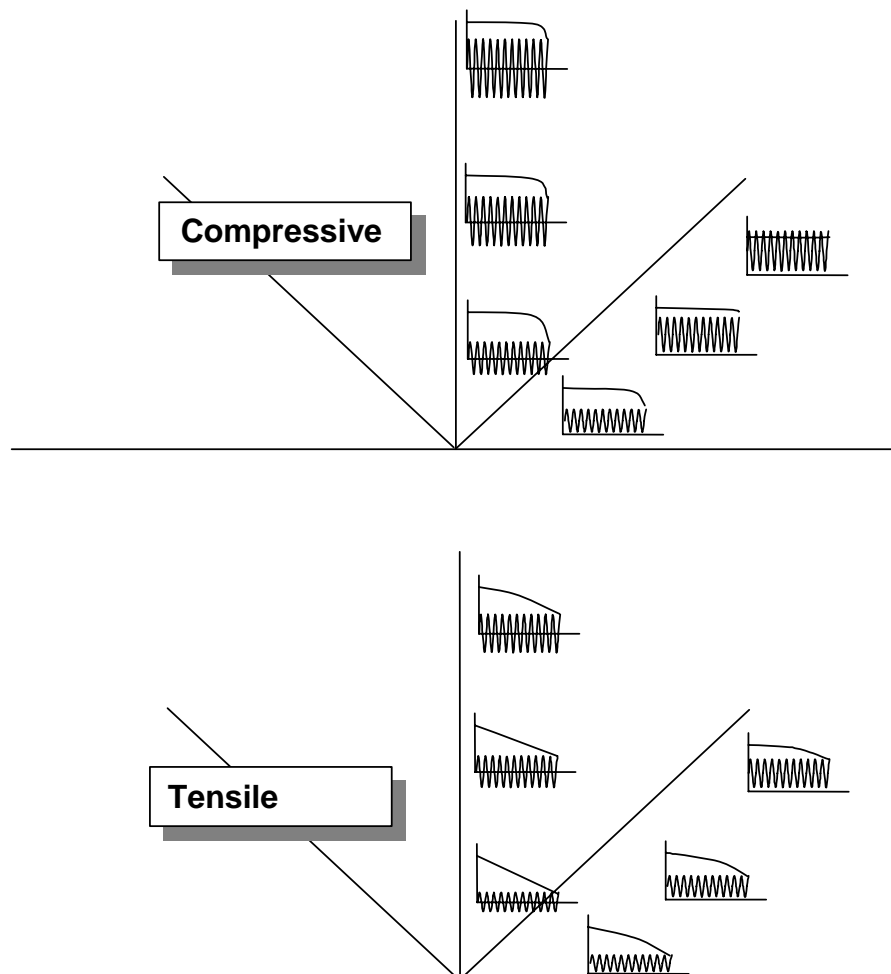


Figure 32: Strength degradation trends for standard UD2 coupons



proportional to life fraction.

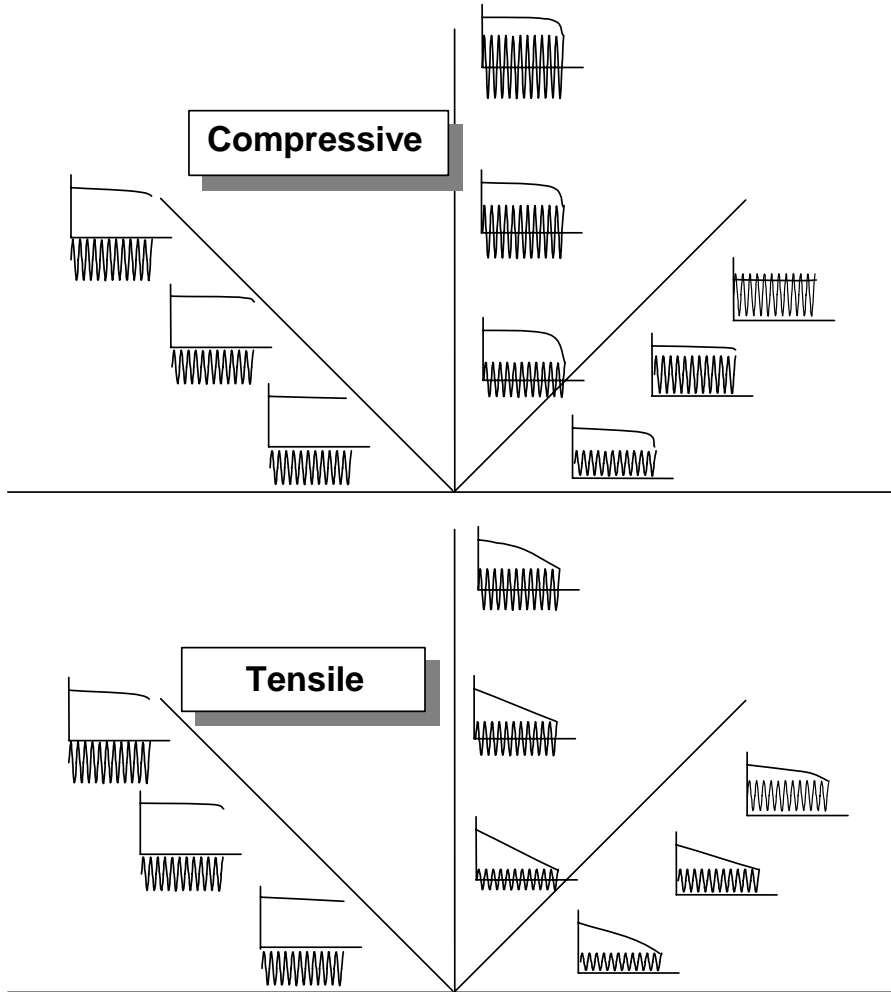


Figure 33: Strength degradation trends for standard MD coupons

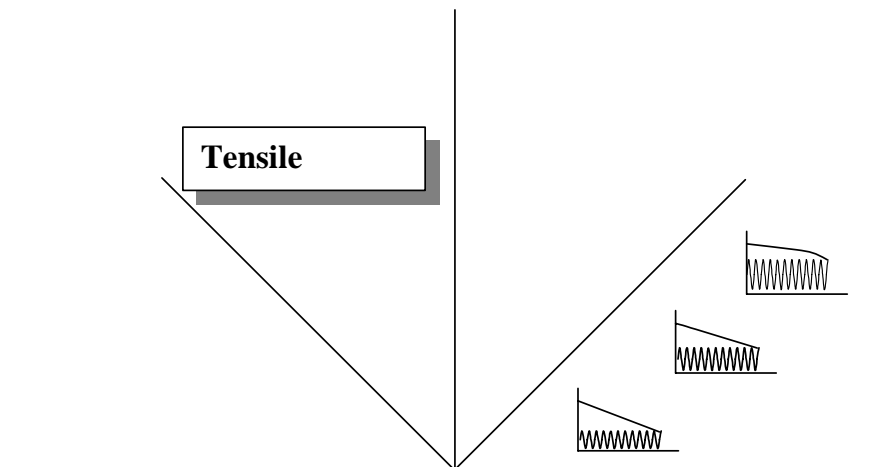


Figure 34: Strength degradation trends of I1000 ( ±45° coupons





### 3.3. Comparison to RST data from literature

In composite fatigue literature, strength and stiffness degradation models are quite abundant, as opposed to actual strength degradation data. An overview of the most relevant data for comparison with the present results is presented.

**Ryder and Walker** [7] have produced extensive residual strength degradation data on graphite/epoxy materials, and they have investigated various R-ratios as well as mixed-sign residual strength. A selection of results by Ryder and Walker is presented in Figure 35. Only a single life fraction was investigated, which does not facilitate finding the strength degradation trend. Some of the data of Ryder and Walker were extensively analysed by Yang and Jones, e.g. [8].

**Yang and Jones** [9] have presented strength degradation in shear fatigue, on  $\pm 45^\circ$  graphite/epoxy specimens. There seems to be some initial strength degradation in early life, but then the strength remains constant up to a high fraction of life, see Figure 36. Strength degradation is consistent with stiffness degradation. Fatigue stress was approximately 50% of the ultimate shear strength (14.25 ksi).

**Joneja** [10] presented strength and modulus degradation data for unidirectional glass-fiber epoxy after 25%, 50%, and 75% of the fatigue life. Essentially the strength and stiffness remained within the scatter bands of the static strengths up to the highest fatigue fraction. Data obtained at 40%, 60%, and 80% of ultimate tensile strength are reproduced in Figure 37.

**Andersons and Korsgaard** [11, 12] recently published strength degradation data for tensile fatigue of wind turbine rotor blade glass-fiber/epoxy composites. Their data are reproduced in Figure 38. It is noted, that within a small fraction of life (ca. 5%), the strength degraded noticeably. Data were collected at several stress levels, but no stress level dependency was evident. Information on premature failures, unfortunately, was not retrievable.

**Wahl** [13] has produced some tensile residual strength data for  $R=0.1$  and  $R=0.5$ . From regression of his data, he deemed a strength degradation parameter  $C$  of 0.285 as describing strength degradation best, Figure 39.

**Nijssen** [14] investigated a nominally identical composite to Wahl. He performed strength degradation research using a similar test procedure and similar conditions as in the OPTIMAT programme. Test specimen geometry and material, however, were quite different from the standard OPTIMAT specimens. One important similarity is the lay-up, which is also multidirectional, with most of the load-bearing fibers in axial direction. Despite the differences, strength degradation patterns were largely similar to the trends observed in OPTIMAT, as is observed from Figure 40-Figure 43. Scatter was generally larger than in OPTIMAT, but plate-to-plate and lab-to-lab variations were excluded. The load levels can be best compared to level 1 and a level '2b' (where 2b is between 2 and 3). In the plots, the value of the strength degradation parameter  $C$  is included, as found using the procedure described later, using the best fit to the average fatigue life. In brackets is the ratio of premature failures to total tested specimens.

Generally, the data from OPTIMAT are consistent with the scarce residual strength data obtained from literature, as far as comparable materials, load levels, and R-ratios have been studied. For  $R=-1$  and  $R=0.1$ , strength degrades in early life and degradation can be described using a linear or S-shaped curve. The Joneja data do not agree as they do not show any property degradation. Compressive strength degradation and strength degradation after compressive fatigue is poorly represented in published data.

Data on graphite aerospace grade laminates show similar behaviour in tension residual strength, but different behaviour in compressive residual strength. In this light, it is interesting to note, that Adam et al. [15] have noted different strength degradation behaviour in graphite and glass laminates.

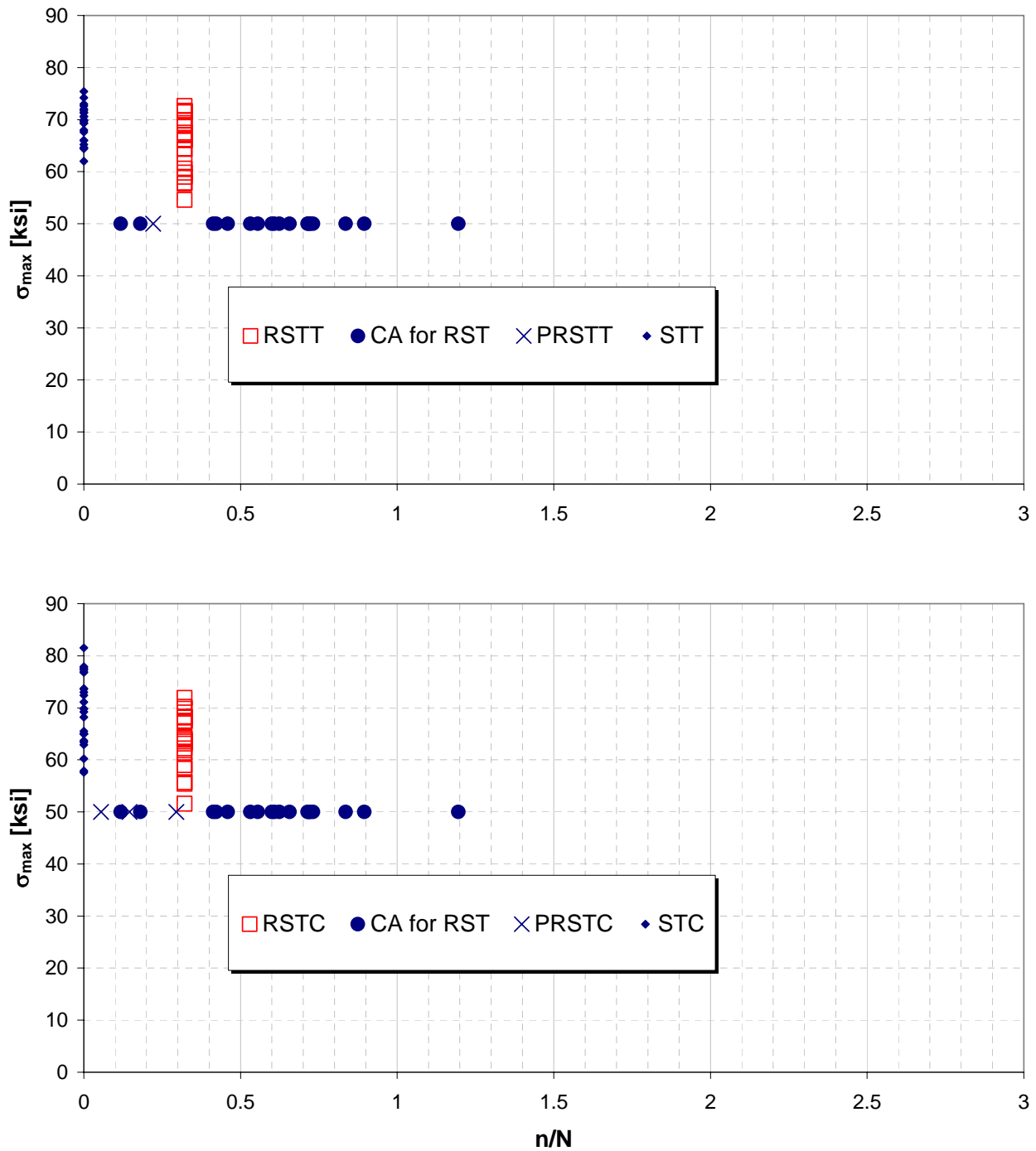


Figure 35: Tensile and compressive strength after R=0 fatigue, graphite/epoxy (Ryder and Walker [7])

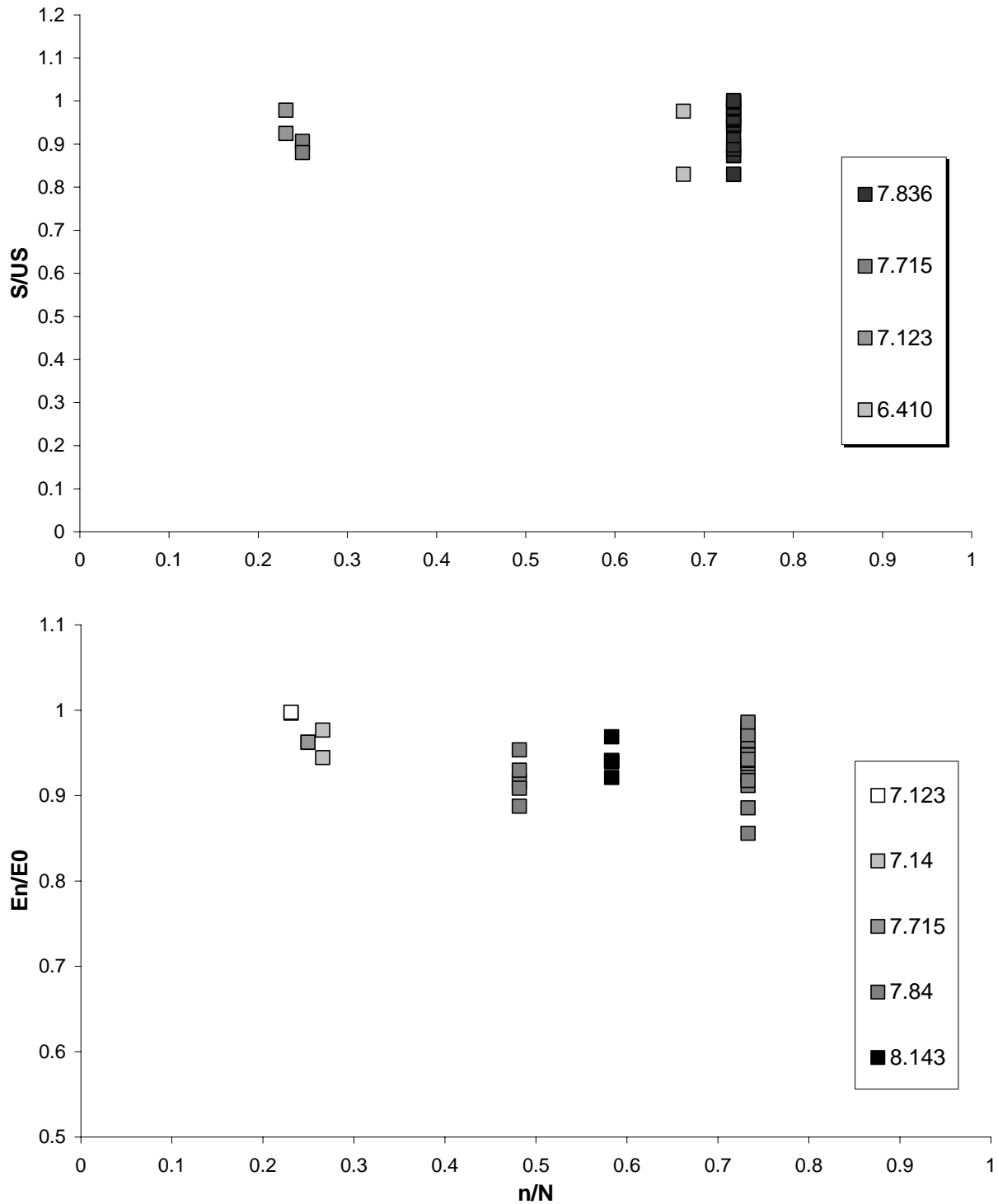


Figure 36: Strength and stiffness degr., shear tension-compression, different levels, Yang and Jones [9]

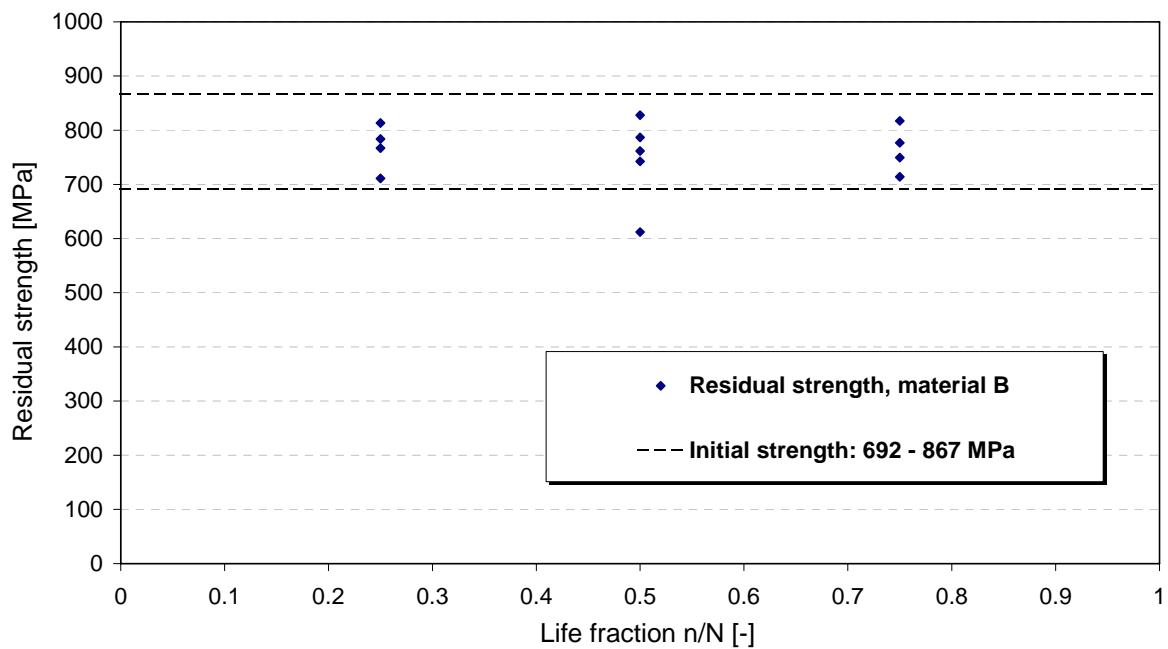
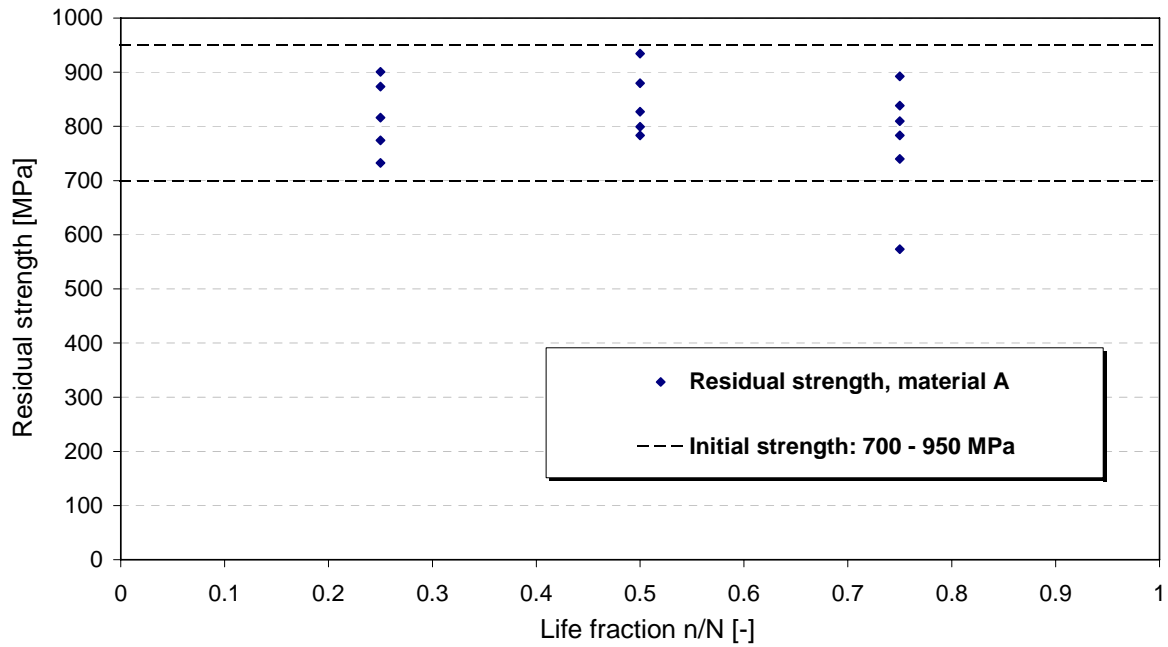


Figure 37: Strength degradation after R=0.1 of two materials, reproduced from Joneja [10]

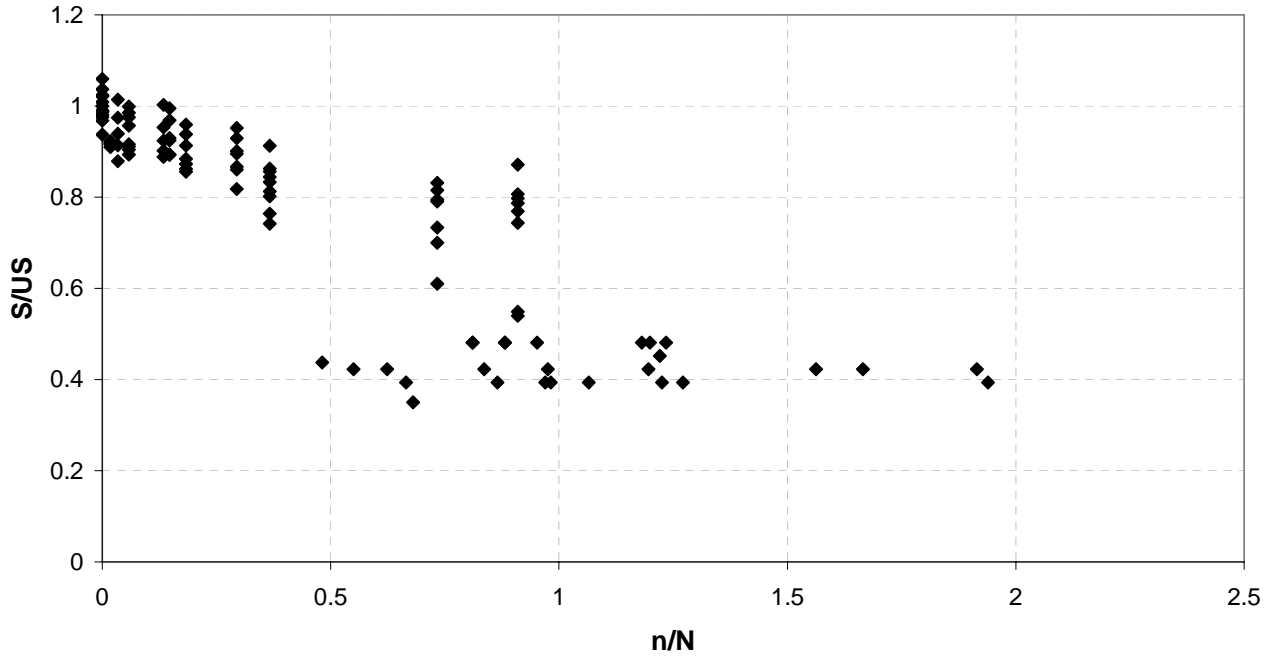


Figure 38: Tensile strength degradation, different stress levels, R=0.1, courtesy Andersons and Korsgaard [11, 12]

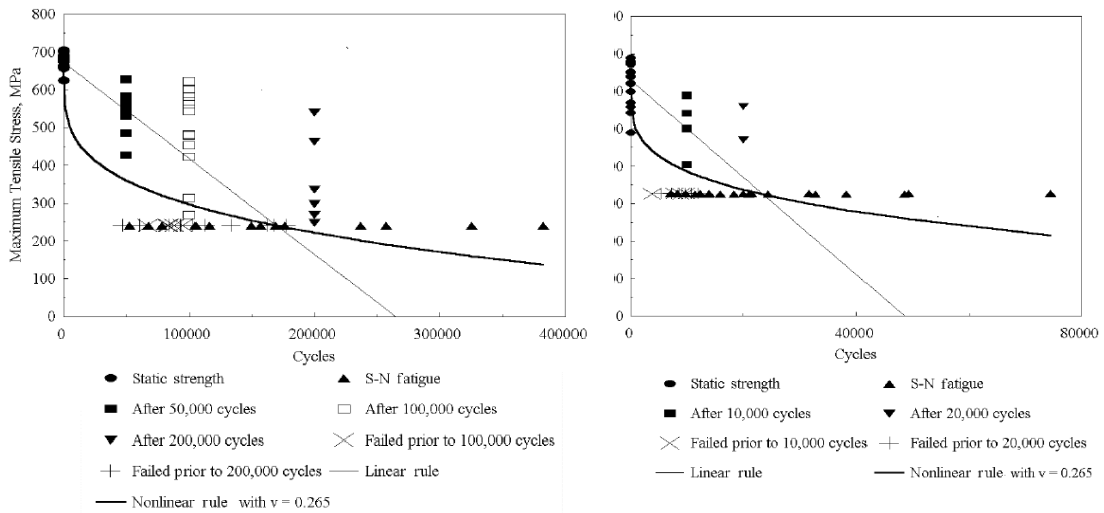


Figure 39: Tensile residual strength data after R=0.1 (left), and R=0.5 (right), from Wahl [13]

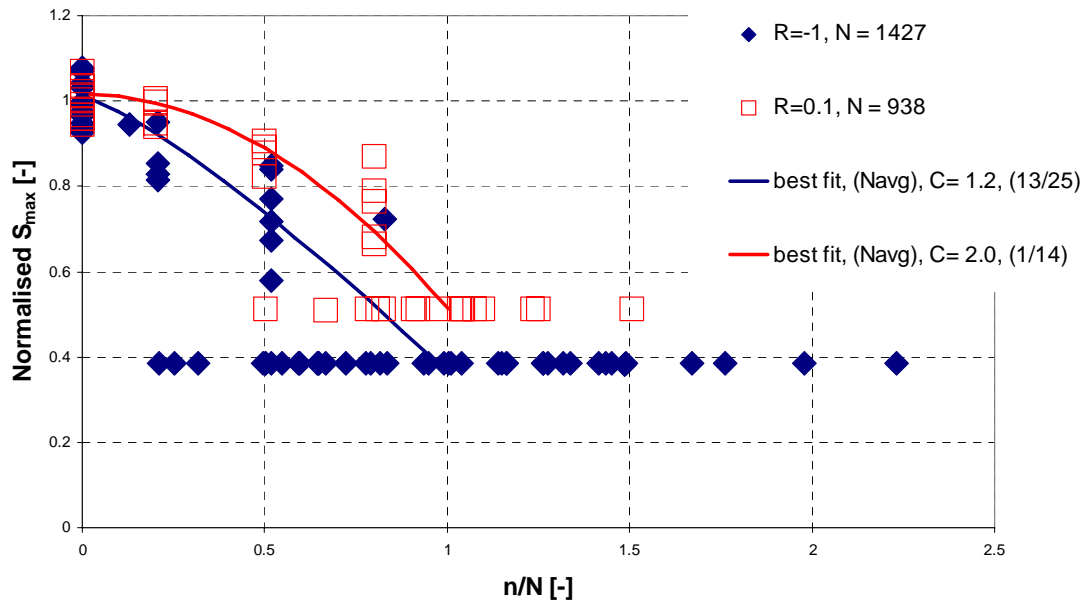


Figure 40: Level 1 residual tensile strength

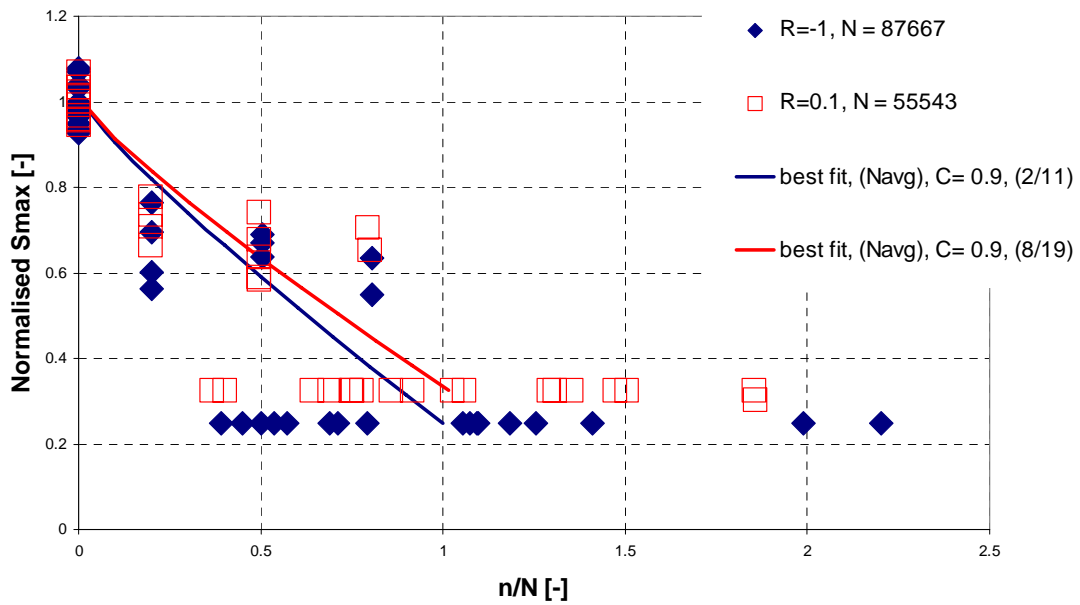


Figure 41: Level '2b' residual tensile strength

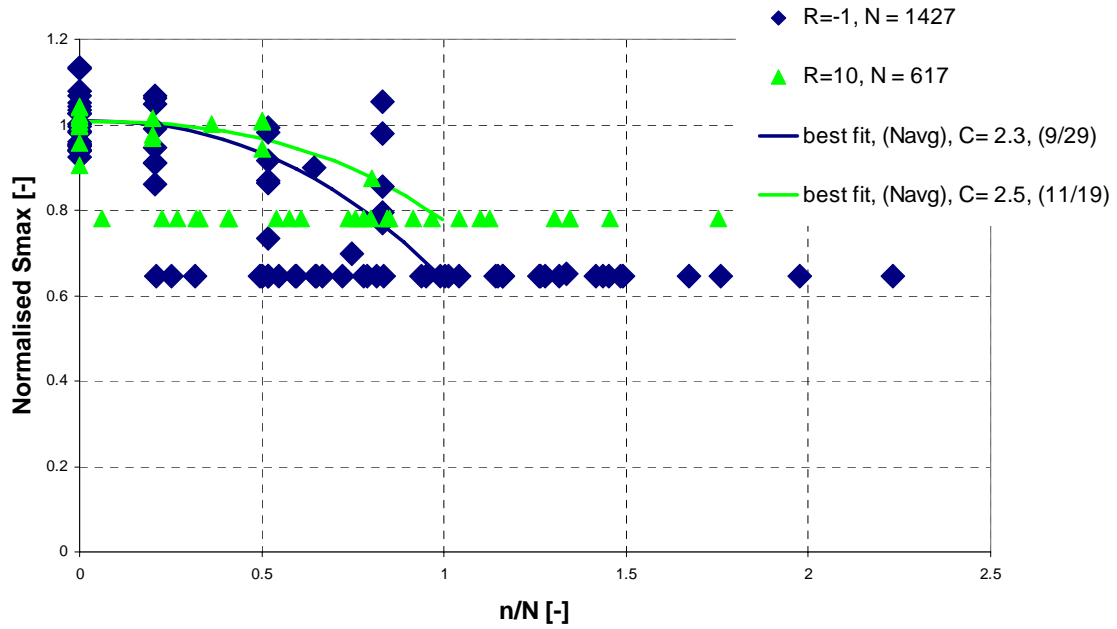


Figure 42: Level 1 Residual compressive strength

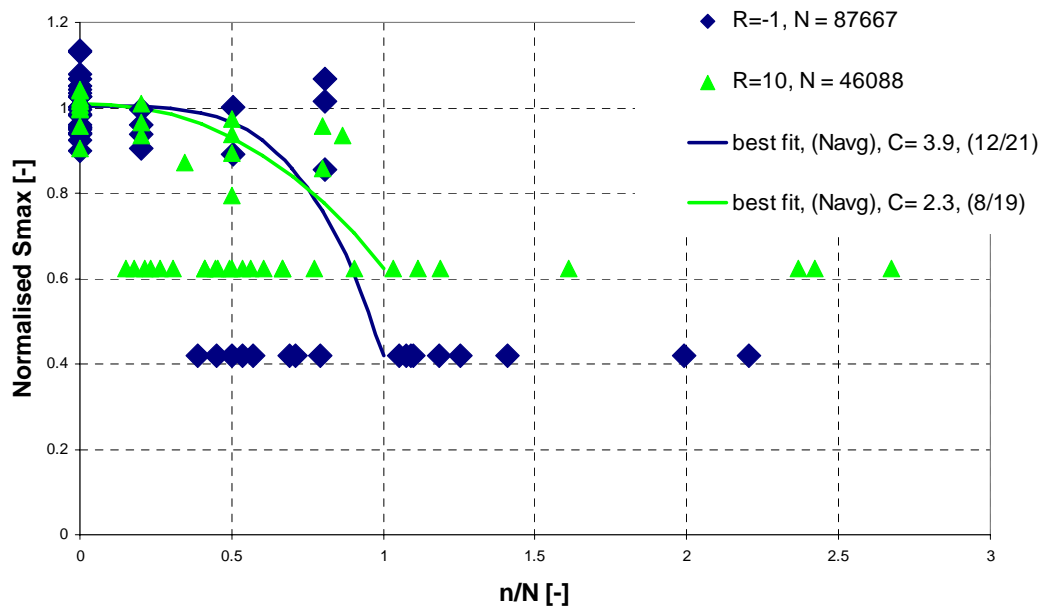


Figure 43: Level '2b' residual compressive strength



### 4. Analysis of the results

Several models have been devised in the past to describe material degradation. This chapter describes a candidate method to derive the model parameter for a one-parameter model from the residual strength data. The role of all the data in the strength degradation plot in this process is addressed.

The model, which is proposed to use for the strength degradation modelling is the one-parameter model of the form:

$$S_r = S_0 - (S_0 - S_{max}) \left( \frac{n}{N} \right)^C \dots\dots\dots (1)$$

, where n/N is life fraction, and C is the strength degradation parameter. Initial static strength is represented by S<sub>0</sub>, residual strength by S<sub>r</sub>, and maximum fatigue stress by S<sub>max</sub>, see Figure 44.

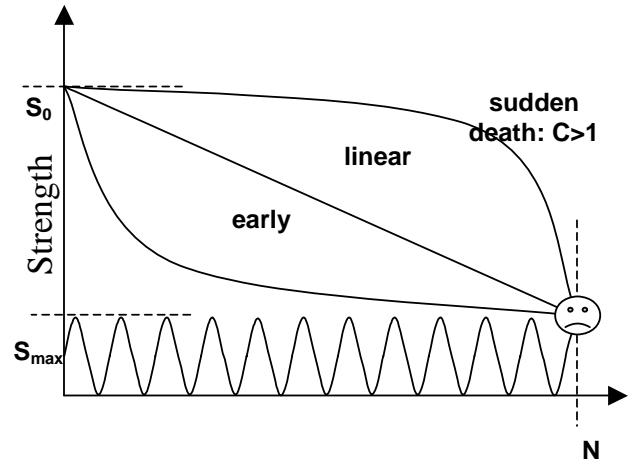


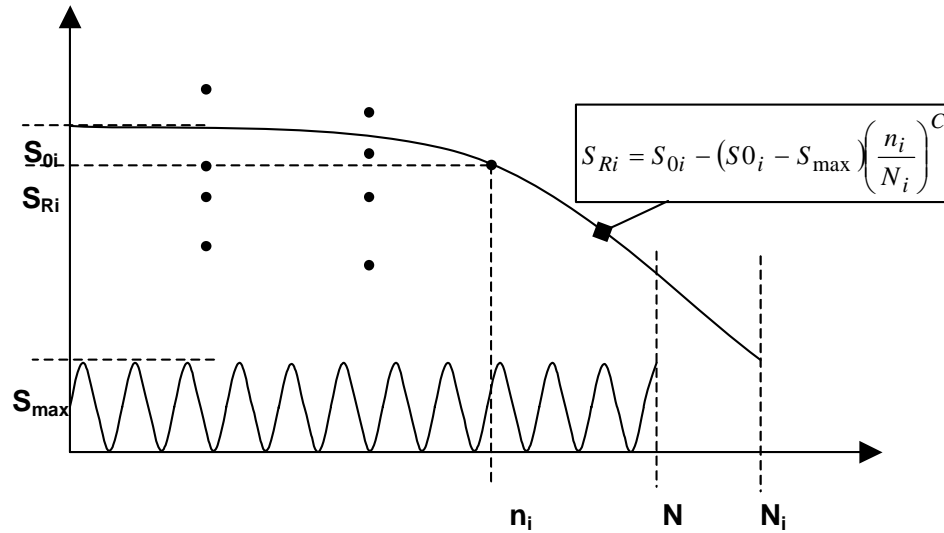
Figure 44: Different types of Residual Strength Degradation

The method to obtain the strength degradation parameter C is a heuristic method, which uses the strength-life-equal-rank-assumption (SLERA) [16, 17]. The SLERA states, that strength and life ranks are correlated, i.e. specimens with a high initial static strength will have longer lifetimes than specimens with a low initial static strength.

In the parameter estimation procedure, outlined in Figure 45, each specimen is assumed to have an initial static strength S<sub>r,i</sub>, and the same strength degradation parameter. Using equation (1) and the residual strength data, a new set of fictitious static strength data and constant amplitude data is generated. Subsequently, the properties of the distribution of the generated datasets and the actual static strength and constant amplitude dataset are compared. Then, the value of C is iteratively adapted so as to find the 'best fit' with the static and fatigue datasets. This best fit can be done using single distribution parameter, such as the mean of the static strengths. Alternatively, a cost function can be minimized, which contains a combination of distribution parameters, as outlined in e.g. [18], and [19]. This method is based on a similar equivalent strength approach by Sendekyj [20]. For different residual strength models, the parameters have been determined for some of the datasets in [21].

Summarising, this method combines a deterministic description of strength degradation with the SLERA, introducing statistical treatment of the data. Essentially, it is similar to the method for

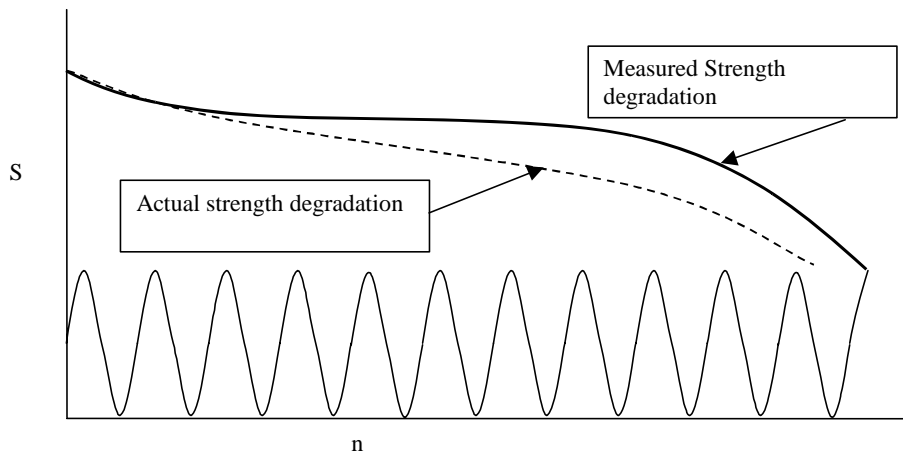




**Figure 45: Strength degradation parameter estimation procedure**

obtaining the S-N curve and Weibull statistics for constant amplitude fatigue and residual strength data as proposed by Sendeckyj [20], which was investigated in the frame of TG1 [22]. In [], this method has been used to find strength degradation parameters for various models.

The resulting parameter C is slightly optimistic for larger life fractions. This is illustrated in Figure 46. According to the SLERA, specimens which have lowest residual strength at a high life fraction have a higher chance of failing prematurely. Therefore, what is seen in the strength degradation plots is the top-percent specimens surviving e.g. 80% of the nominal fatigue life. Thus, the residual strength described by C, which was calculated disregarding the premature failures, is an overestimation. The degree of overestimation depends on the life fraction and the distribution of constant amplitude life and of the residual strength distribution at the relevant life fraction.



**Figure 46: Influence of strength censoring by fatigue**

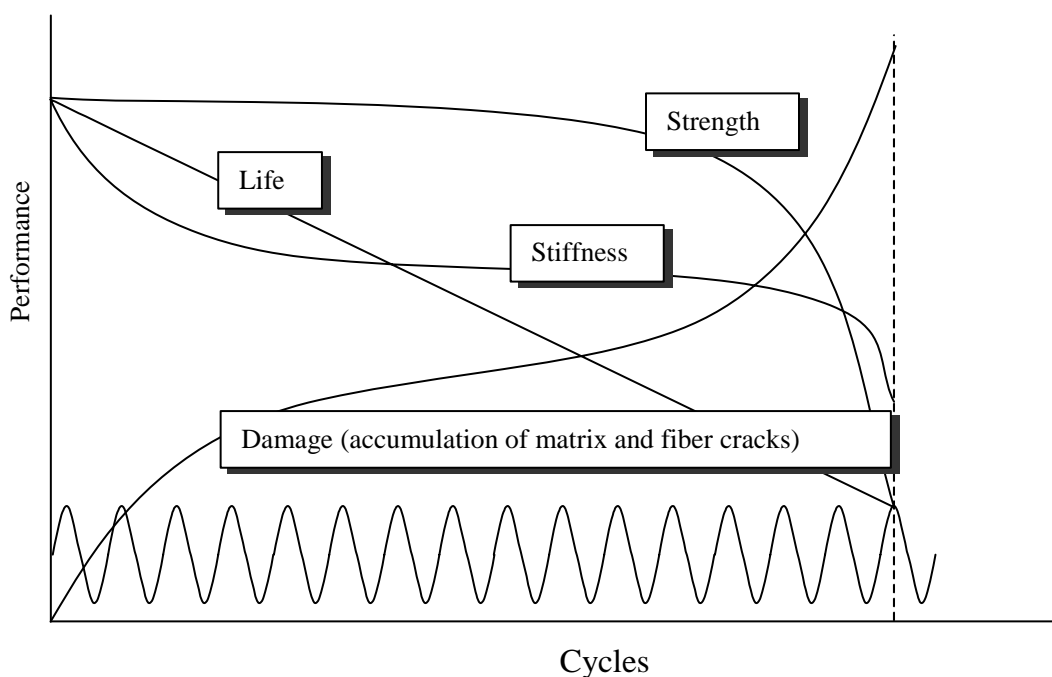
Premature failures should be included in this analysis to more accurately normalise life fractions. These data, although they are not constant amplitude data, contain information on the constant amplitude fatigue behaviour of the laminate. Theoretically, it is possible to compare the actual number of premature failures to the calculated number of premature failures (from the distribution

of constant amplitude fatigue data). The difference indicates, that the actual mean life may be different from the measured mean life of the CA tests.

The success of such an analysis is determined in part by the number of CA data and of RST-attempts, and should not be hampered by plate-to-plate or lab-to-lab variations. Unfortunately, for the OPTIMAT data, such a statistical analysis is not facilitated by the fact, that the data in the strength degradation plot are produced by different laboratories and are taken from different plates. Finally, the formulation of equation (1) presupposes, that residual strength is of the same sign as the maximum fatigue stress. In practice and in the experiments, data were collected where residual strength and maximum fatigue stress had the opposite sign. In these cases, determining the parameter C requires an adaptation of the formulation of equation (1), not only to find the descriptive parameters, but also to implement the model into a life prediction method. For instance, both tensile and compressive strength need to be tracked in a fatigue load spectrum to evaluate for each subsequent peak *and* valley if the residual strength is exceeded.

### 4.1. Stiffness Degradation Plot

As has been suggested by several authors, if stiffness were to be correlated to strength, this would be an interesting diagnostic parameter to evaluate non-destructively the residual strength or life of a laminate structure, as is schematically shown in Figure 47 (after [23]). Through modulus measurements, and a theoretical relationship between modulus and one of the parameters



**Figure 47: Composite performance and characteristics in fatigue**

outlined in Figure 47, the operator of the composite structure would be able to monitor the structures health.

On the other hand, in practice, it is not feasible to measure the stiffness throughout a structure. The modulus measured at (one) specific location(s) in the structure is likely to give only limited information on the structural health. For instance, large stiffness degradations might occur in structural 'hot spots' such as design details, but these modulus changes are poorly reflected in the stiffness of the structure as a whole. Redistribution of strains due to damage accumulation in the structure might also complicate structural health assessment using stiffness monitoring.



Notwithstanding any questions regarding stiffness measurement in practical structural applications, they might be helpful in reducing scatter. For instance, if static strength and initial stiffness are related, the spread in the static dataset could be reduced. The same might apply to the fatigue data, and the residual strength data can be ranked with respect to their stiffness prior to residual strength testing.

In the OPTIMAT programme, continuous stiffness measurements were made during the fatigue part of the measurement. In OptiDAT, only the initial and final modulus are given for part of the residual strength data set. Generally, stiffness measurements were included if the back-to-back strains did not differ more than ca. 10%. In many cases, clip gauge measurements exceeded this limit and were not included in the data. A comparison of initial and final stiffness of the residual strength tests is plotted in Figure 48 and Figure 49.

From these plots, the relative stiffness degradation does not seem to be correlated to the residual strength. No correlation between strength and stiffnesses seems apparent from table 1, either. Very low correlation of stiffness and strength was reported in [25, 26]

Generally, stiffness degradation is similar for compressive and tensile modulus, and independent of the sign of the residual strength test (which makes sense). For UD R=0.1 loading, there is not any notable average stiffness degradation. This is surprising, especially for the compression modulus, since this would be expected to be influenced by (partial) delaminations, which might be expected in the material after fatigue cycling. CRES has reported stiffness degradations, of which both the final value and the rate seemed to decrease with increasing life [24]. In some cases, stiffness *increase* is reported.

Maximum average stiffness degradation is reported for MD R=-1, at about 15%. Although the UD and MD laminates were demonstrated to be similar on strain base [3], stiffness prior to residual strength is generally lower for the MD laminate at R=-1 than for the UD laminate at the same R-ratio. This could be explained by delamination of, and damage in, the off-axis layers.

## 4.2. Acoustic emission measurements

These were reported in [25, 26].

## 5. Implementation in life-prediction

Life prediction using, among other methods, the residual strength degradation, is described in [27, 28]. The strength degradation can fundamentally improve the life prediction methodology by replacing Miner's sum by an approach which uses the physical parameter(s) strength (and stiffness). The Classical Fatigue Analysis (CFA) and Residual Property Analysis (RPA) are schematically shown in Figure 50. However, with determining the model parameters of the strength degradation model, not yet all the ingredients for a fully operative life prediction methodology are available.

In this section, some important aspects that facilitate further use and success of the results are discussed:

- Interpolation of strength degradation parameters
- Accomodation for mixed-sign strength degradation
- Rate dependency

First of all, the strength degradation data were obtained at distinct R-ratios and load levels. In order to implement the strength degradation model into the life prediction of a structure subjected to a spectrum, which contains other load levels an R-ratios, the model parameters should be interpolated.

A similar approach to the interpolation in the Constant Life Diagram is proposed, viz. linear interpolation between known points in the  $S_{amp}$ ,  $S_{mean}$ -space, as illustrated in Figure 51. For 'S-N' curves of the strength degradation parameter, a log-log expression is proposed of the form:



$\log C = A \log N + B$  ..... (2)

, where A and B depend on R-ratio and load level. Such an interpolation method has been proposed for similar parameters by e.g. Schaff and Davidson [29].

Life prediction using the residual property method means, that the strength and stiffness are tracked using a strength and/or stiffness degradation model and the load input up to the current peak or valley, compare it to the load of the next peak or valley, and determine, whether the current strength is exceeded by the load. As this formulation implies, both tensile and compressive residual strength need to be tracked, since the next peak or valley can be either tensile or compressive. The data contain information on mixed sign residual strength, e.g. compressive strength after tensile fatigue and v.v.. The model of equation (1) is accomodated for mixed-sign residual strength in [28].

Another important aspect is, that in the life prediction rate-effects should be taken into account. It was seen from previous work, that static strength is likely to be rate-dependent, [30] for a small investigation of rate effects as an addition to the OPTIMAT programme. The residual strengths obtained at the prescribed rates of 1 mm/min or 0.25 mm/min are valid for this loading rate. In real life, however, the loading rate might be quite different and rate dependency should be taken into account for modeling purposes. As the loading rate in a realistic loading environment is likely to be higher than that in the tests, the measured residual strengths are likely to be somewhat conservative. Figure 52 describes the measured strength degradation in comparison with the actual strength degradation that is calculated from models including premature failures and rate dependency. The dependency on rate can, according to the literature, generally be described by a linear expression linking the logarithm of loading rate to the maximum stress in a static test, first described by Eyring [31]. Figure 53 shows strain rate data for the OPTIMAT specimens, as described in [30].

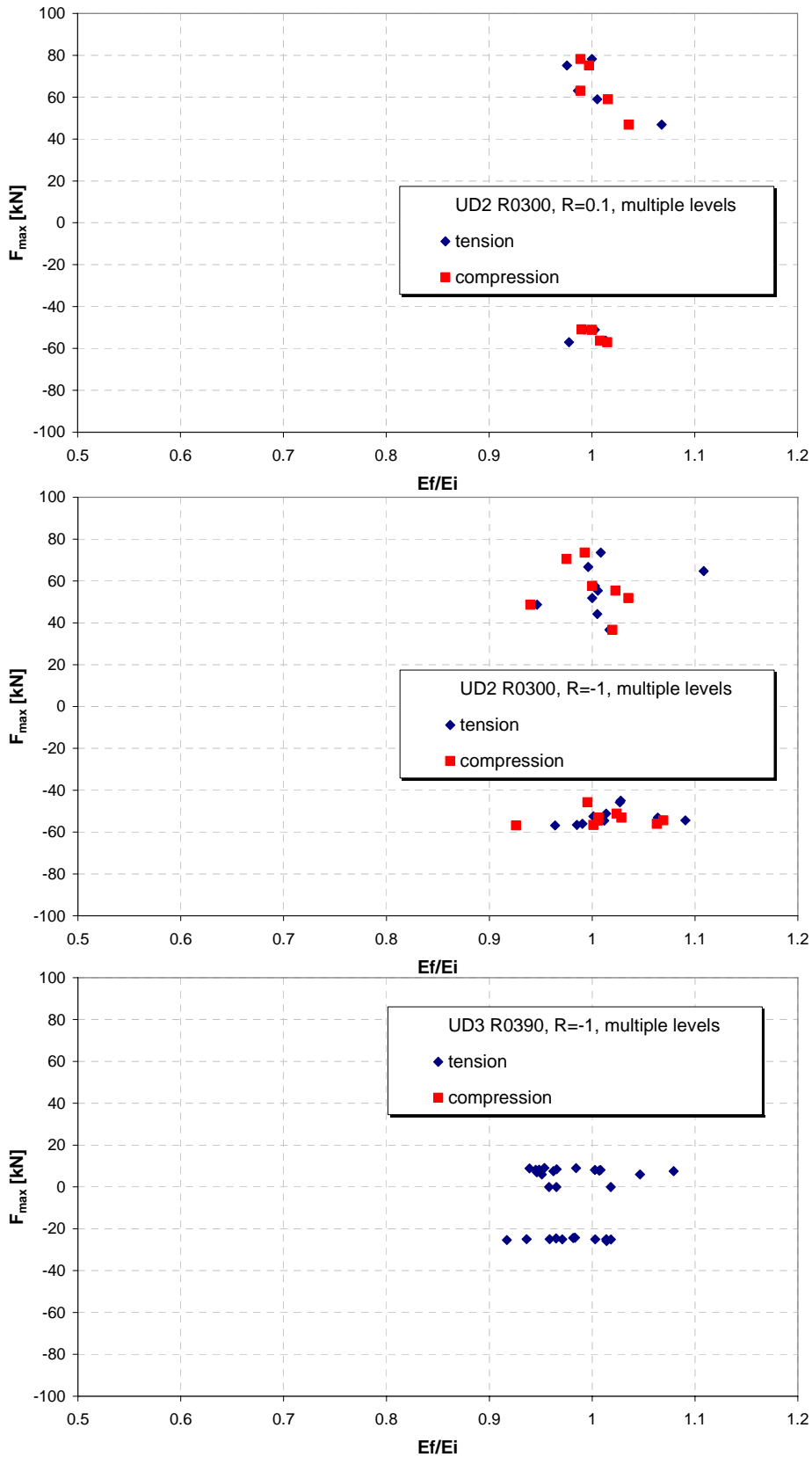


Figure 48: Stiffness degradation in OB UD coupons

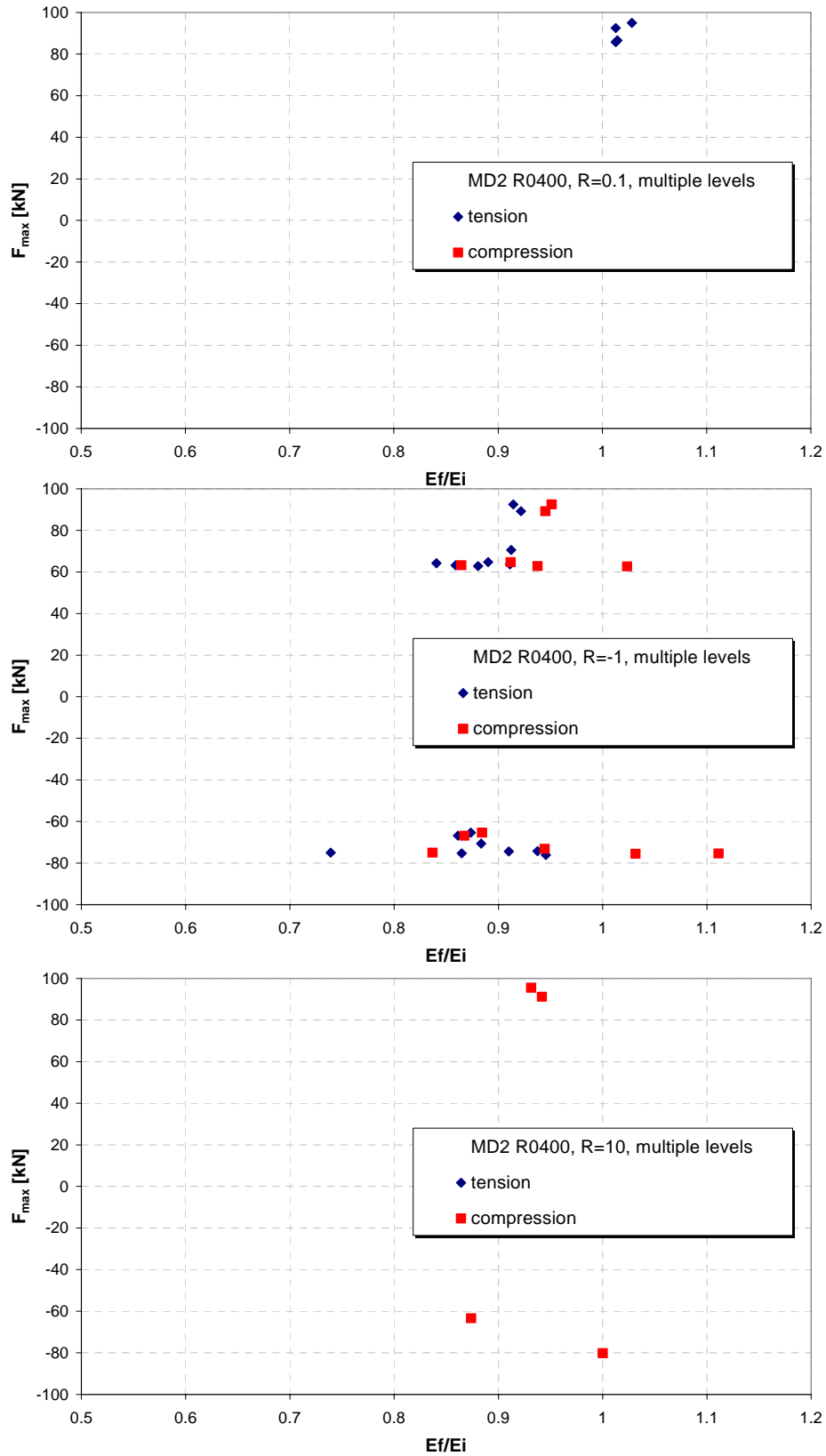


Figure 49: Stiffness degradation in OB MD coupons



Table 1: Maximum force versus ratio of initial and final stiffness

R	Test type	level	Optimat/FACT name	Ei	Ef	F <sub>max</sub>	Ef/Ei
0.1	RSTT20	2	GEV208_I1000_0058	13.76	13.37	10.36	0.97
			GEV208_I1000_0059	13.59	13.19	10.23	0.97
			GEV208_I1000_0060	13.72	13.73	10.18	1.00
			GEV208_I1000_0069	13.13	13.4	10.64	1.02
		3	GEV208_I1000_0047	12.56	12.94	10.08	1.03
			GEV208_I1000_0048	13.29	13.6	9.863	1.02
			GEV208_I1000_0050	12.99	13.26	10.36	1.02
			GEV208_I1000_0057	13.59	14.19	10	1.04
		1b	GEV208_I1000_0074	13.01	13.57	10.06	1.04
			GEV208_I1000_0075	12.85	13.07	10.16	1.02
			GEV208_I1000_0076	12.51	12.73	9.888	1.02
			GEV208_I1000_0077	13.34	13.34	9.988	1.00
	RSTT50	2	GEV208_I1000_0052	13.48	13.08	9.975	0.97
			GEV208_I1000_0053	13.53	12.49	9.175	0.92
			GEV208_I1000_0054	13.24	12.78	9.625	0.97
			GEV208_I1000_0056	13.54	13.12	9.913	0.97
		3	GEV208_I1000_0035	12.65	11.7	8	0.92
			GEV208_I1000_0036	13.05	10.13	7.8	0.78
			GEV208_I1000_0049	13.46	12.43	8.333	0.92
			GEV208_I1000_0051	13.53	11.35	7.313	0.84
		1b	GEV208_I1000_0065	12.67	11.83	9.763	0.93
			GEV208_I1000_0066	13	13.31	10.14	1.02
			GEV208_I1000_0067	13.07	12.29	9.538	0.94
			GEV208_I1000_0068	13.32	13.28	10.11	1.00
	RSTT80	2	GEV208_I1000_0070	13.57	11.49	7.9	0.85
			GEV208_I1000_0072	12.77	9.97	7.938	0.78
			GEV208_I1000_0082	13.18	12.48	8.963	0.95
			GEV208_I1000_0083	13.2	11.92	8.85	0.90
			GEV208_I1000_0084	13.45	11.73	8.9	0.87
		3	GEV208_I1000_0063	13.88	11	7.988	0.79
			GEV208_I1000_0064	13.72	11.49	8.225	0.84
			GEV208_I1000_0085	13.51	11.51	7.988	0.85
			GEV208_I1000_0087	12.96	12.37	8.325	0.95
		1b	GEV208_I1000_0078	13.21	12.35	8.225	0.93
			GEV208_I1000_0079	13.55	11.56	8.013	0.85
			GEV208_I1000_0080	13.37	12.89	9.738	0.96
			GEV208_I1000_0081	12.97	11.98	9.6	0.92

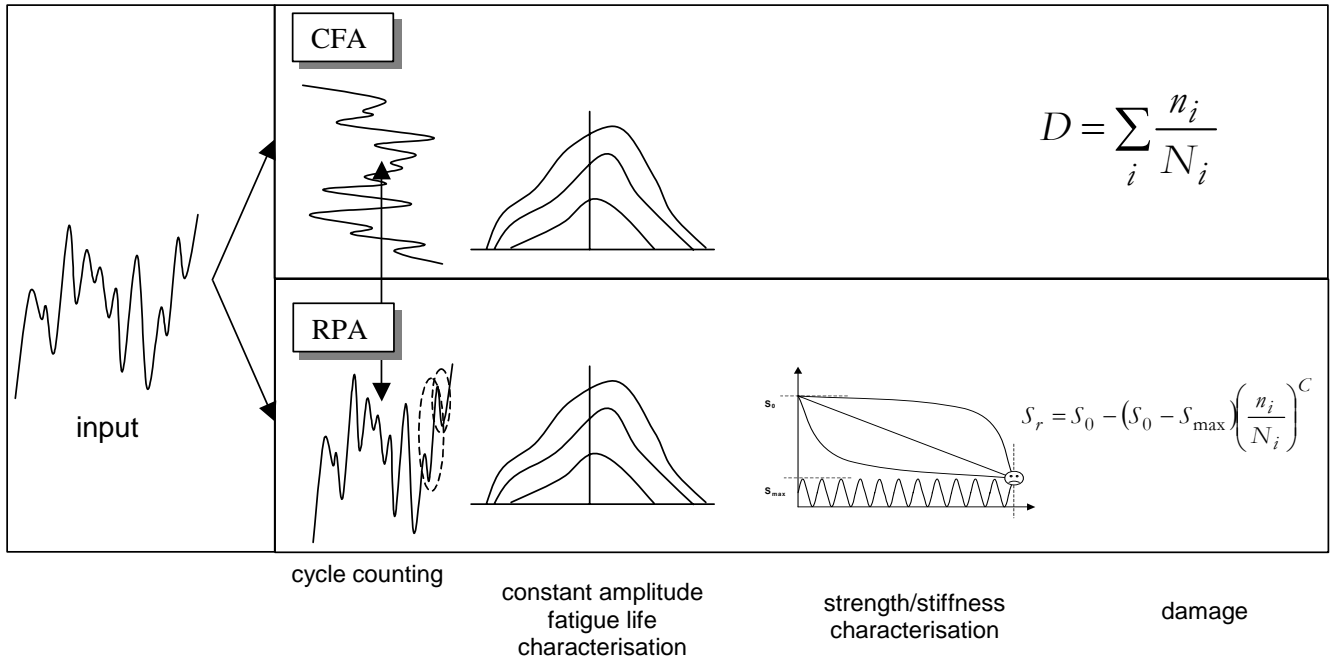


Figure 50: Schematic of Classical fatigue analysis and Residual strength/stiffness analysis

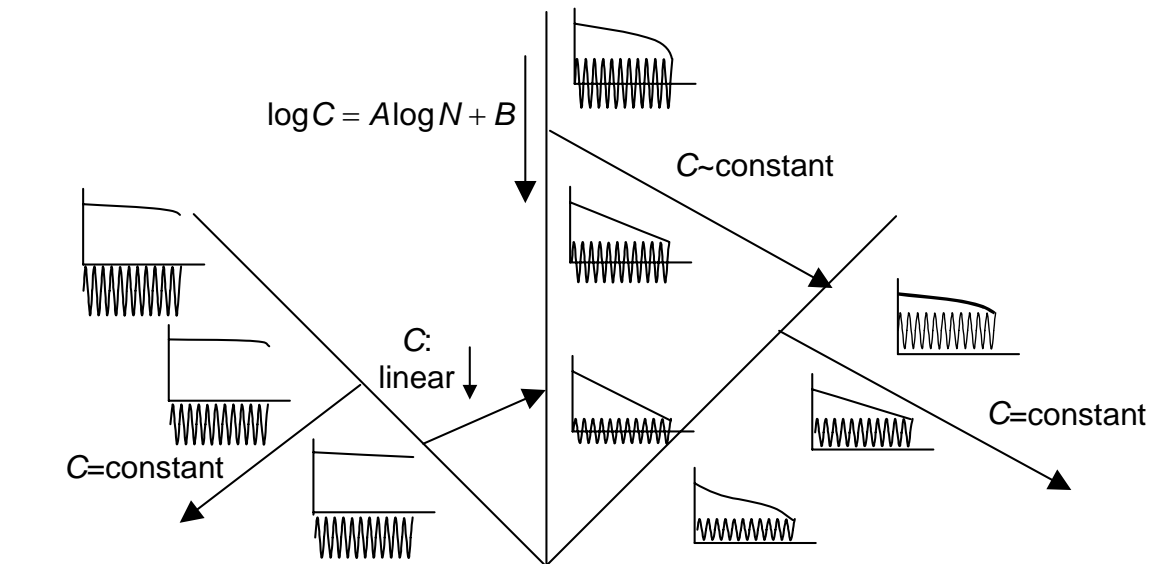


Figure 51: Interpolation of strength degradation trends



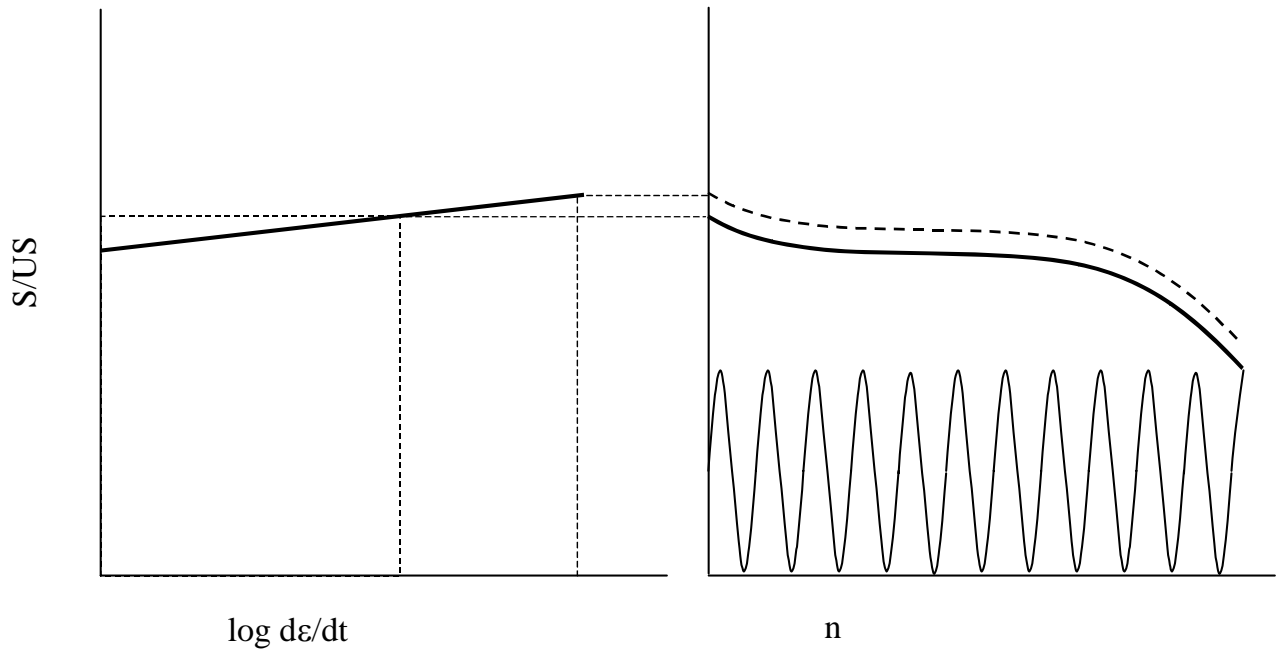


Figure 52: Influence of static strain rate

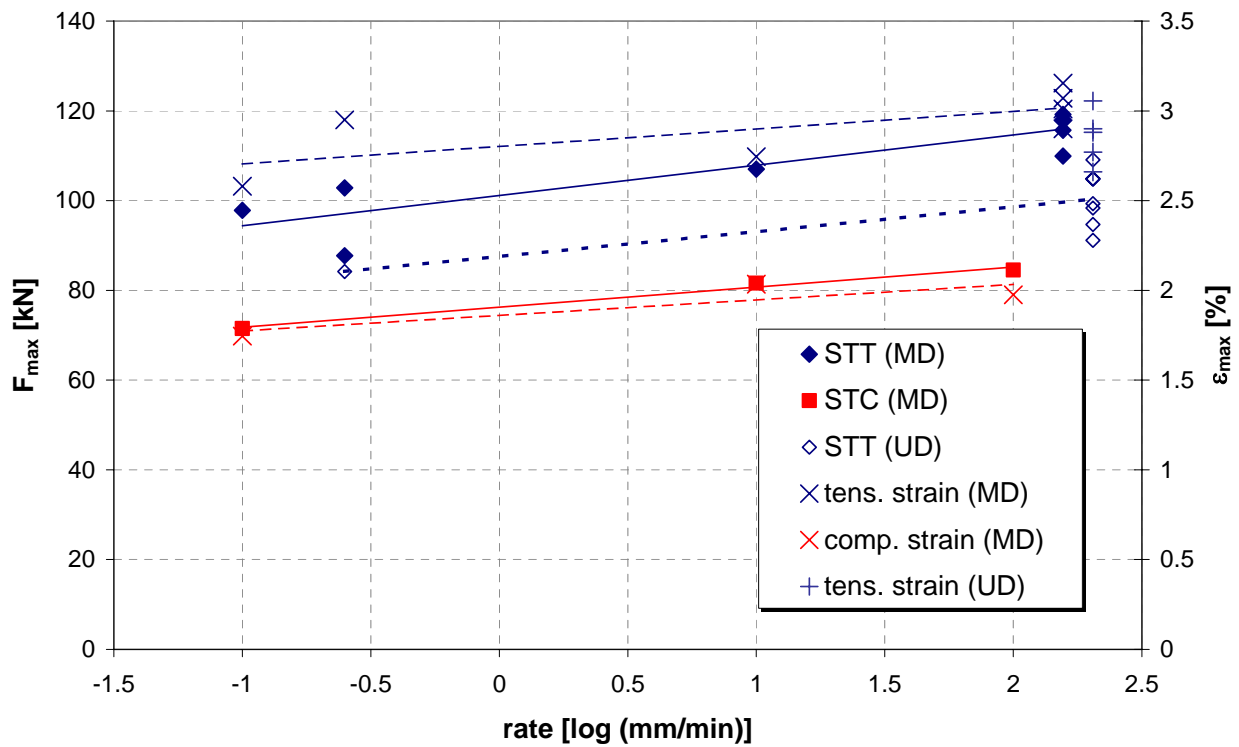


Figure 53: Influence of strain rate on static strength



## 6. Concluding remarks

- Extensive data are available describing strength degradation of various laminates. The degradation trends can be qualified as in Figure 54
- Quantitative parameter estimation should include data reduction accounting for plate-to-plate and machine-to-machine variations, rate effects, and premature failures. These effects are not likely to significantly affect the trends shown in Figure 54;
- No obvious correlation was discovered between stiffness degradation and residual strength

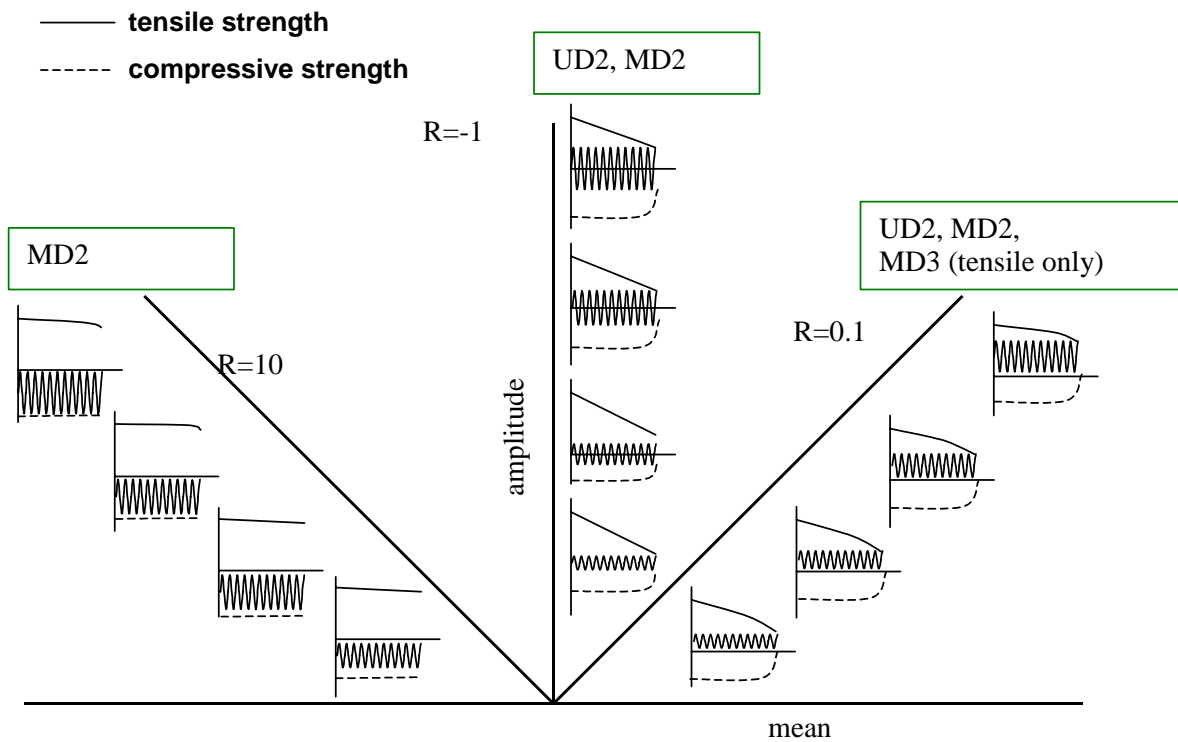


Figure 54: Schematic summary of strength degradation trends

## 7. References

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