OPTIMAT BLADES
Task Group 5
Residual Strength & Condition Assessment

Task Group Leader: Dr Geoff Dutton

Energy Research Unit, CCLRC Rutherford Appleton Laboratory

Participants: WMC, UP, VUB, CRES, CCLRC

EC Contract No. NNE5-2001-00174

Objectives

Work Package 13 : Residual Strength and Condition Assessment

To establish engineering models to account for residual static strength reduction of reference material induced by cyclic loading.

To define and validate condition monitoring strategies for blade materials subjected to fatigue loading, by adapting NDT techniques, in order to assess residual strength/life.

Work Package 14 : Residual Strength of Alternative Materials

To validate the predictive engineering model for residual strength and life, established for the reference material in WP13, by comparing theoretical predictions and experimental data from the alternative materials.

Task breakdown

Work Package 13 : Residual Strength and Condition Assessment

13.1. Review of residual strength assessment concepts

13.2. Experimental evaluation of residual strength after fatigue

13.3. Development of condition monitoring techniques

13.4. Establishment of predictive engineering model

Single reference material

Work Package 14 : Residual Strength of Alternative Materials

14.1. Selection of alternative materials and test plan

14.2. Residual strength of alternative materials

14.3 Condition monitoring applied to alternative materials

14.4. Final evaluation of predictive engineering model

Actually tested UD & MD material

Residual strength tests – characterisation (1) Task 13.1/13.4

- The in-plane static strength of an orthotropic lamina under a biaxial state of loading can be characterised by 5 strength values related to the principal material directions:
- The resultant residual strengths X_R, X_R', Y_R, Y_R', and S_R after a certain number of cycles, N, at a stress ratio $R_I = \sigma_{imin} / \sigma_{imax} /$ can be expressed as:

$X_R = f_{XR}\,(X, \sigma_{xmax}, \sigma_{ymax}, \sigma_{smax}, R_x, R_y, R_s, N)$ tensile strength dir^n 1

$Y_R = f_{YR}\,(Y, \sigma_{xmax}, \sigma_{ymax}, \sigma_{smax}, R_x, R_y, R_s, N)$ tensile strength dir^n 2

$X_R' = f_{XR'}\,(X', \sigma_{xmax}, \sigma_{ymax}, \sigma_{smax}, R_x, R_y, R_s, N)$ compr. strength dir^n 1

$Y_R' = f_{XR'}\,(Y, \sigma_{xmax}, \sigma_{ymax}, \sigma_{smax}, R_x, R_y, R_s, N)$ compr. strength dir^n 2

$S_R = f_{SR}\,(S, \sigma_{xmax}, \sigma_{ymax}, \sigma_{smax}, R_x, R_y, R_s, N)$ shear strength pl. 1-2

Residual strength tests – characterisation (2) Task 13.1/13.4

- A more simplified approach is possible if each strength component is reduced to a function of load cycling in the same direction.

$X_R = f_{XR}(X, \sigma_{xmax}, R_x, N)$ tensile strength dir^n 1

$Y_R = f_{YR}(Y, \sigma_{ymax}, R_y, N)$ tensile strength dir^n 2

$X_R' = f_{XR'}(X', \sigma_{xmax}, R_x, N)$ compressive strength dir^n 1

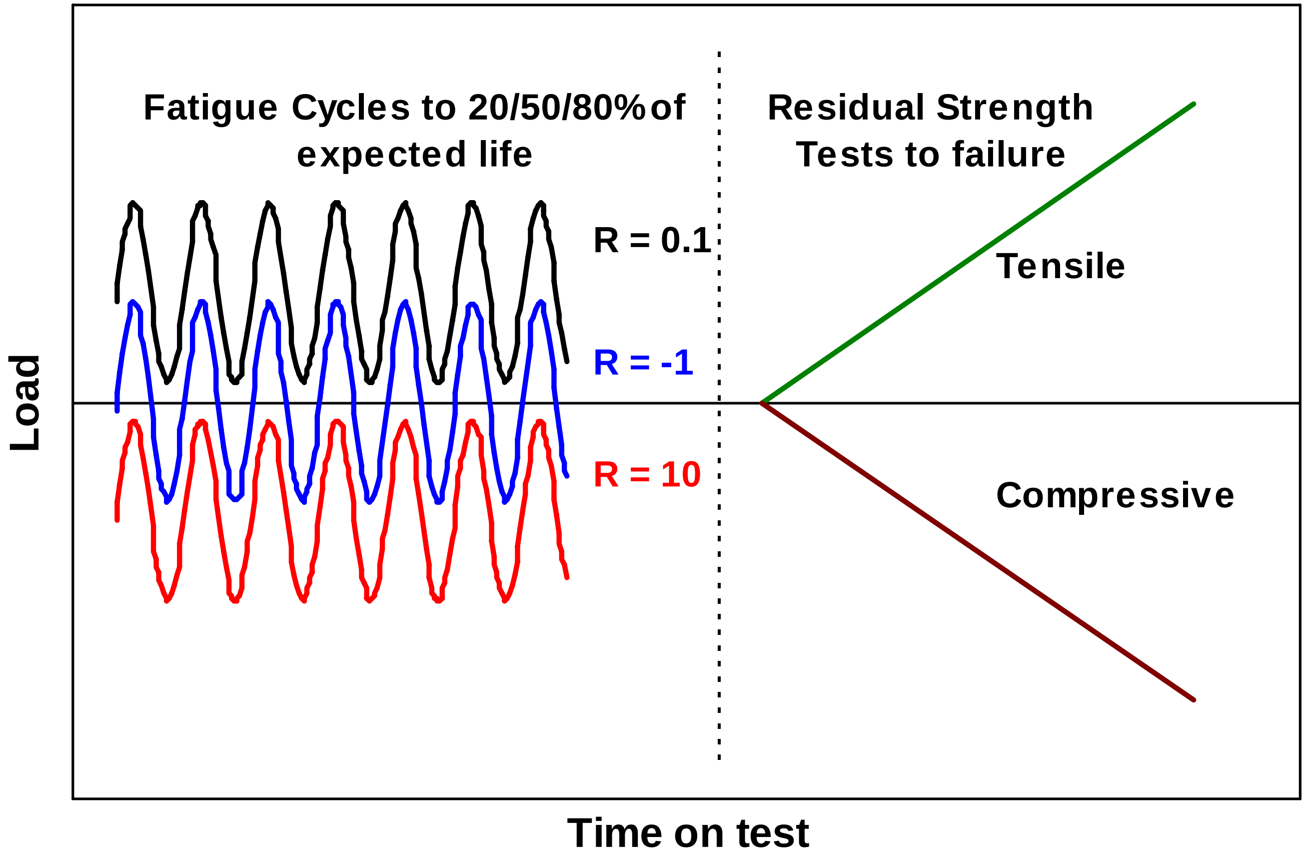
$Y_R' = f_{XR'}(Y', \sigma_{ymax}, R_y, N)$ compressive strength dir^n 2

$S_R = f_{SR}(S, \sigma_{smax}, R_s, N)$ shear strength pl. 1-2

Residual Strength Test procedure

- Initial static “proof” load (or AE proof test) for stiffness evaluation
- Constant amplitude fatigue loading
- Final static “proof ” load (or AE proof test) for stiffness evaluation
- Residual strength test to failure

Residual Strength Test procedure



Test programme – overall (Task 13.2)

Residual Strength Tests

Partner			EC	TU	DL	DE	CC	RIS	CR	VU	UP	VT	EC	TU	DL	DE	CC	RIS	CR	VU	UP	VT	EC	TU	DL	DE	CC	RIS	CR	VU	UP	VT	
lay-up	R	Type of test																															Remarks
Standard Optimat Specimens																																	
Axial (//)	0.1	20/50/80%					36			36							36			36											36		
	-1	20/50/80%		36			36							36			36																
	10	20/50/80%		36							36			36					36														
	0.1	long life		3			3										3			3													
	-1	long life		3			3												3	3													
	10	long life							3		3										6												
Transverse (⊥)	0.1	20/50/80%								36	36																						
	-1	20/50/80%							36		36																						
	10	20/50/80%							36		36																						

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Test programme – overall (Task 13.2)

Residual Strength tests - finer resolution test breakdown

Partner			WMC	CCLRC	CRES	VUB	UP	WMC	CCLRC	CRES	VUB	UP	WMC	CCLRC	CRES	VUB	UP	
lay-up	Lifetime	R	UD					MD					Shear					Total
Standard Optimat Specimens																		
Axial (//)	1.00E+03	0.1		12		12			12		12						12	60
		-1	12	12				12	12									48
		10	12				12	12		12								48
	5.00E+04	0.1		12		12			12		12						12	60
		-1	12	12				12	12									48
		10	12				12	12		12								48
	1.00E+06	0.1		12		12			12		12						12	60
		-1	12	12				12	12									48
		10	12				12	12		12								48
	1.00E+07	0.1	3	3					3		3							12
		-1	3	3						3	3							12
		10			3		3					6						12
Transverse	1.00E+03	0.1				12	12											24
		-1			12		12											24
		10			12		12											24
	5.00E+04	0.1				12	12											24
		-1			12		12											24
		10			12		12											24
	1.00E+06	0.1				12	12											24
		-1			12		12											24
		10			12		12											24

indicates tests deferred to Phase 2

indicates tests for which priority must be decided

Test programme – overall (Task 13.2)

Residual Strength Tests

Partner			EC	TU	DL	DE	CC	RIS	CR	VU	UP	VT
lay-up	R	Type of test										
Standard Optimat Specimens												
Axial (//)	0.1	20/50/80%					36			36		
	-1	20/50/80%		36			36					
	10	20/50/80%		36							36	
	0.1	long life		3			3					
	-1	long life		3			3					
	10	long life							3		3	
Transverse (⊥)	0.1	20/50/80%								36	36	
	-1	20/50/80%							36		36	
	10	20/50/80%							36		36	

Partner			EC	TU	DL	DE	CC	RIS	CR	VU	UP	VT
lay-up	R	Type of test										
Standard Optimat Specimens												
Axial (//)	0.1	20/50/80%					36			36		
	-1	20/50/80%		36			36					
	10	20/50/80%		36					36			
	0.1	long life					3			3		
	-1	long life							3	3		
	10	long life									6	
Transverse (⊥)	0.1	20/50/80%										
	-1	20/50/80%										
	10	20/50/80%										

Partner			EC	TU	DL	DE	CC	RIS	CR	VU	UP	VT	
lay-up	R	Type of test											Remarks
Standard Optimat Specimens													
Axial (//)	0.1	20/50/80%									36		
	-1	20/50/80%											
	10	20/50/80%											
	0.1	long life											
	-1	long life											
	10	long life											
Transverse (⊥)	0.1	20/50/80%											
	-1	20/50/80%											
	10	20/50/80%											

Test programme – current status (Task 13.2/14.2)

Residual Strength tests

Partner																	
				WMC	RAL	CRES	VUB	UP	WMC	RAL	CRES	VUB	UP	WMC	RAL	CRES	VUB
lay-up	R	Type of test															
Standard Optimat Specimens			UD					MD					Shear				
Axial (//)	0.1	20/50/80%		42%		128%			56%		119%						100%
	-1	20/50/80%	61%	31%				139%	6%								
	10	20/50/80%	0%				0%	78%		0%							
Transverse (⊥)	0.1	20/50/80%				0%	0%										
	-1	20/50/80%			0%		100%										
	10	20/50/80%			0%		0%										

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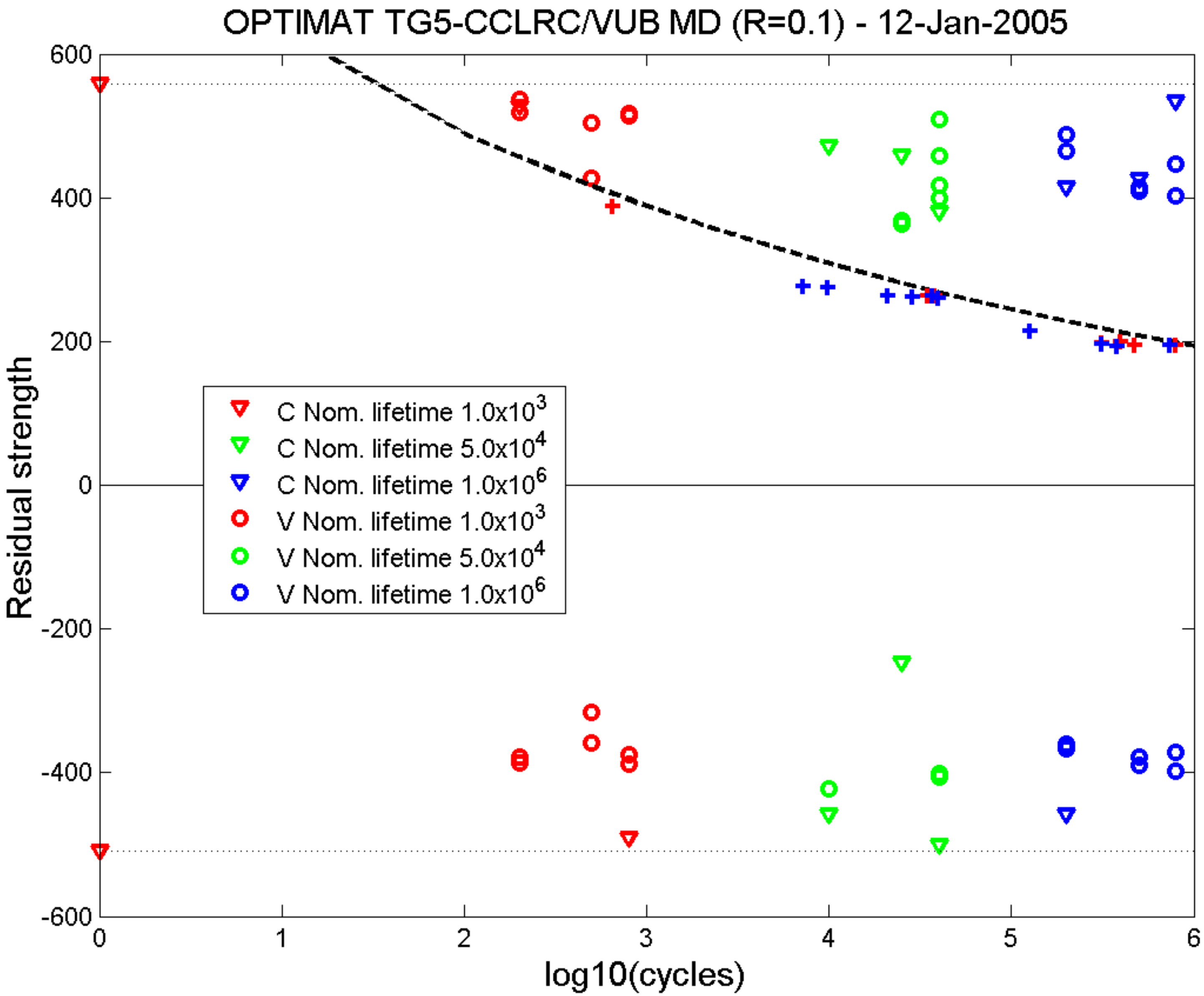
Progress (January 2005)

- Progress with testing (results reported to Optidat) by 12 January 2005 was as follows:
  - CCLRC : 48 reported (32 valid RST; 16 prem.) of 144
  - CRES : 0 reported (0 valid RST) of 108
  - UP : 72 reported (64 valid RST; 8 prem.) of 144
  - VUB : 93 reported 62 valid RST; 31 prem.) of 108
  - WMC : 51 reported (39 valid RST; 12 prem.) of 144

Residual strength tests – sample results

MD (R = 0.1 & R = -1) : results from VUB, WMC & CCLRC

UD (R = 0.1 & R = -1) : results from VUB, WMC & CCLRC



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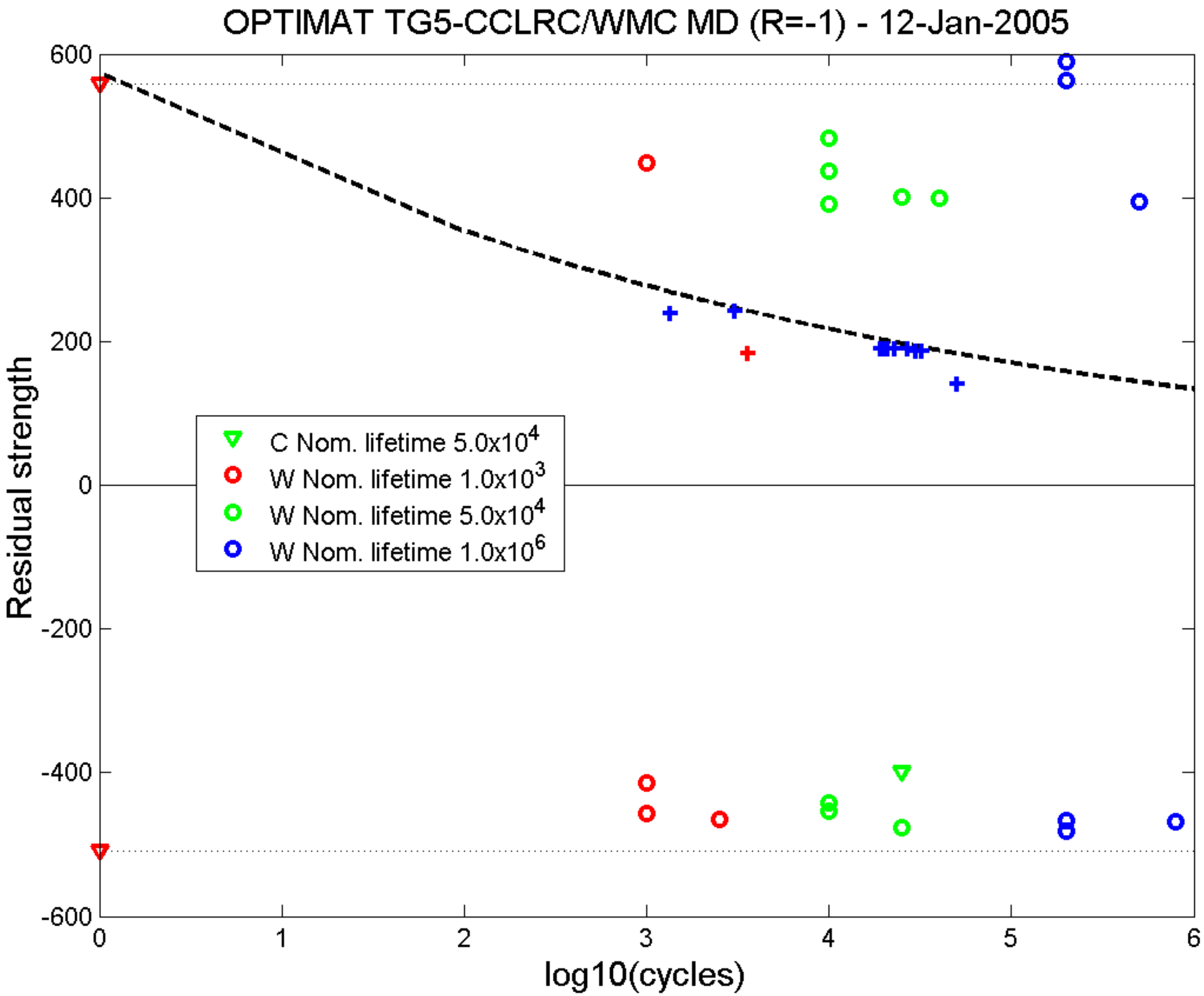
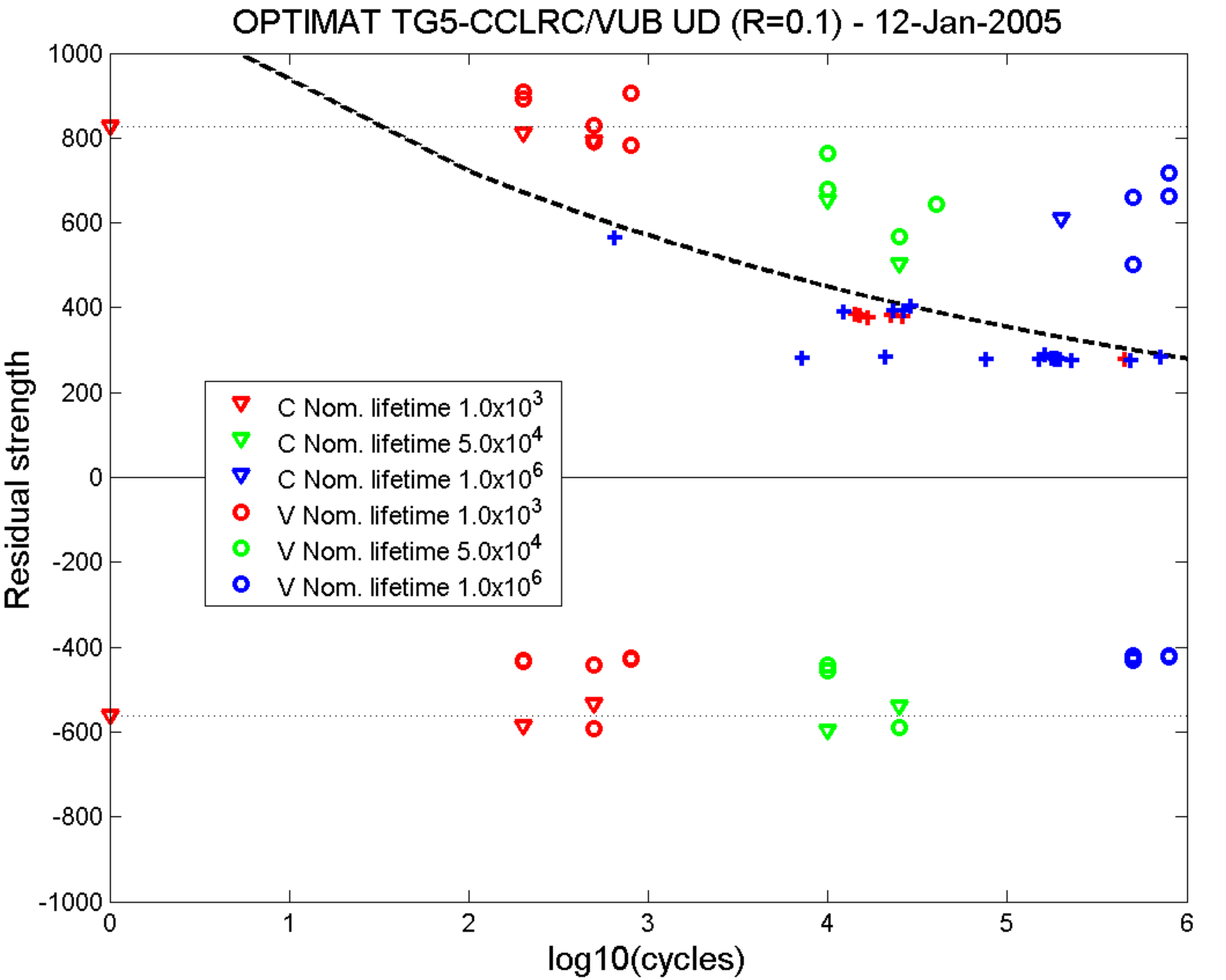


OPTIMAT TG5-CCLRC/WMC MD (R=-1) - 12-Jan-2005
Residual strength
log10(cycles)
600
400
200
0
-200
-400
-600
0
1
2
3
4
5
6
C Nom. lifetime 5.0x10^4
W Nom. lifetime 1.0x10^3
W Nom. lifetime 5.0x10^4
W Nom. lifetime 1.0x10^6



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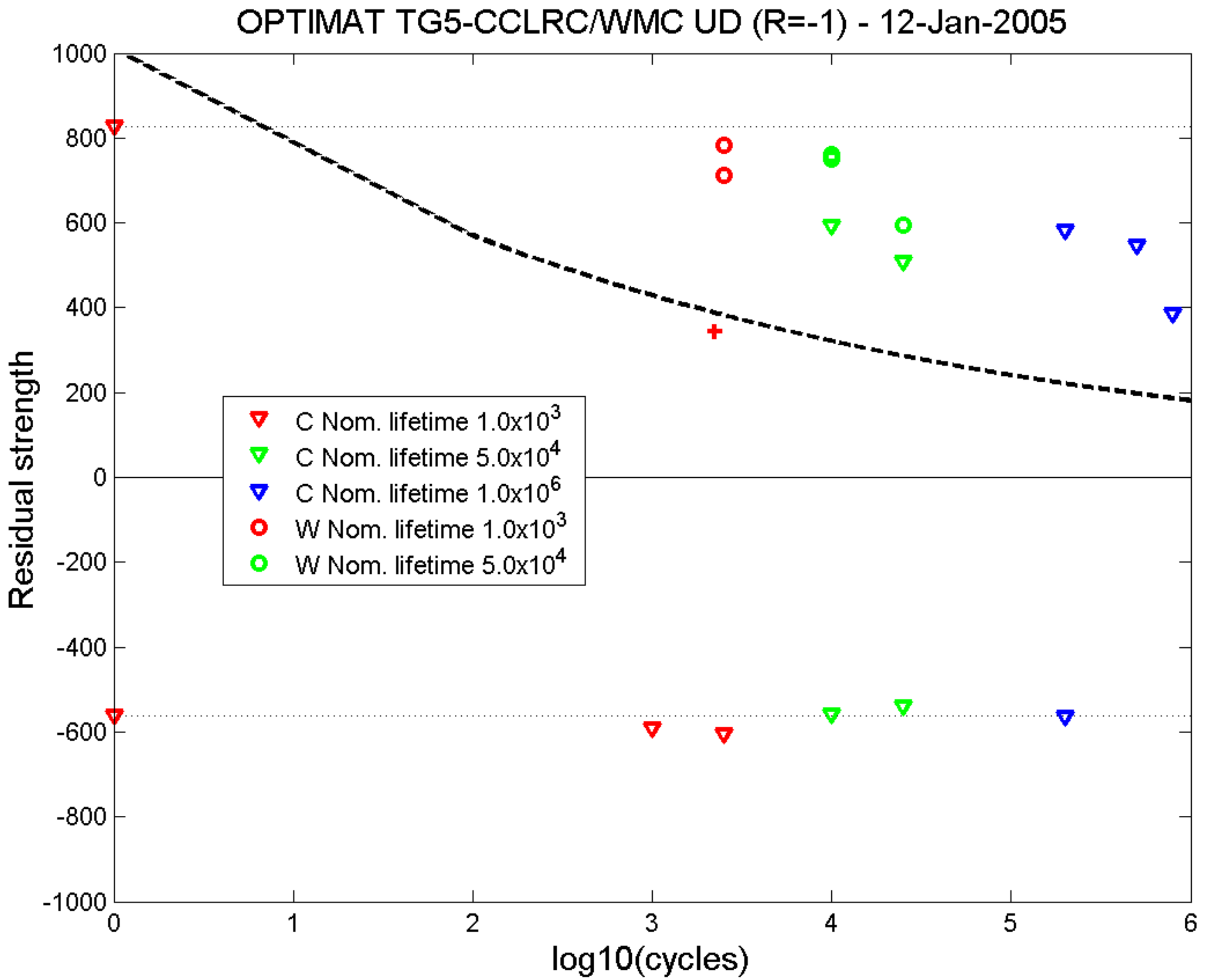

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Residual strength tests – characterisation (3) Task 13.1/13.4

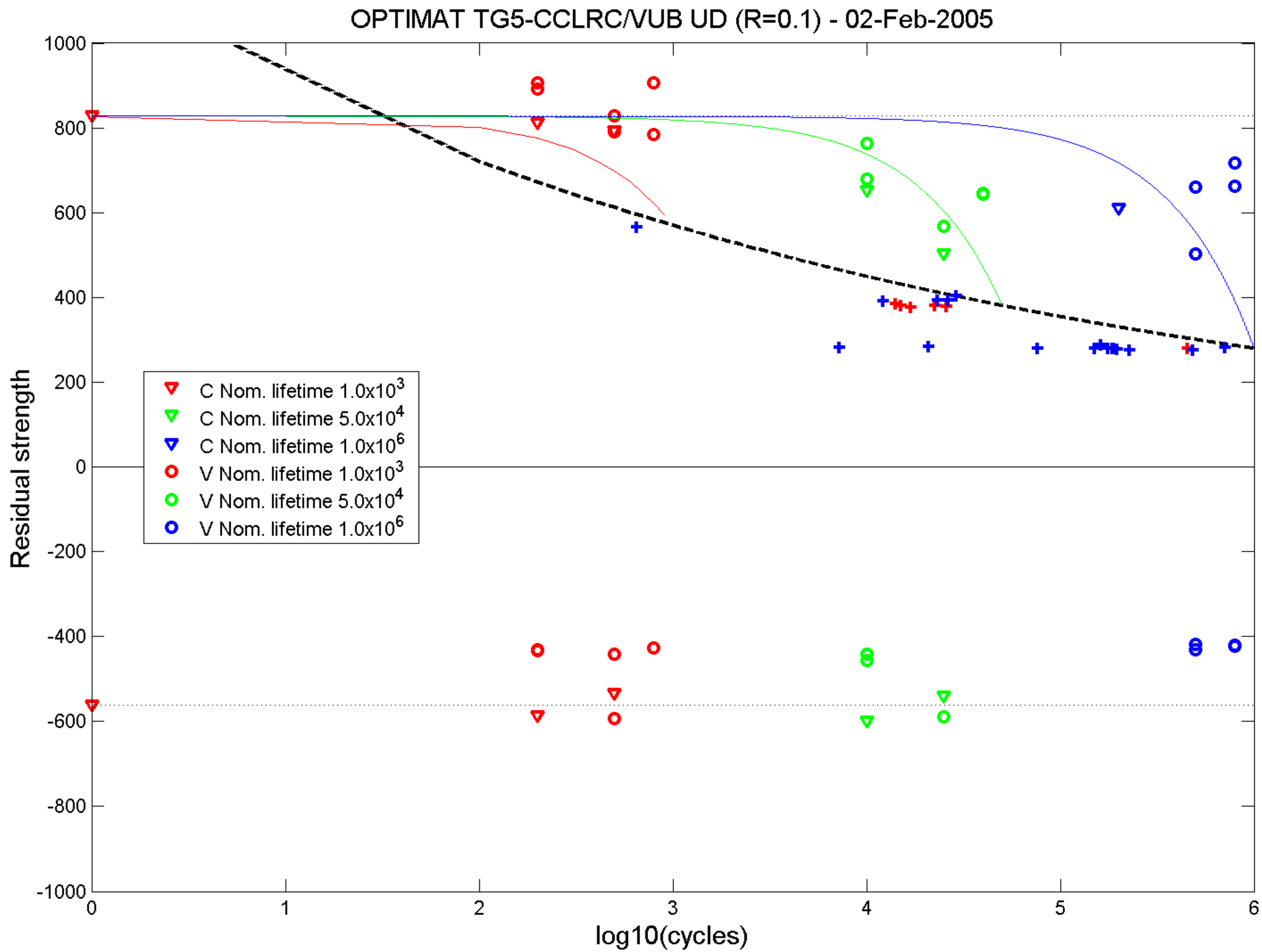
Task 13.1 Review: Philippidis, T.P., Passipoularidis, V.A., *Residual strength characterisation of orthotropic ply material*, OB_TG2_003_UP, April 2002 (D6 – complete)

- Linear degradation model (Broutman & Sahu, 1972)

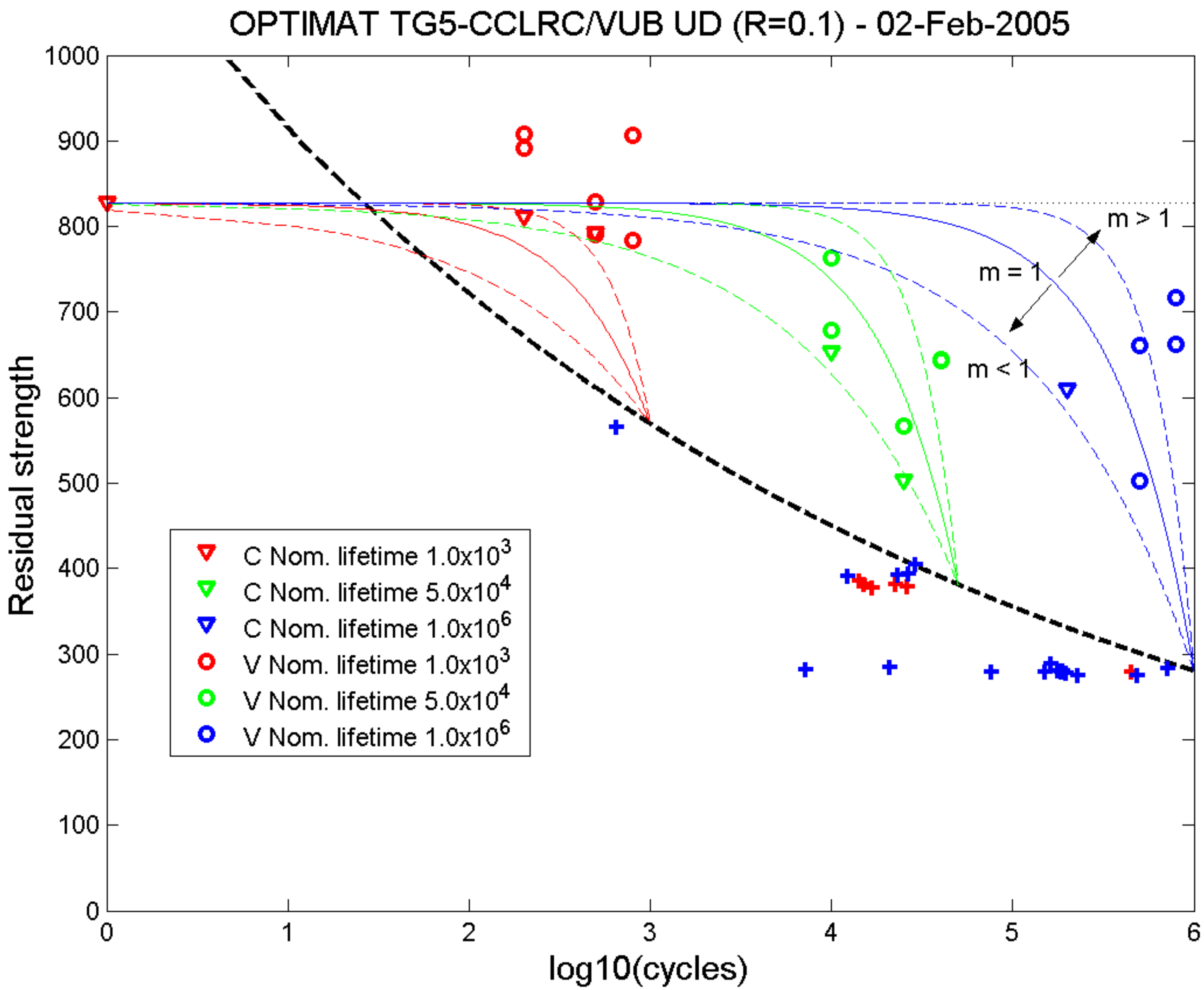
$$X_R = X - \left(X - \sigma_{\max}\right)\left[\frac{n}{N}\right]$$

- Power law degradation model (Schaff & Davidson, 1997)

$$X_R = X - \left(X - \sigma_{\max}\right)\left[\frac{n}{N}\right]^m$$



OPTIMAT TG5-CCLRC/VUB UD (R=0.1) - 02-Feb-2005
Residual strength
log10(cycles)
1000
800
600
400
200
0
-200
-400
-600
-800
-1000
0
1
2
3
4
5
6
C Nom. lifetime 1.0x10^3
C Nom. lifetime 5.0x10^4
C Nom. lifetime 1.0x10^6
V Nom. lifetime 1.0x10^3
V Nom. lifetime 5.0x10^4
V Nom. lifetime 1.0x10^6



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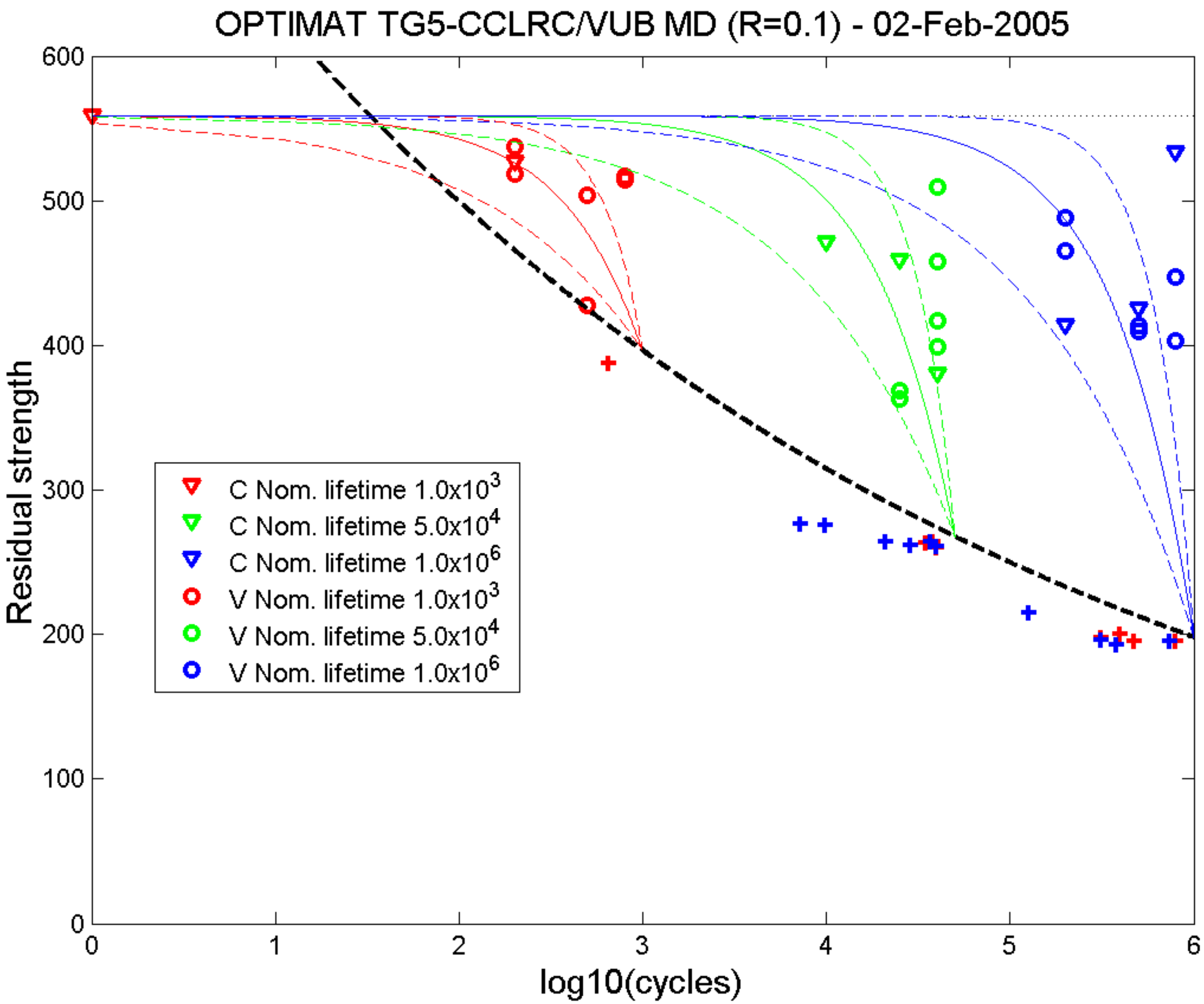

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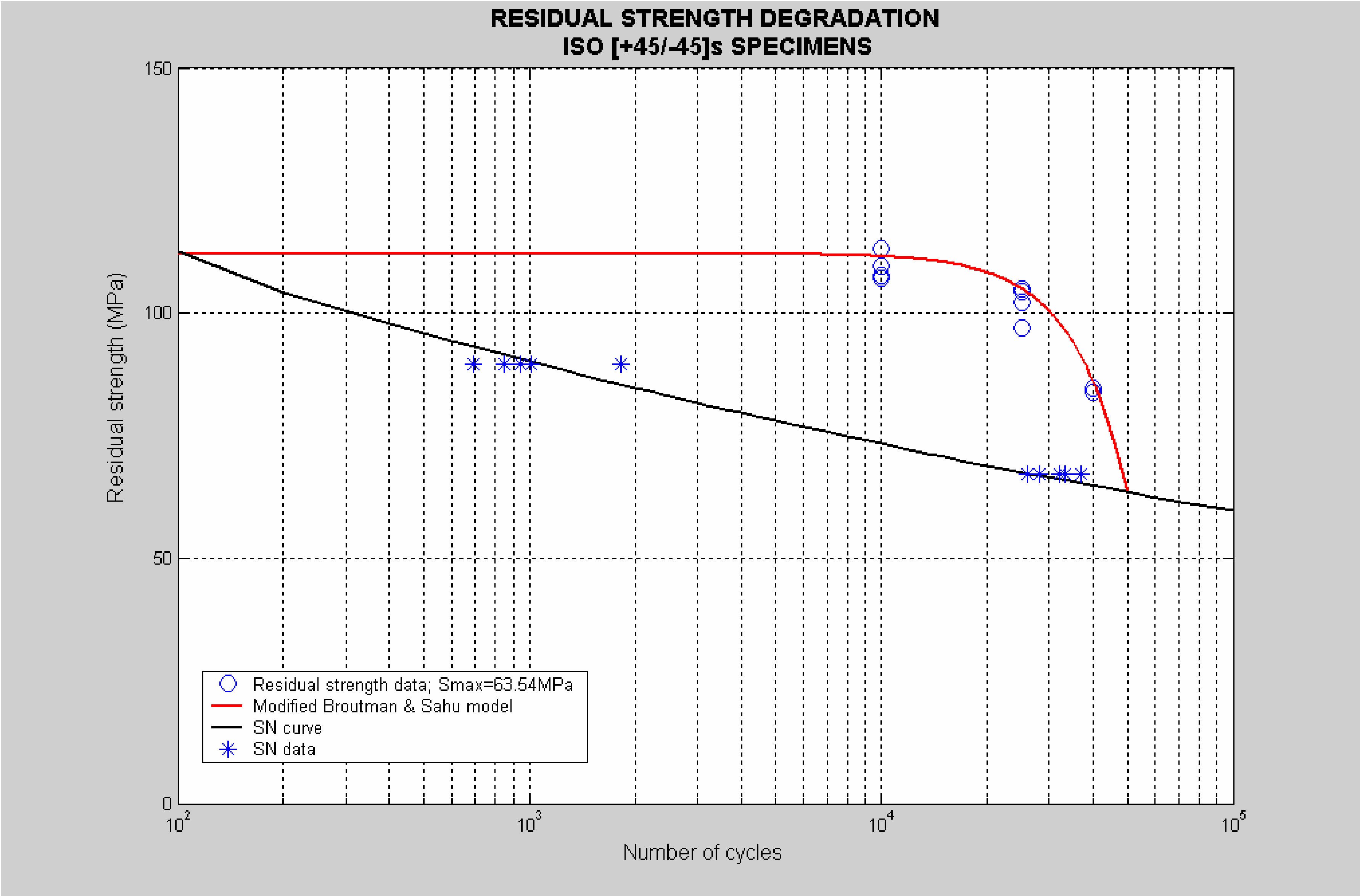


RESIDUAL STRENGTH DEGRADATION
ISO [+45/-45]s SPECIMENS
150
100
50
0
Residual strength (MPa)
10^2
10^3
10^4
10^5
Number of cycles
Residual strength data; Smax=63.54MPa
Modified Broutman & Sahu model
SN curve
SN data

Residual strength tests – characterisation (4)
Task 13.1/13.4

A key issue is the ability of the model(s) to accurately predict the statistical distribution of residual strength at specific {load level, life fraction}.

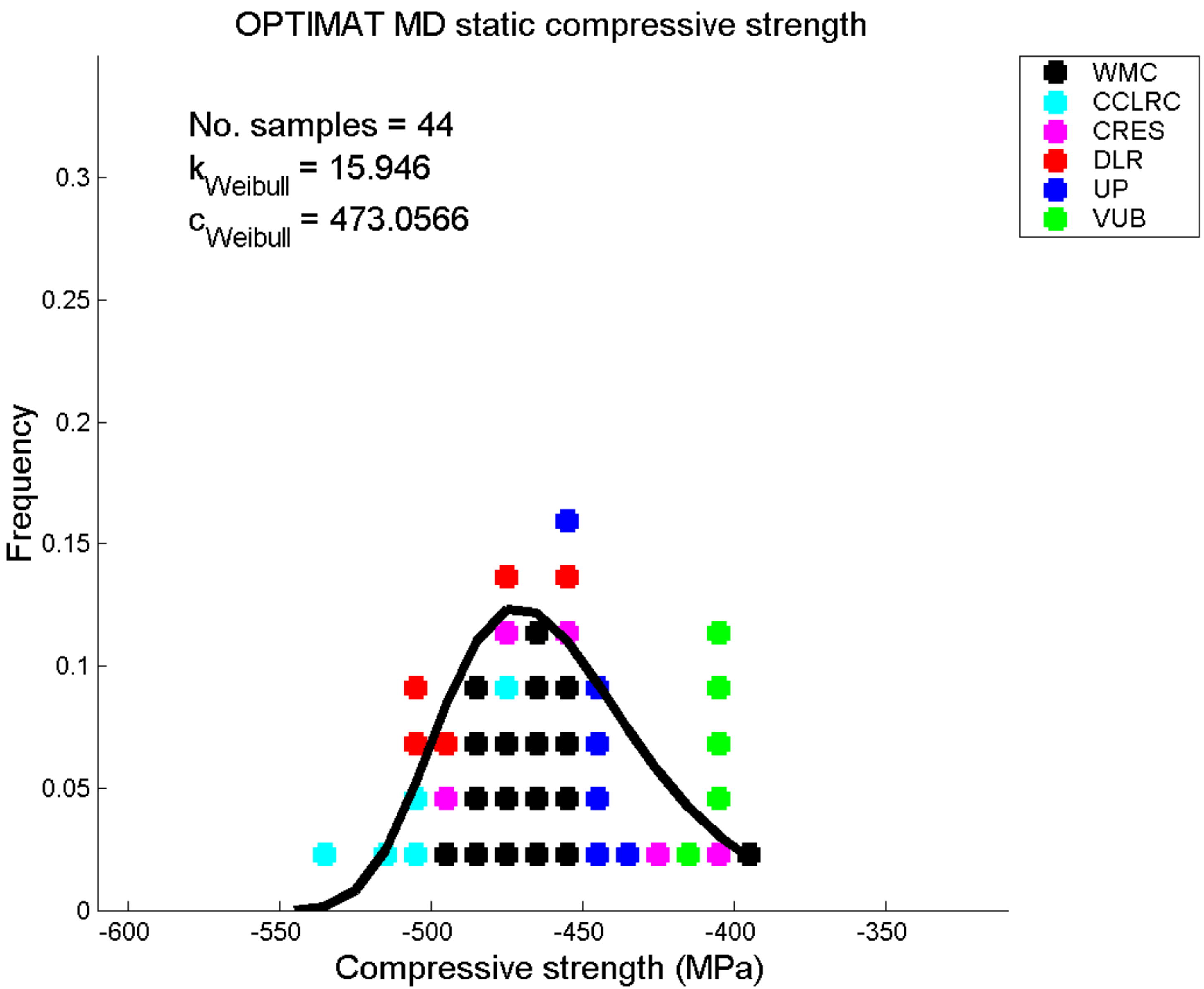
Typically, static strength and fatigue life distribution are fitted by two-parameter Weibull distributions

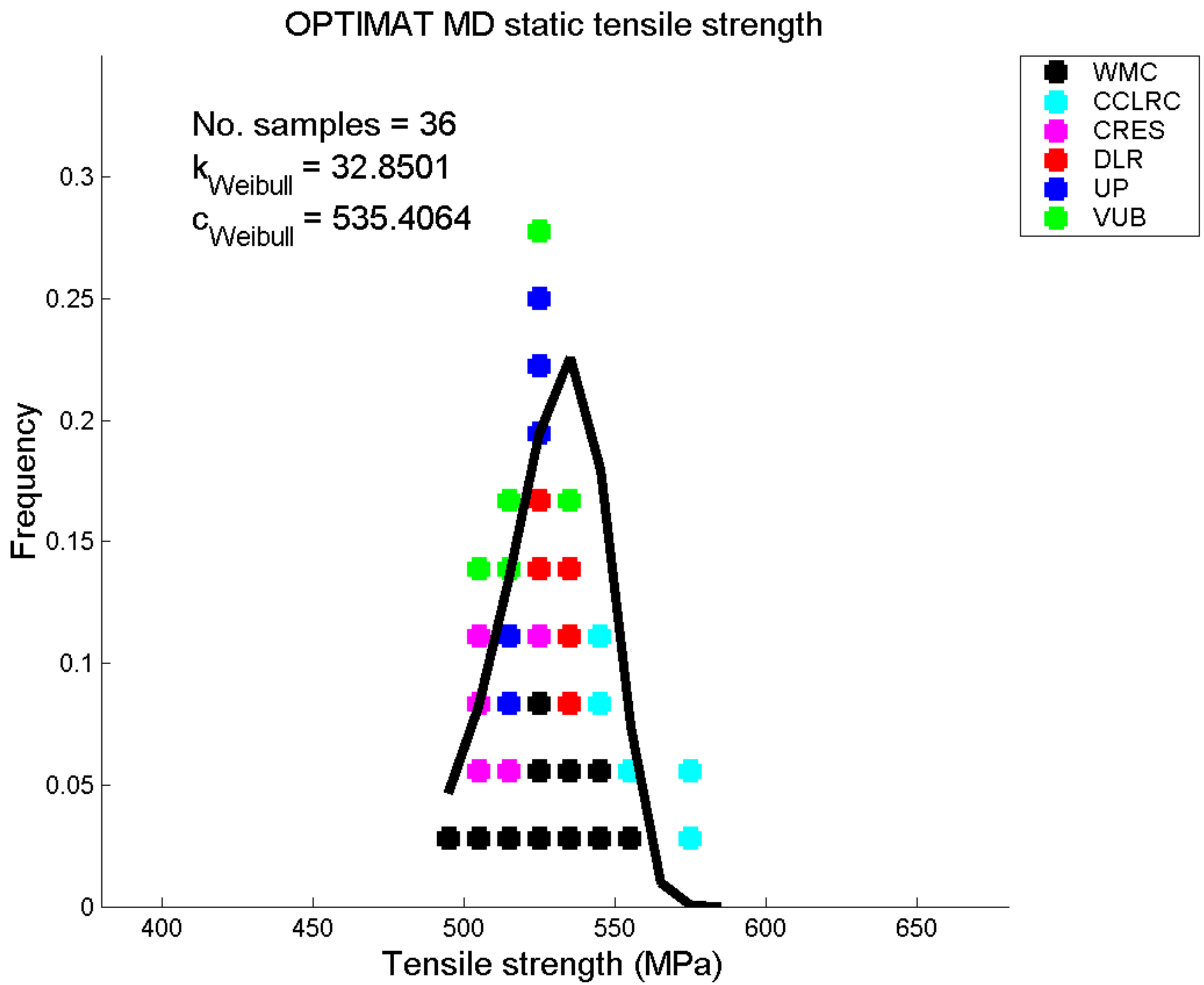
- Residual static strength:

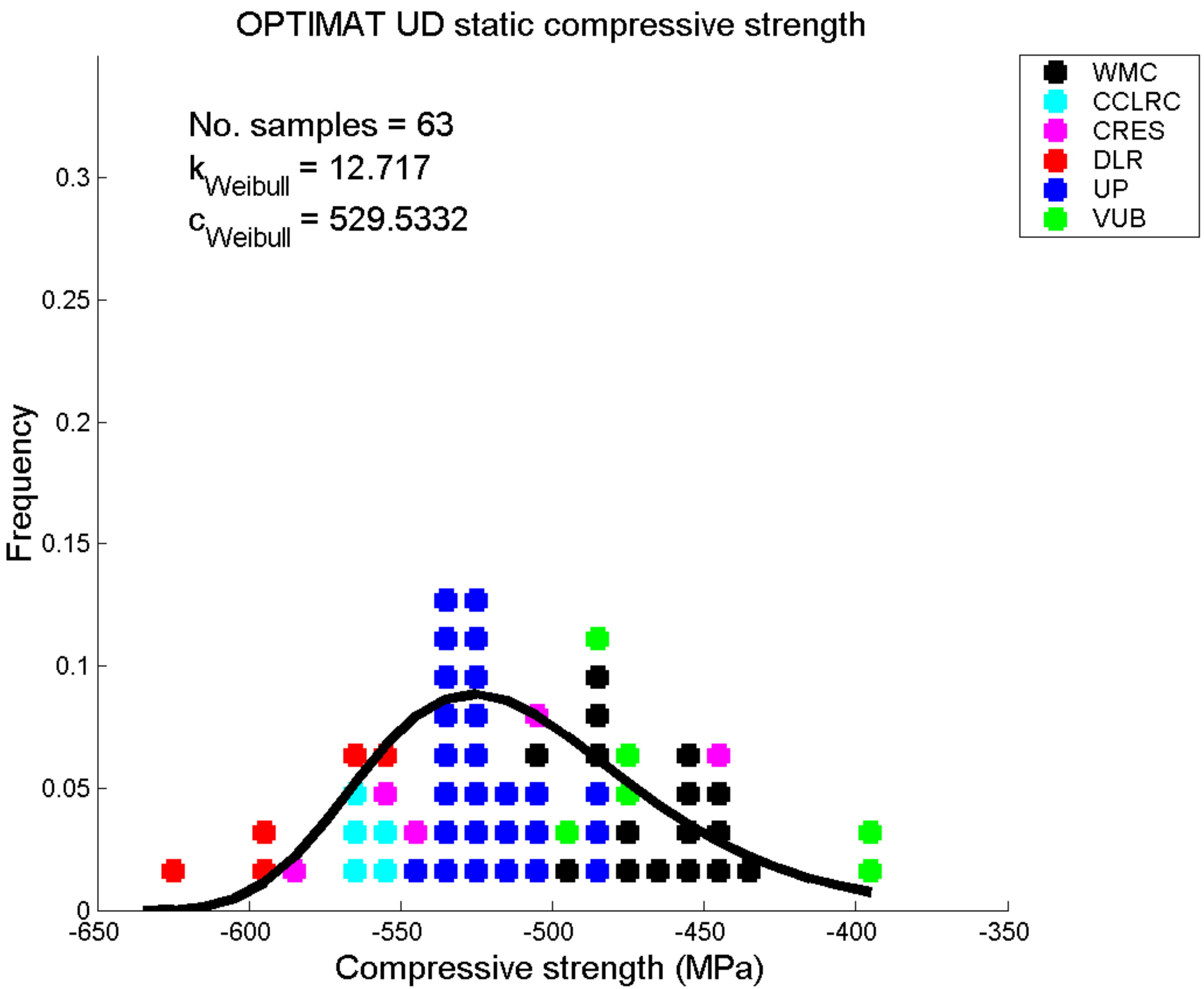
$$P_x(X) = \exp\left[-\left(\frac{X}{\beta}\right)\right]^{\alpha}$$

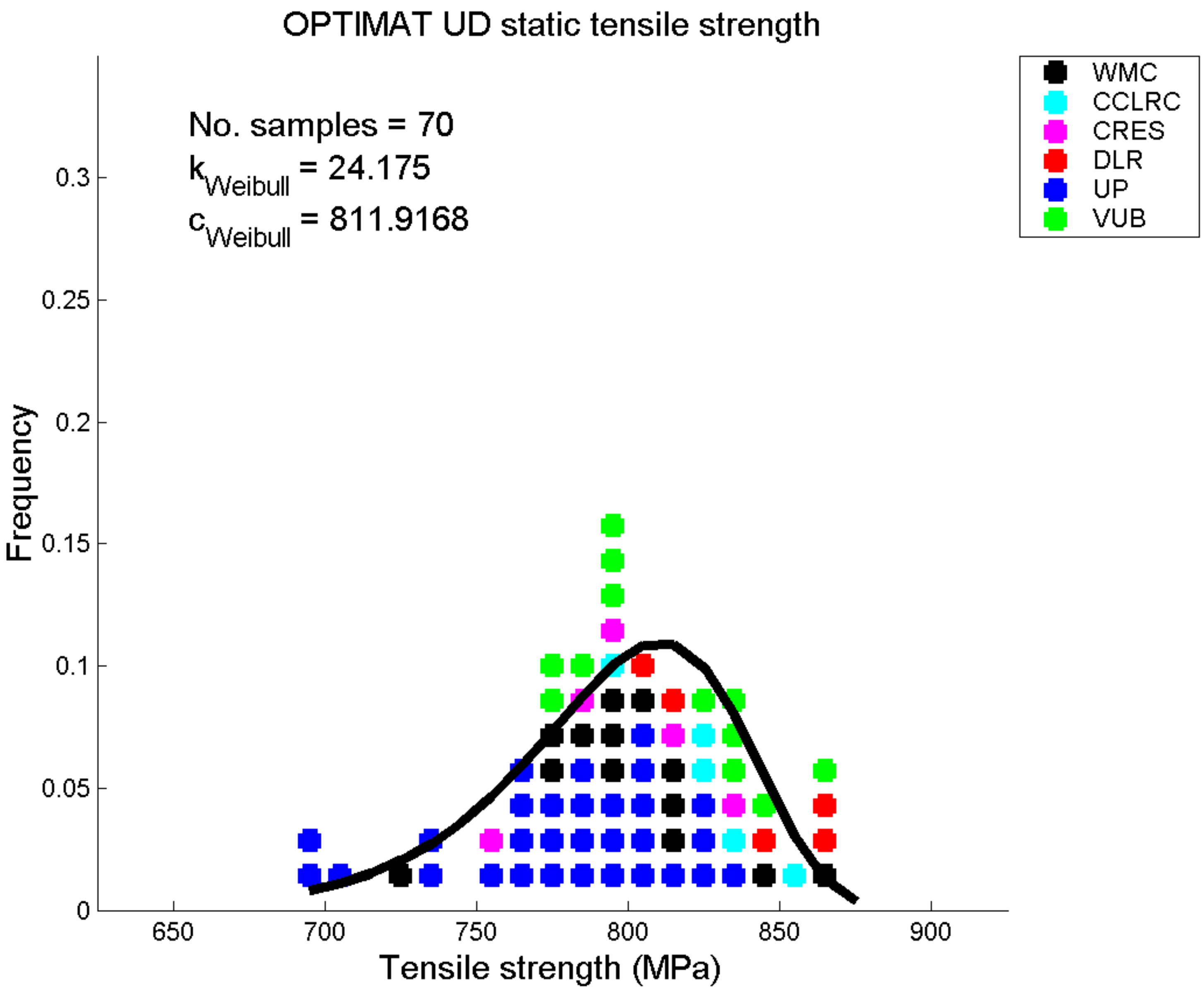
- Lifetime:

$$P_N(n) = \exp\left[-\left(\frac{n}{N}\right)\right]^{\alpha_f}$$


OPTIMAT MD static compressive strength
No. samples = 44
$k_{Weibull}$ = 15.946
$c_{Weibull}$ = 473.0566
WMC
CCLRC
CRES
DLR
UP
VUB
Frequency
0
0.05
0.1
0.15
0.2
0.25
0.3
-600
-550
-500
-450
-400
-350
Compressive strength (MPa)


OPTIMAT MD static tensile strength
No. samples = 36
$k_{Weibull}$ = 32.8501
$c_{Weibull}$ = 535.4064
WMC
CCLRC
CRES
DLR
UP
VUB
Frequency
Tensile strength (MPa)
0
0.05
0.1
0.15
0.2
0.25
0.3
400
450
500
550
600
650


OPTIMAT UD static compressive strength
No. samples = 63
$k_{Weibull}$ = 12.717
$c_{Weibull}$ = 529.5332
WMC
CCLRC
CRES
DLR
UP
VUB
Frequency
0
0.05
0.1
0.15
0.2
0.25
0.3
-650
-600
-550
-500
-450
-400
-350
Compressive strength (MPa)



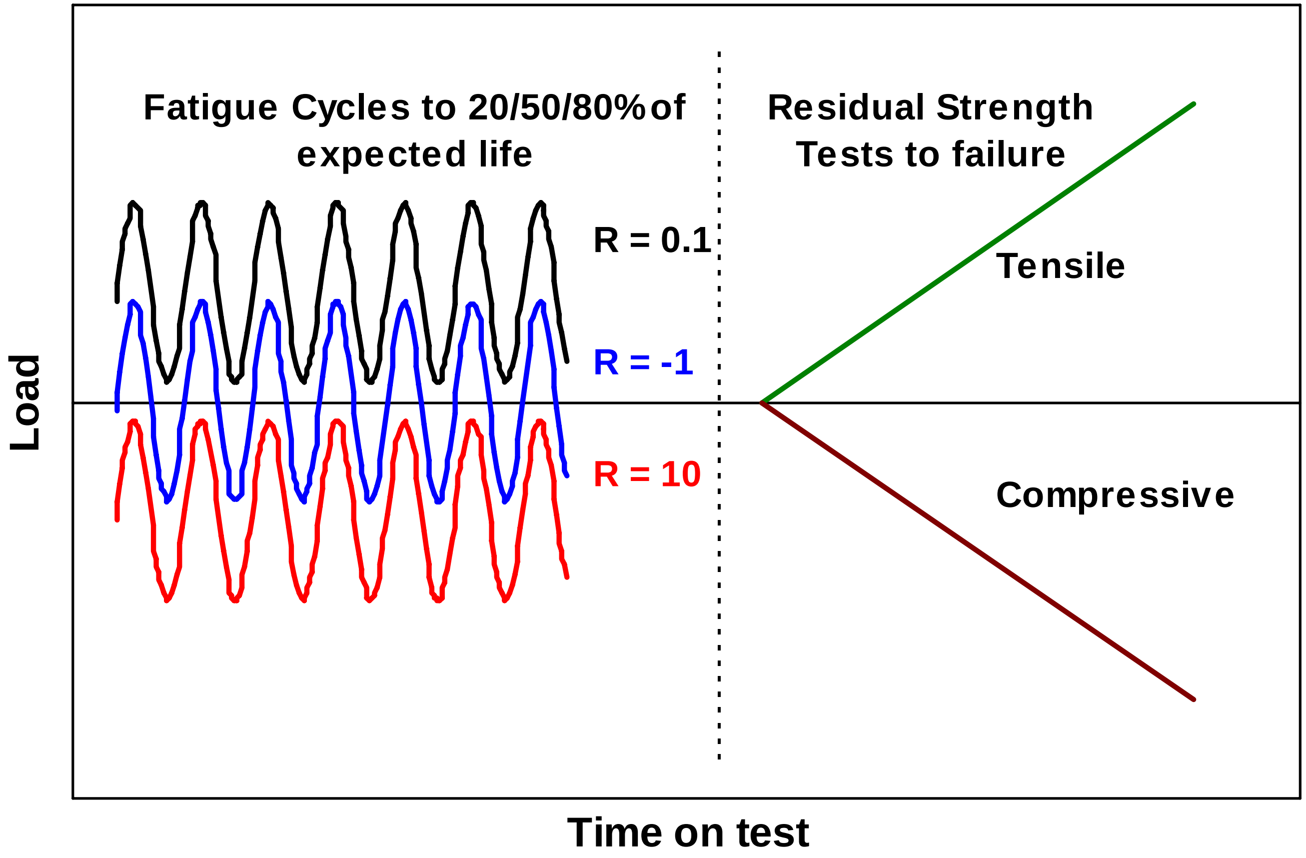
OPTIMAT UD static tensile strength
No. samples = 70
$k_{Weibull}$ = 24.175
$c_{Weibull}$ = 811.9168
WMC
CCLRC
CRES
DLR
UP
VUB
Frequency
0
0.05
0.1
0.15
0.2
0.25
0.3
650
700
750
800
850
900
Tensile strength (MPa)

Residual strength tests (Task 13.3) – NDT techniques (preliminary results)

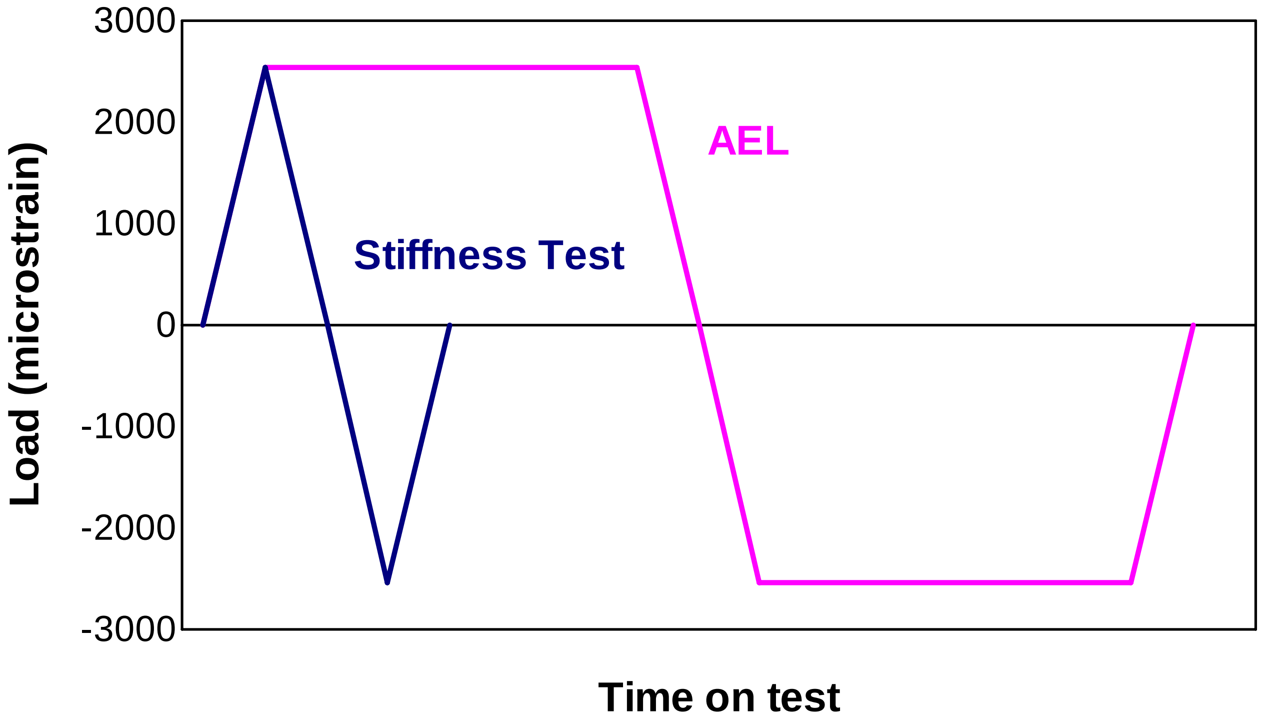
AE testing:

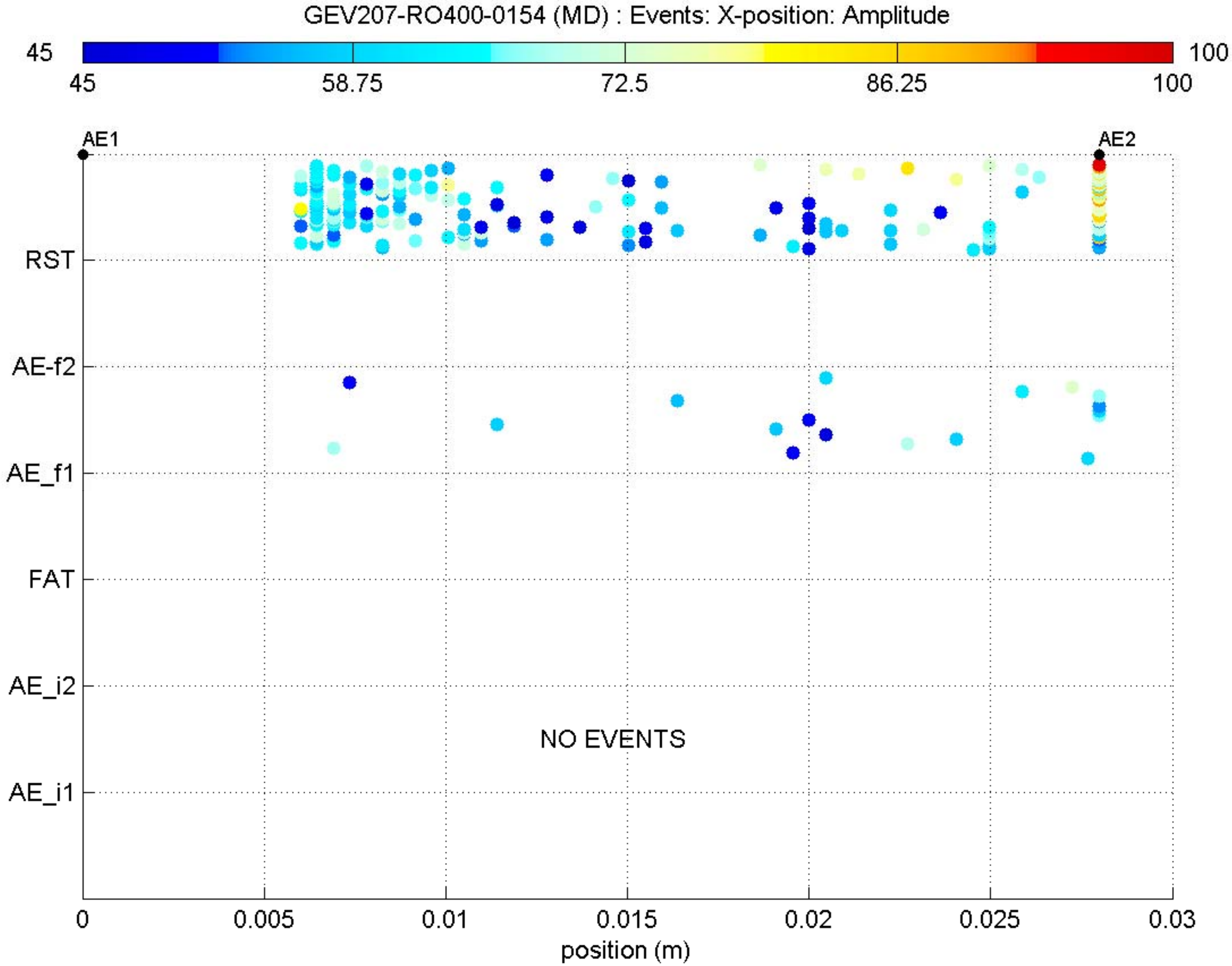
- MD (R = 0.1) : tests 154, 156 (CCLRC)
- MD (R = -1) : test 394 (CCLRC)
- UD (R = 0.1) : test 637 (CCLRC)
- ISO 14129 geometry [+45/-45]s (UP)

Residual Strength Test procedure



Residual Strength Test procedure





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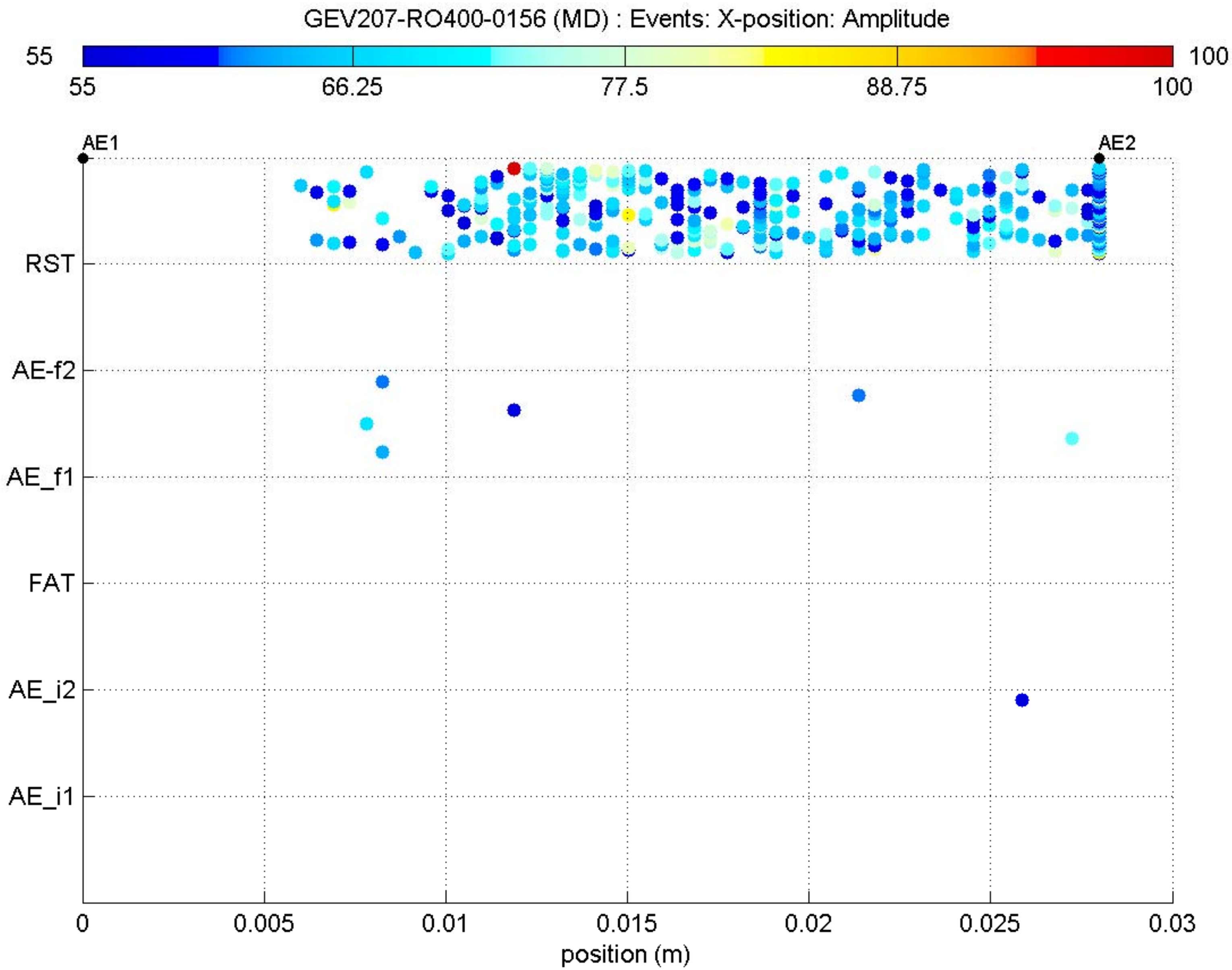

OPTIMAT BLADES

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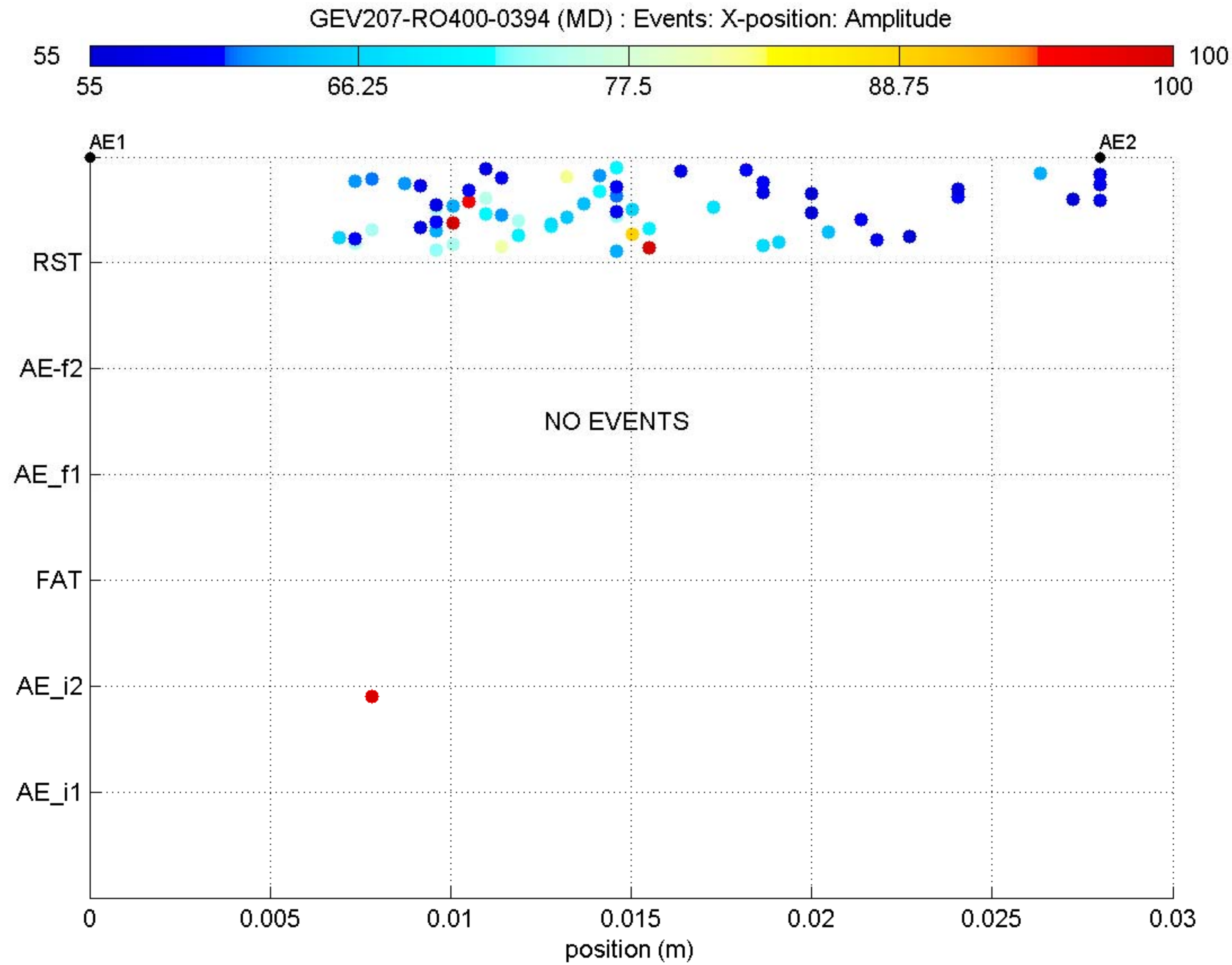

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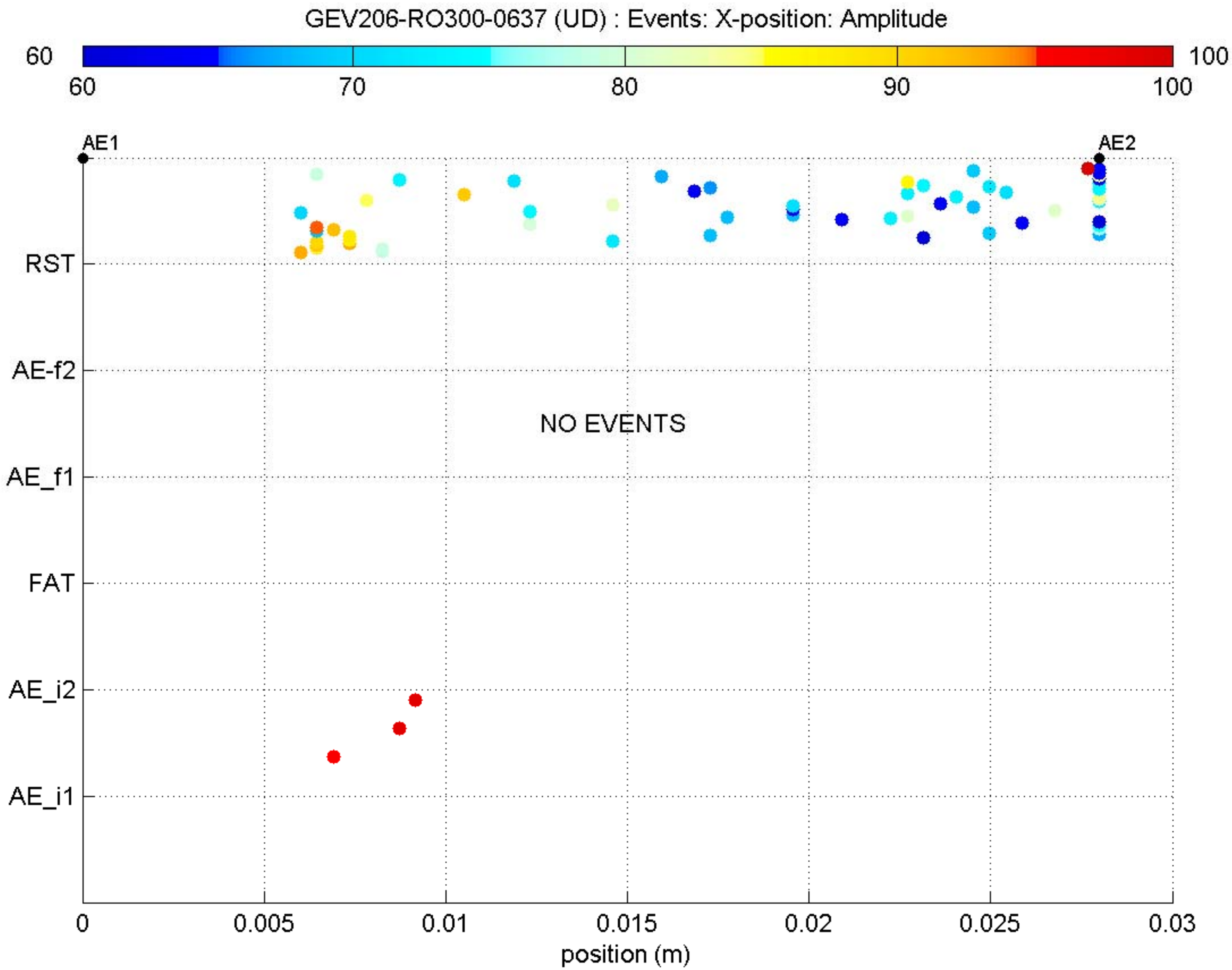

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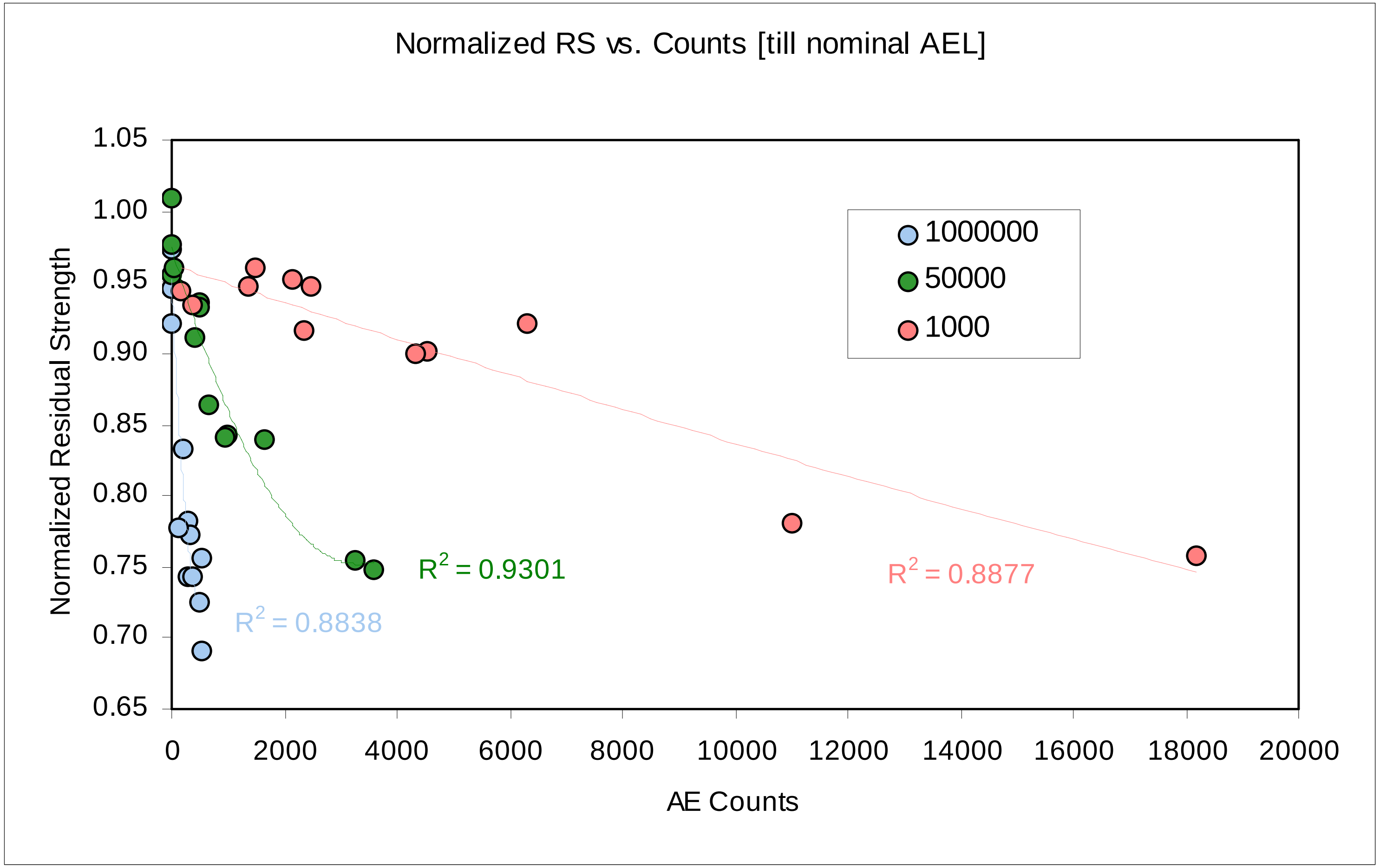
AE Counts during RST (UPatras)



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Residual strength tests (Task 13.3) – NDT techniques (preliminary results)

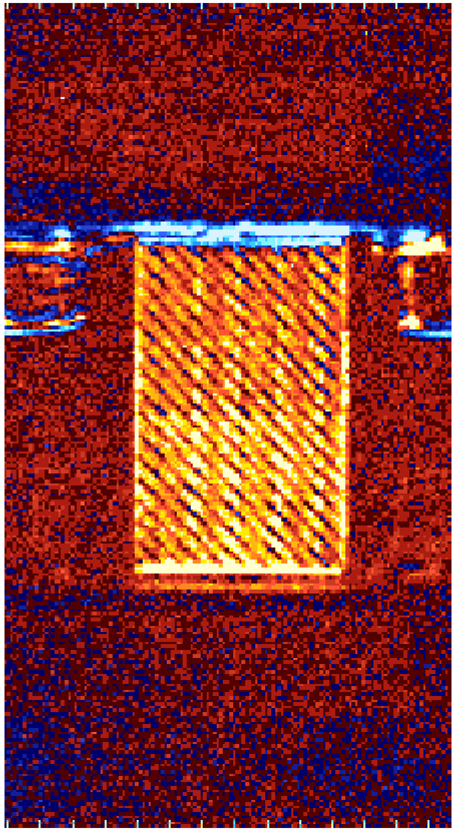
Thermoelastic stress analysis:

- MD (R = 0.1) : tests 154, 164, 165, 166 (CCLRC)
- UD (R = 0.1) : test 384 (CCLRC)

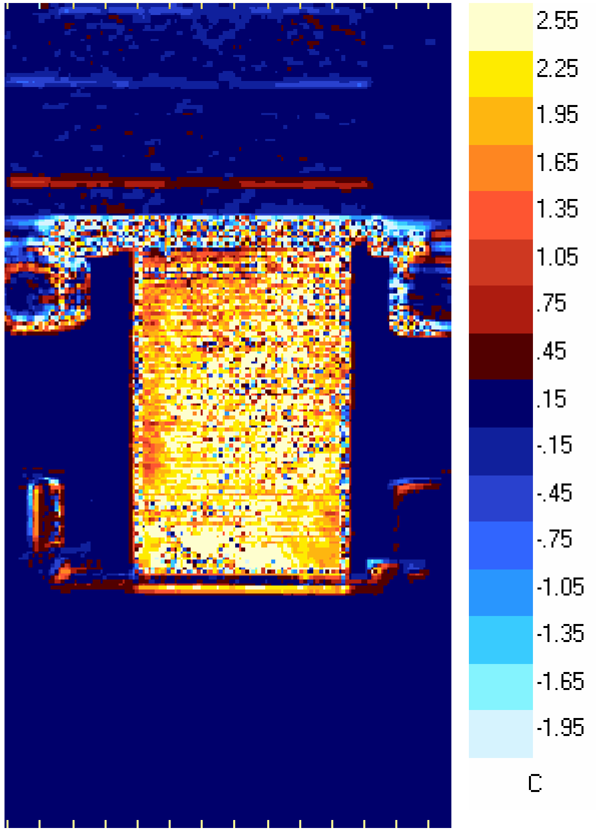
Initial findings:

- Cross-ply structure of MD surface layer visible on first fatigue loading
- Early failure of surface plies reduces signal (MD)
- Surface temperature distribution shows higher T than expected

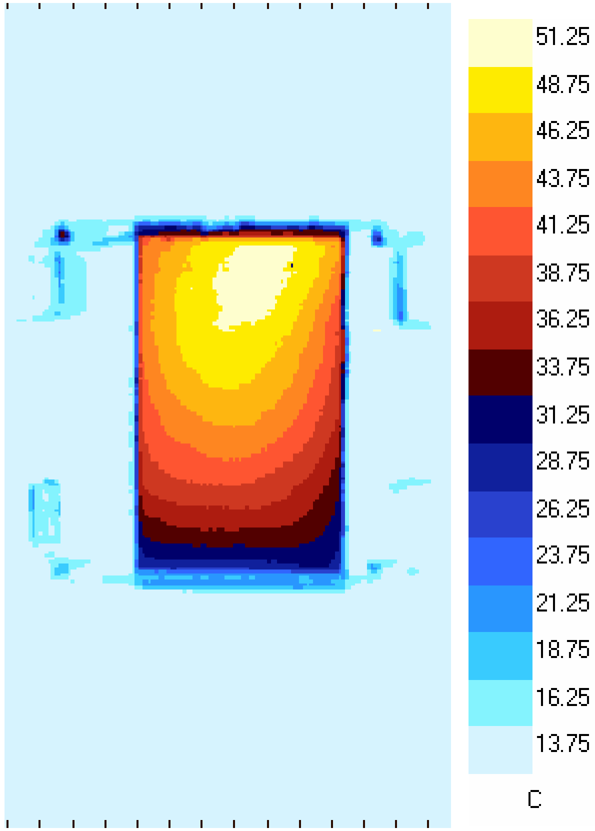
Residual strength tests – NDT techniques (preliminary results)



First fatigue (OP)



Middle fatigue (IP)



Temperature (deg. C)

Deliverables / Milestones

No.	Deliverable / Milestone	Project month	Revised	% DONE
6	Review of existing residual strength predictive models	Report 05 (CO)	**-**	**100**
M8	DPA on condition monitoring and residual life and strength	05	**-**	**100**
24	Experimental database from residual strength tests	Report/CD 26 (PU)	**48**	**50**
25	Validated engineering model for residual strength evaluation	Report 26 (PU)	**48**	**40**
26	Validated engineering model for residual life evaluation and strategy for condition assessment	Report 26 (PU)	**48**	**30**
M20	Validated engineering model for residual life and strength	27	**48**	**50**
M21	DPA for residual strength programme (phase 2)	27	**48**	**90**
31	Experimental database from residual strength tests on alternative materials **(note enlarged extent of D24)**	Report/CD 42 (PU)	**50**	**DELETE**
39	Validated engineering model for residual strength and life prediction using condition assessment (alternative materials) **(modify to MD, UD, +/-45 shear)**	Report 43 (PU)	**50**	**15**
M30	Fully evaluated residual strength model	43	**52**	**10**

Conclusions - TG5
Residual strength and condition assessment

- Phase I test matrix was comprehensive, over-ambitious, and contained 2 specimen lay-ups (where only 1 was envisaged in the DoW)
- Phase 1 testing is more than 50% complete but will now extend to end 2005 (D24)
- Potential engineering models have been identified and are being evaluated (D25)
- NDT evaluation of residual strength has achieved only limited success – some re-evaluation necessary (D26)
- The most important deliverable is a validated engineering model for residual strength degradation (D25/D39)
- Phase II tests on alternative materials (14.1-14.3) limited to WMC in WP5 / other partners to complete Phase I tests (additional model validation in 14.4 based on UD/MD comparison)