



Work carried out by The Institute of Fundamental Technological Research (IFTR)





Main Actions



- Summarize the probabilistic design methodology
- Formulate new design criteria
- Apply the probabilistic design methodology to a selected hydraulic cylinder

- **Main achievements**
 - Probabilistic design methodology along with new design criteria
 - Application of probabilistic design methodology to a selected hydraulic cylinder
 - Development of demonstration software for probabilistic Fatigue and Buckling analysis
 - Preparation of a Design Practice for probabilistic fatigue design of hydraulic cylinders
- **Work in the task carried out according to workprogramme**

IFTR Objectives of WP2.1 & WP2.4:

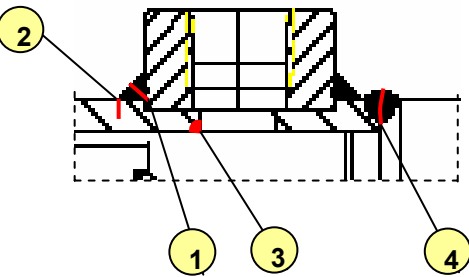
- Develop deterministic fatigue life assessment methodology
- Develop probabilistic design methodology
 - Determine variability of design parameters
 - Develop methods for probabilistic analyses
 - Formulate new design criteria.



Partners involved:

- PEDRO ROQUET S.A.,
- CIMNE
- UPC LABSON
- FADROMA

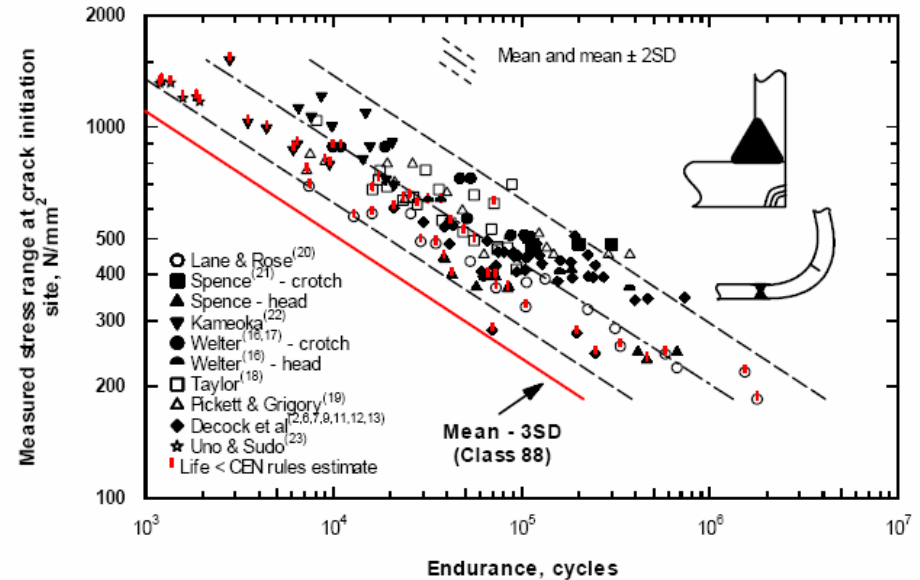
Critical locations (example)



Practical observations

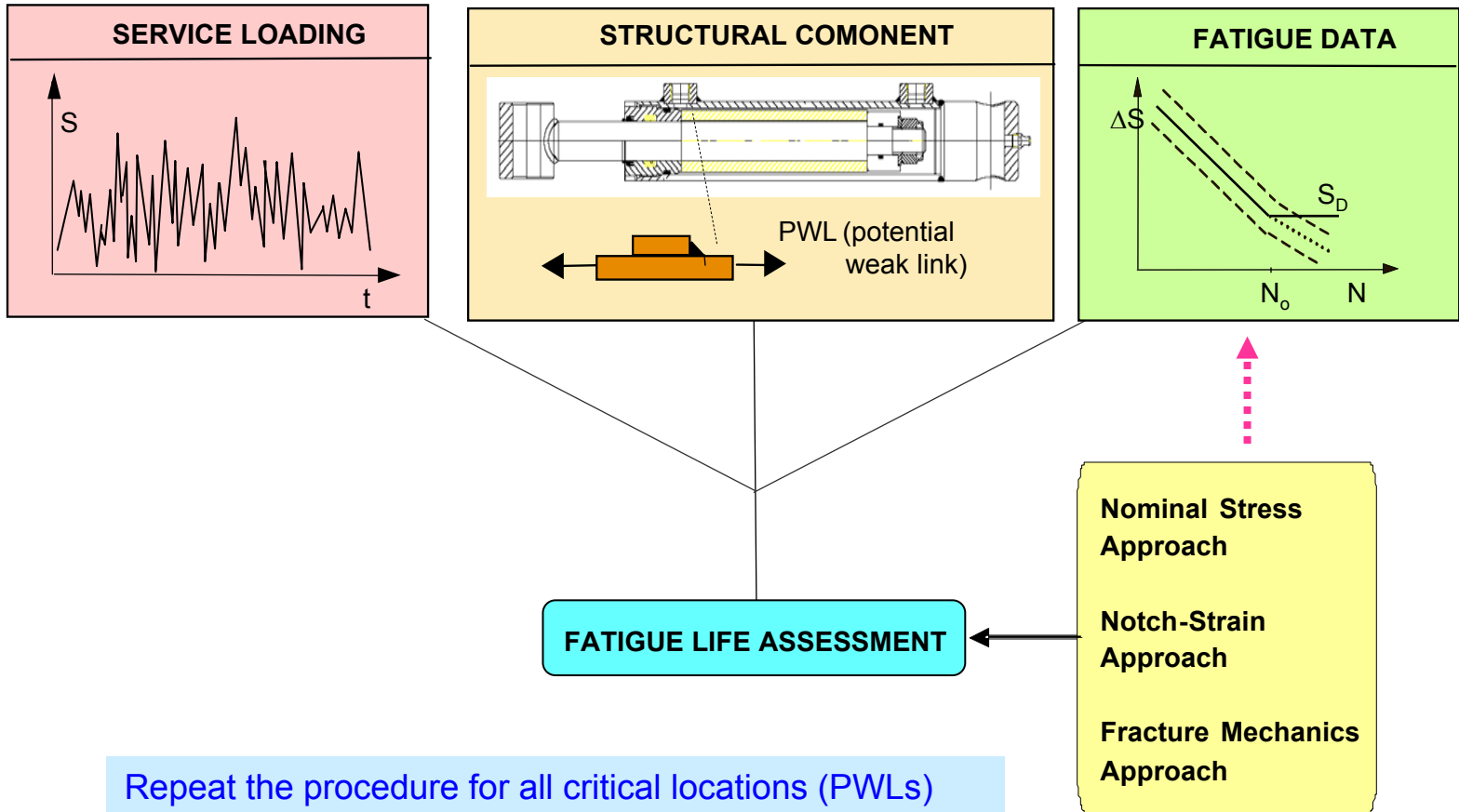


Fatigue data



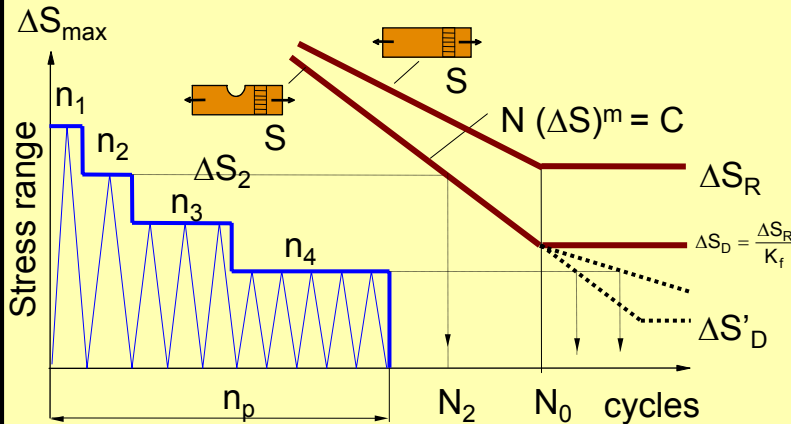
- Safe life design concept (finite life)
- Deterministic design using Local Approach
- Fatigue data account for the worst manufacturing quality
- -3 σ curves used for greater safety
- Variability of other data covered by factor of safety
- No consideration on reliability in service

Local Fatigue Life Assessment



Repeat the procedure for all critical locations (PWLs)
Fatigue life of the cylinder = minimum calculated life

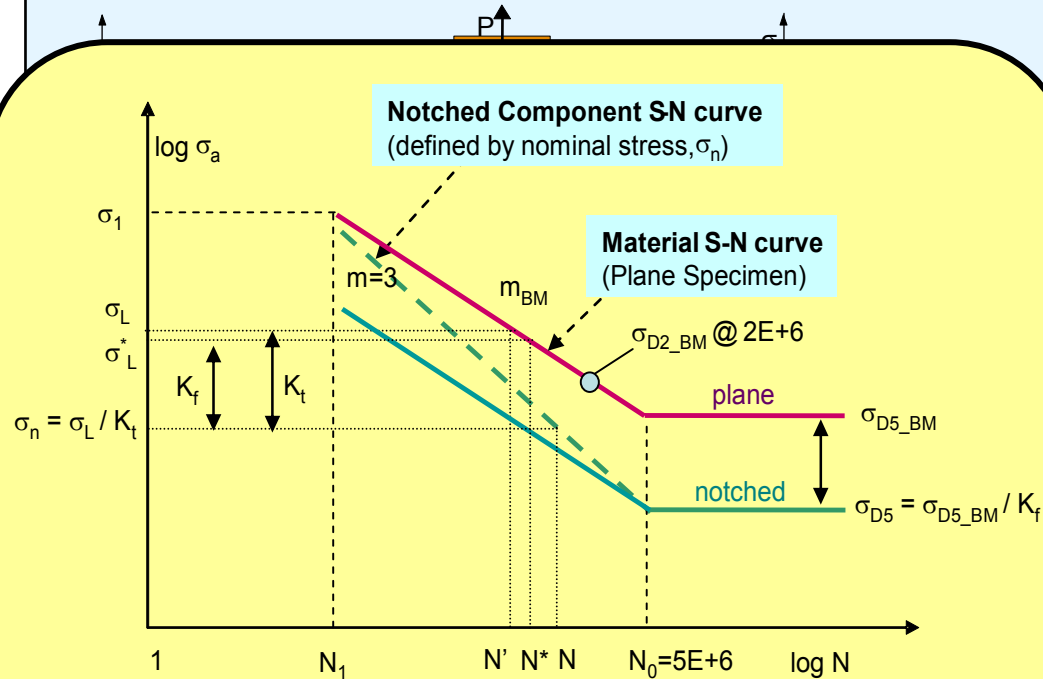
Nominal Stress Approach (NSA)



Life: $N = \text{BLK } n_p [\text{cyc}]$ $T = \text{BLK } t_r [\text{h}]$

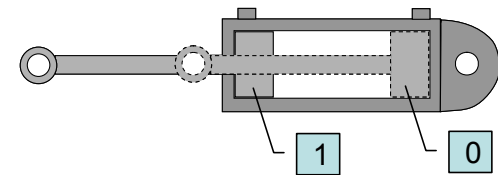
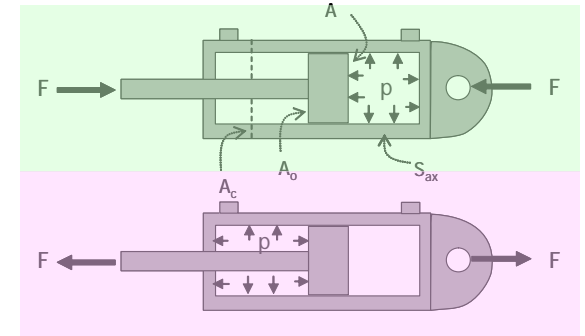
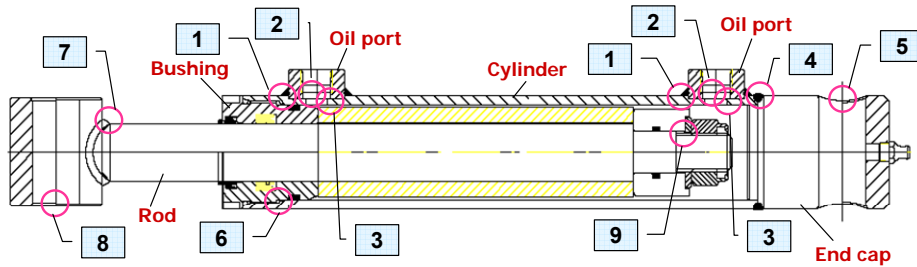
$$\text{BLK} = \frac{d}{D} = \left(\frac{\Delta S_D}{\Delta S_{\max}} \right)^m \frac{d N_D}{\sum_k (s_i)^m n_i}$$

Notch-strain approach - modified method Cycle Fatigue (LCF)

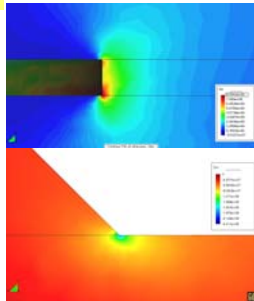
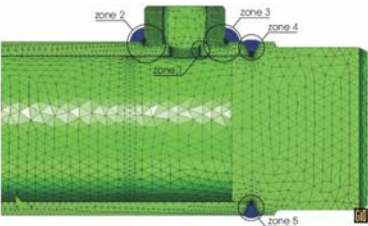


- Allows life assessment based on FEA stress
 - Requires the notch sensitivity
- $\sigma(\mathbf{x})$ – local stress (FE analysis, without crack)

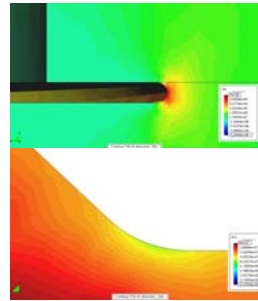
Identification of critical locations (Roquet results)



PWL modeling in FE



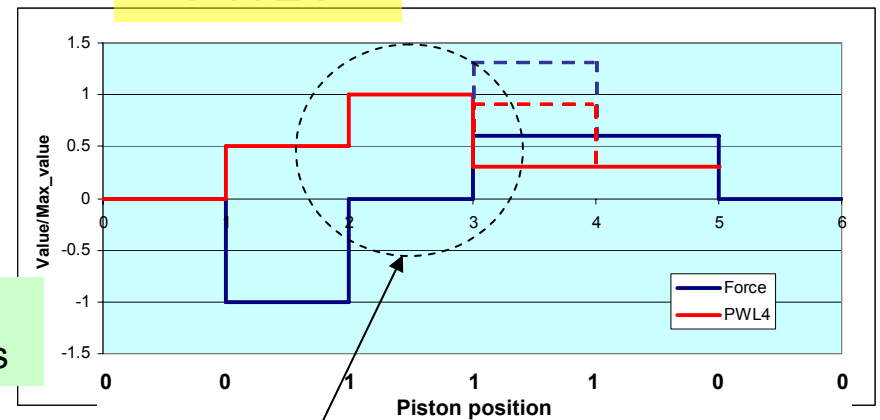
Wrong



Correct

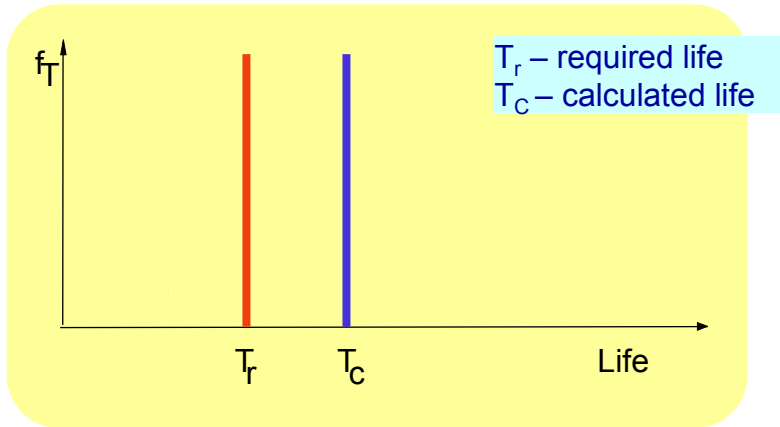
Loading – stress flow diagrams indicate critical cylinder loading for specified PWLs

PWL4



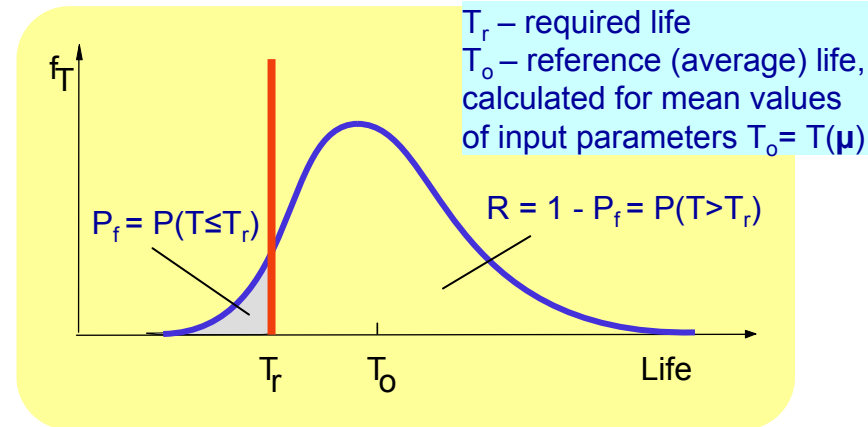
Avoiding this situation may significantly increase cylinder's life!

Deterministic fatigue design



Design condition: $T_c > SF \cdot T_r$
(SF = experience based Factor of Safety)

Probabilistic fatigue design



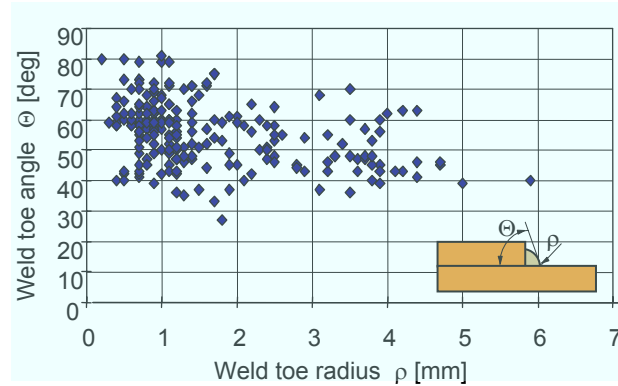
Design condition: ???

What is needed for probabilistic design?

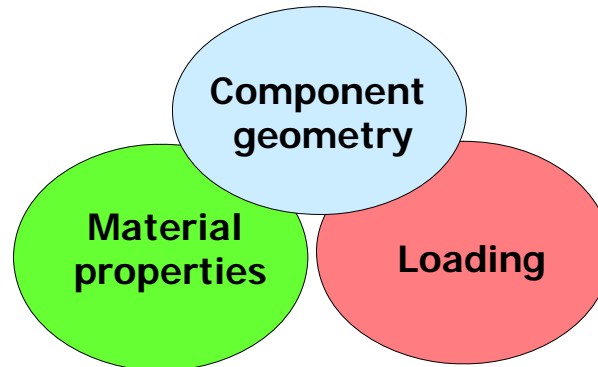
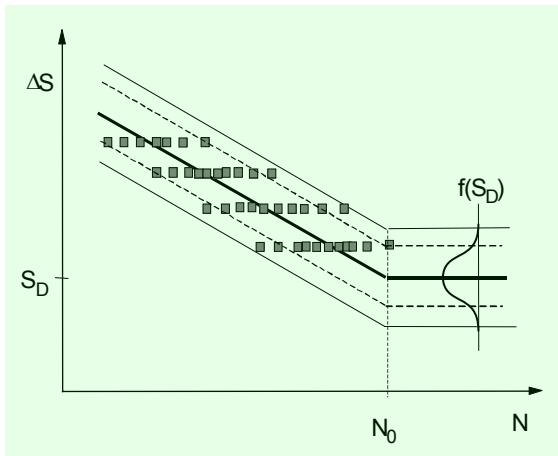
- Variability of design parameters
- Probabilistic analysis method
- Design criteria

Variability of Design Parameters

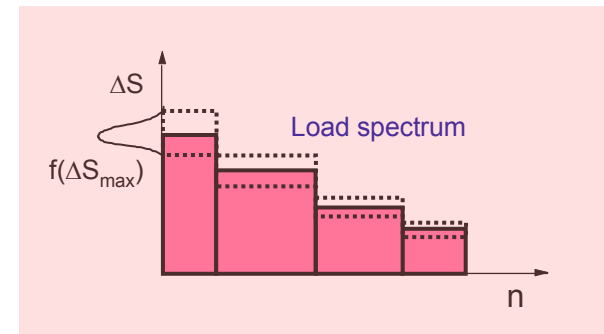
Component geometry



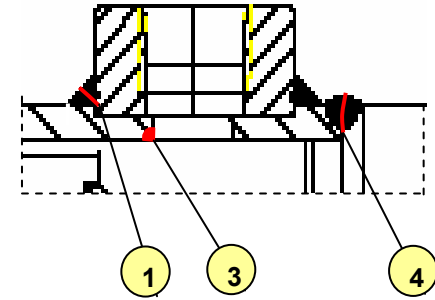
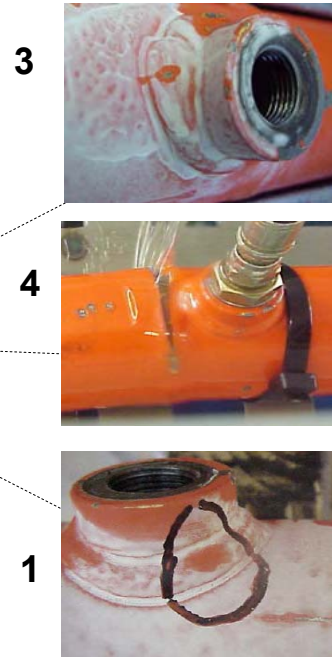
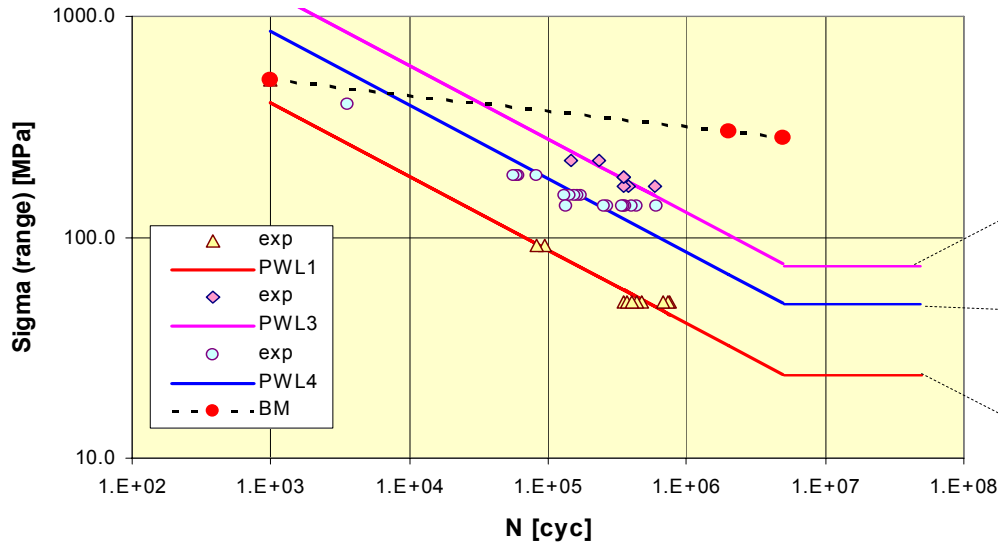
Fatigue data (S-N)



Service loading



Probabilistic design requires definition of scatter of design parameters related to 3 groups



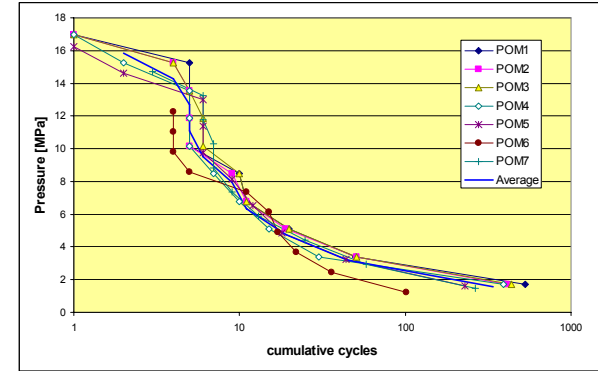
- S-N curves estimated based on full-scale fatigue tests of hydraulic cylinders by Pedro Roquet S.A.
- Estimated S-N curve parameters and their scatter: $COV_x = V_x = \sigma_x / \mu_x$
- Literature studies

	PWL1	PWL3	PWL4
m	3.0	3.0	3.0
m2	5.0	5.0	5.0
S_{D2} mean	32.3	102.2	67.9
$S_{D2} - 3\sigma_R$	24.3	83.2	41.9
S_{D5} mean	23.8	75.3	50.0
$S_{D5} - 3\sigma_R$	17.9	61.3	30.9
COV_2	0.109	0.076	0.207
COV_5	0.082	0.062	0.128

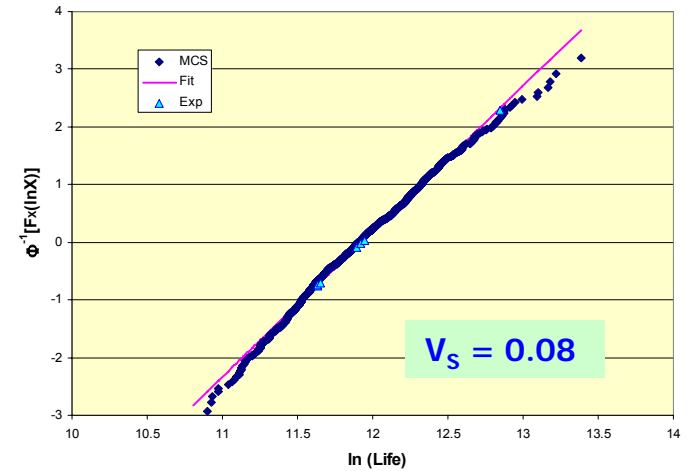
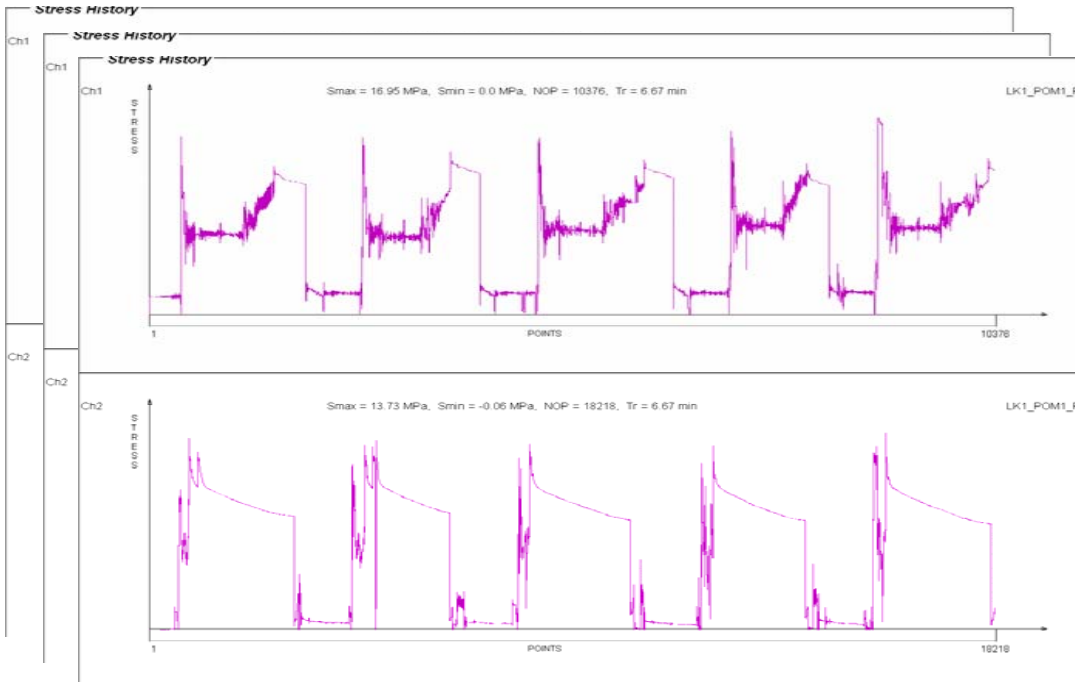
Scatter of Service Loading



An **inverse method** was developed for estimation of variability in the service loading (field measurements by FADROMA Development)

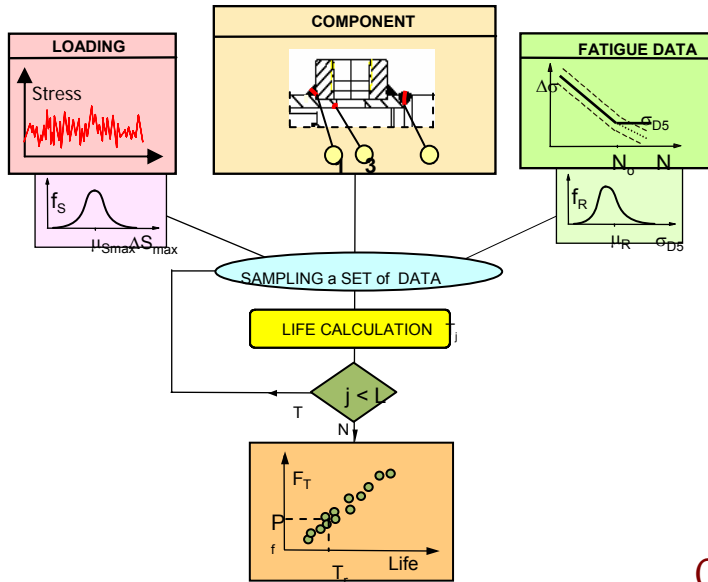


Cylinder P1

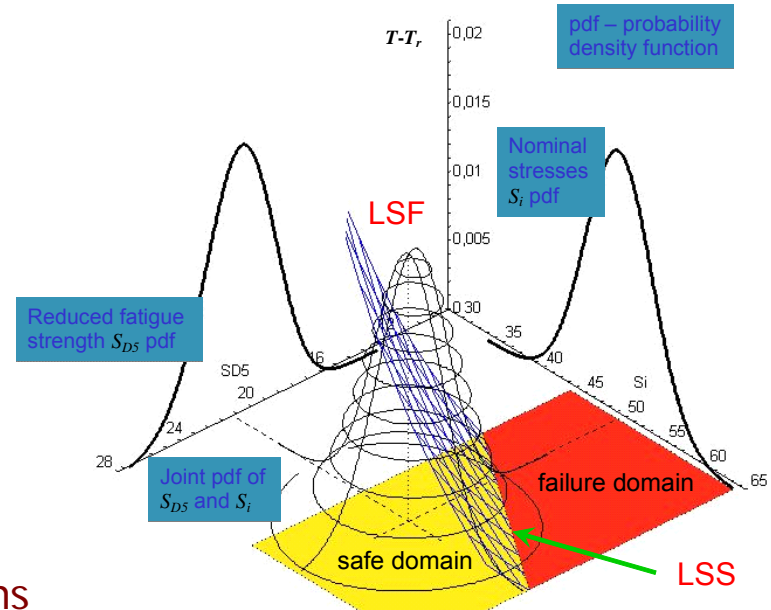


Probabilistic Analysis

Direct Monte Carlo Simulation

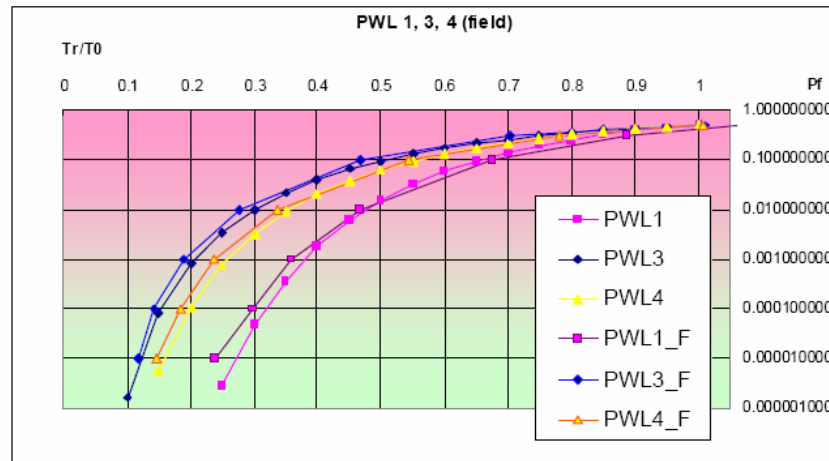


Response Surface Method



Comparisons

Simulations:
L = 100000



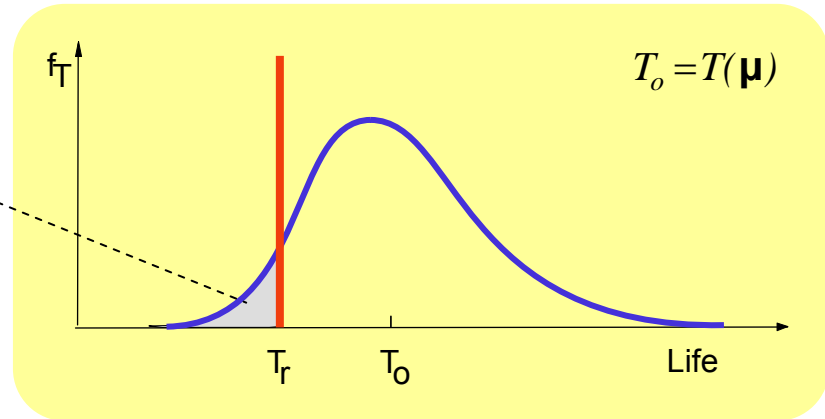
Simulations:
L = 25

Probabilistic Fatigue Design Criteria



Design criteria must take into account the scatter of predicted fatigue life (due to variability in design parameters: geometry, fatigue and loading data)

Grey area represents probability of failure:
 $P_f = P(T \leq T_r)$
 $R = 1 - P_f$



Probabilistic analysis	
Requirement	Response
Life, T_r	Reliability, R
Reliability, R	Safe life, T_r

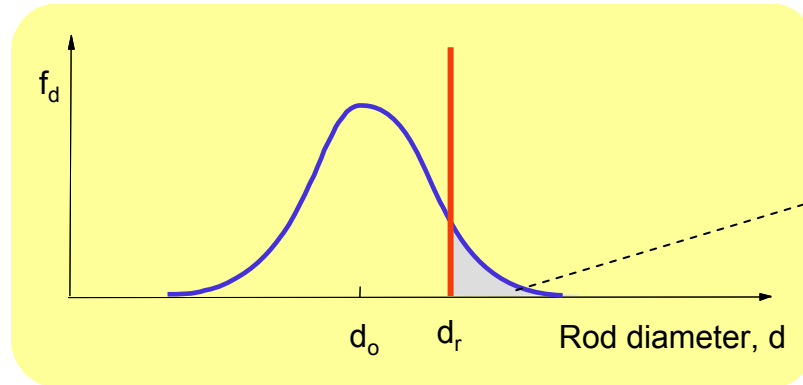
Probability of failure: $P_f = P(T \leq T_r) = \int_0^{T_r} f_T(t) dt$

Probabilistic design criteria	
Reliability requirement	$P_f = P(T \leq T_r) \leq P_{fr}$
Life requirement	$T_s = T(P_f = P_{fr}) > T_r$

Probabilistic Buckling Design Criteria



Design criteria must take into account the scatter of predicted cylinder's buckling resistance (due to variability in design parameters: loading, geometry and other data)

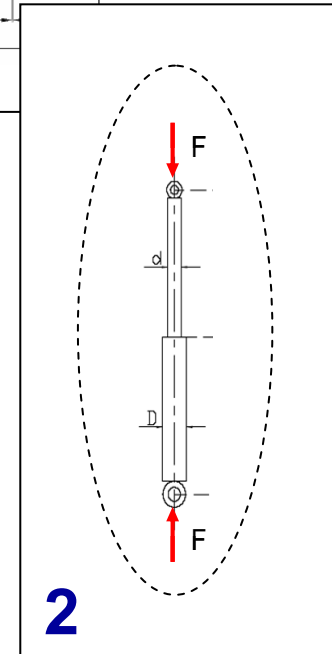
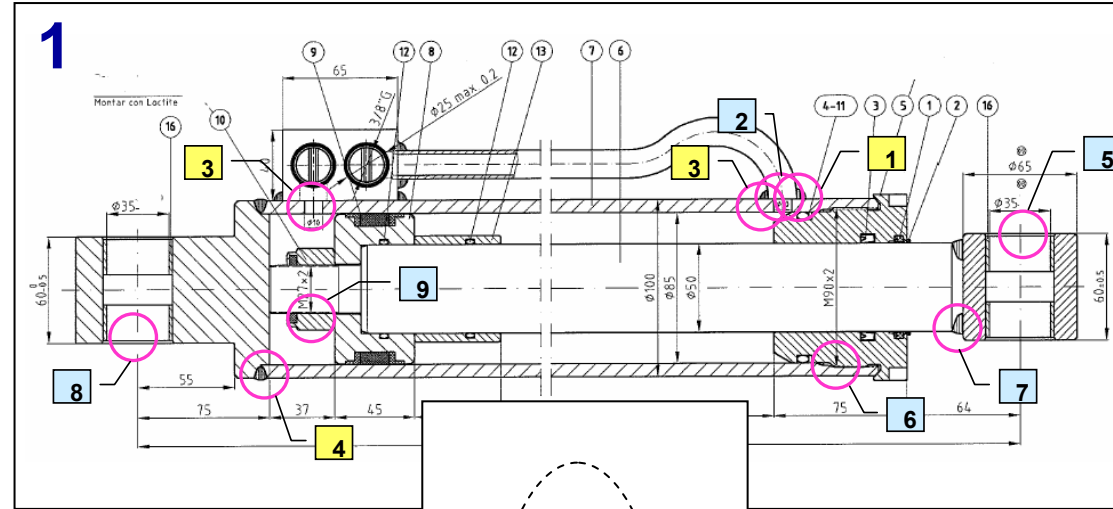


Grey area represents probability of failure:
 $P_f = P(d > d_r)$
 $R = 1 - P_f$

Probabilistic analysis	
Requirement	Response
Rod dia, d_r	Reliability, R
Reliability, R	Rod dia, d_r

Probability of failure: $P_f = P(d > d_r) = \int_0^{d_r} f_d(t) dt$

Probabilistic design criteria	
Reliability requirement	$P_f = P(d > d_r) \leq P_{fr}$
Rod dia requirement	$d_s = d(P_f = P_{fr}) > d_r$

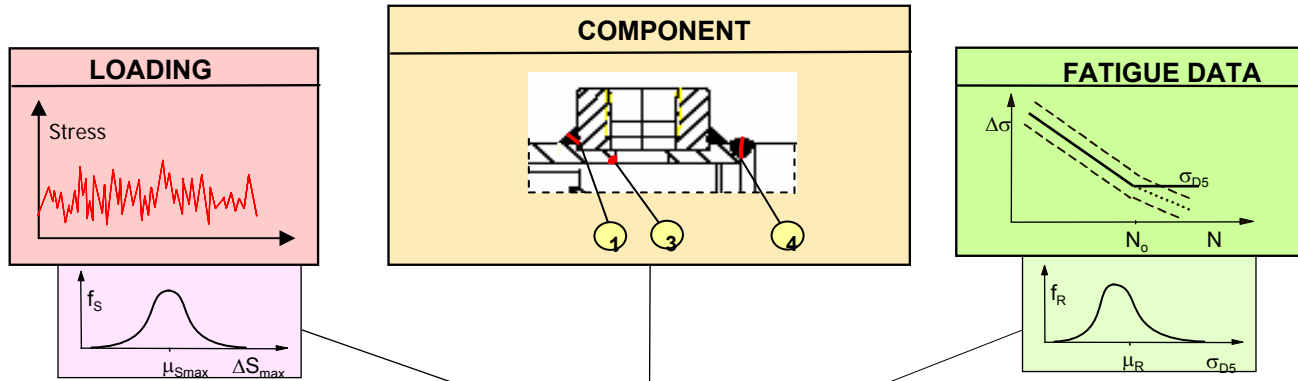


Deere 6420 tractor with a 6000-4 loader work attachment

➤ Redesign of the elevation cylinder

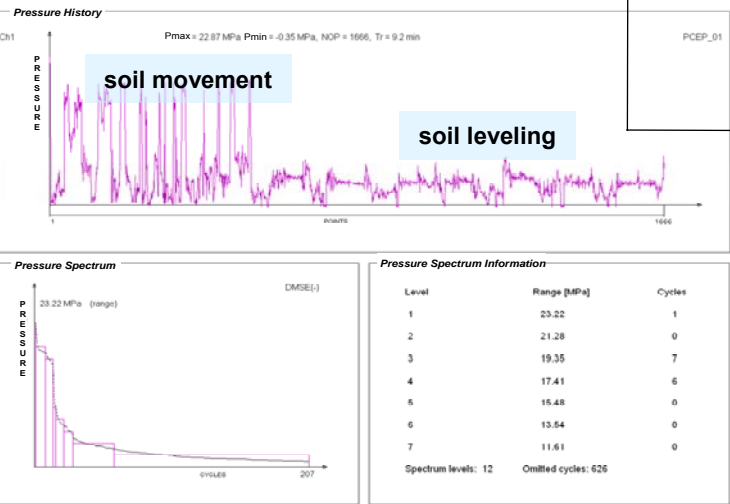
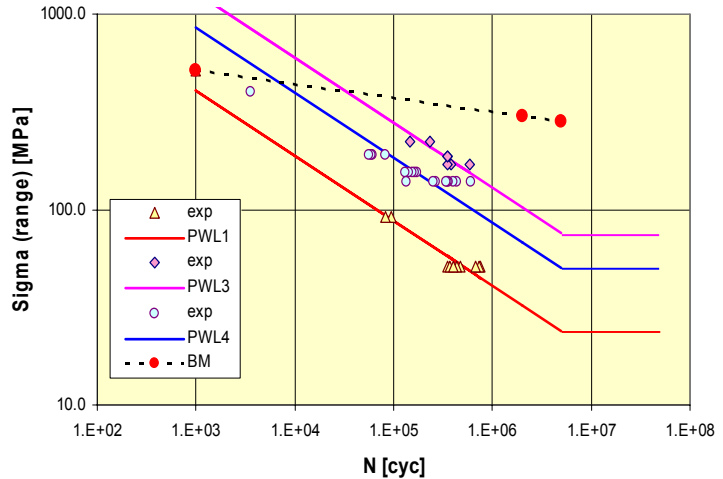
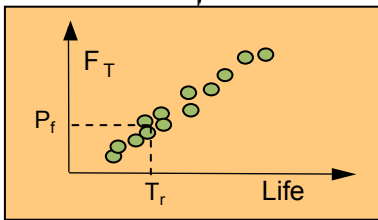
Failure modes:

1. Fatigue failure
2. Buckling of cylinder's rod



SAMPLING a SET of UNCERTAIN DATA

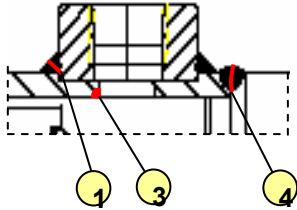
LIFE CALCULATION T_j



Probabilistic life assessment performed for 3 critical locations

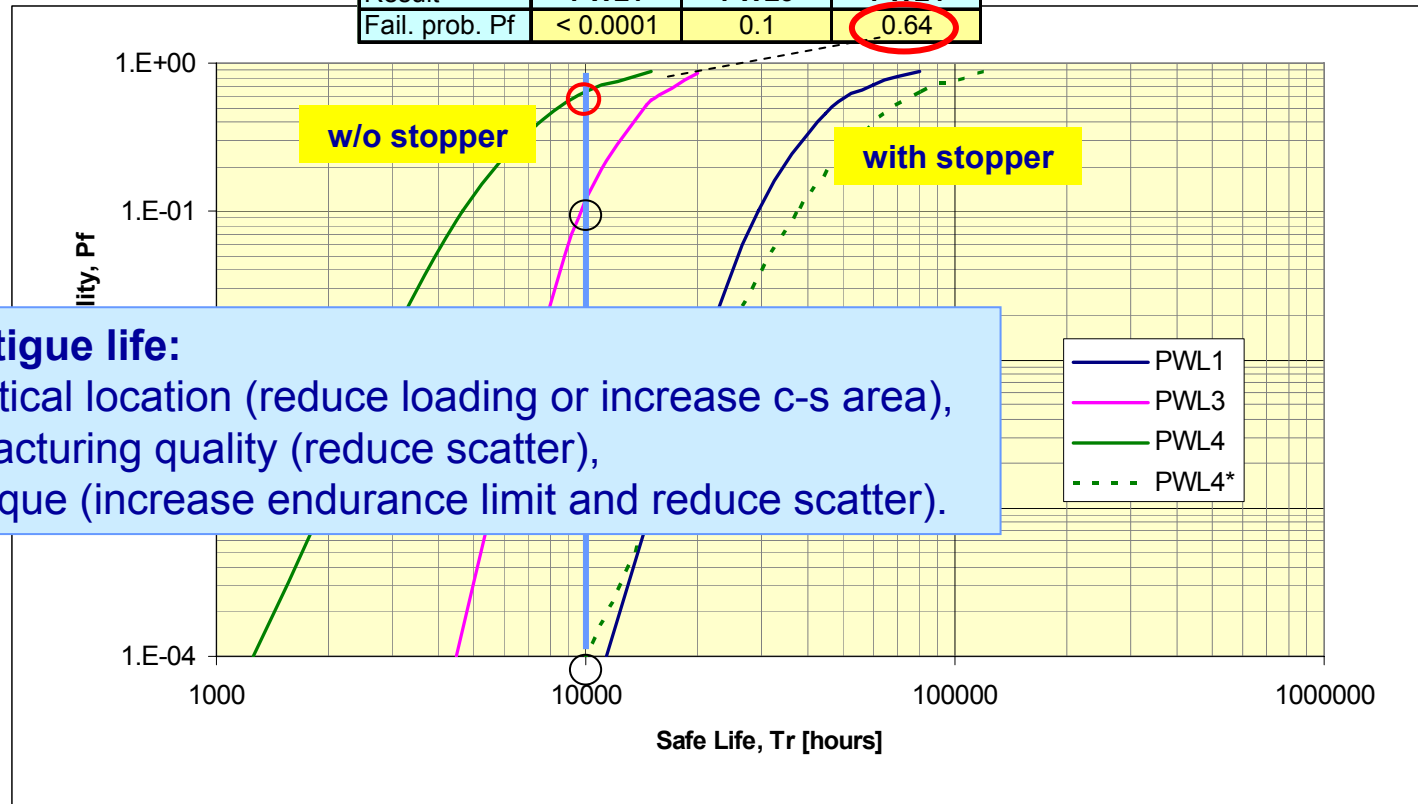
Simulation Result - Baseline

2



Required life: $T_r = 10000$ hours
 (4 hours/day x 5 days/week x 50 weeks/year x 10 years)

	Baseline design		
Result	PWL1	PWL3	PWL4
Fail. prob. Pf	< 0.0001	0.1	0.64

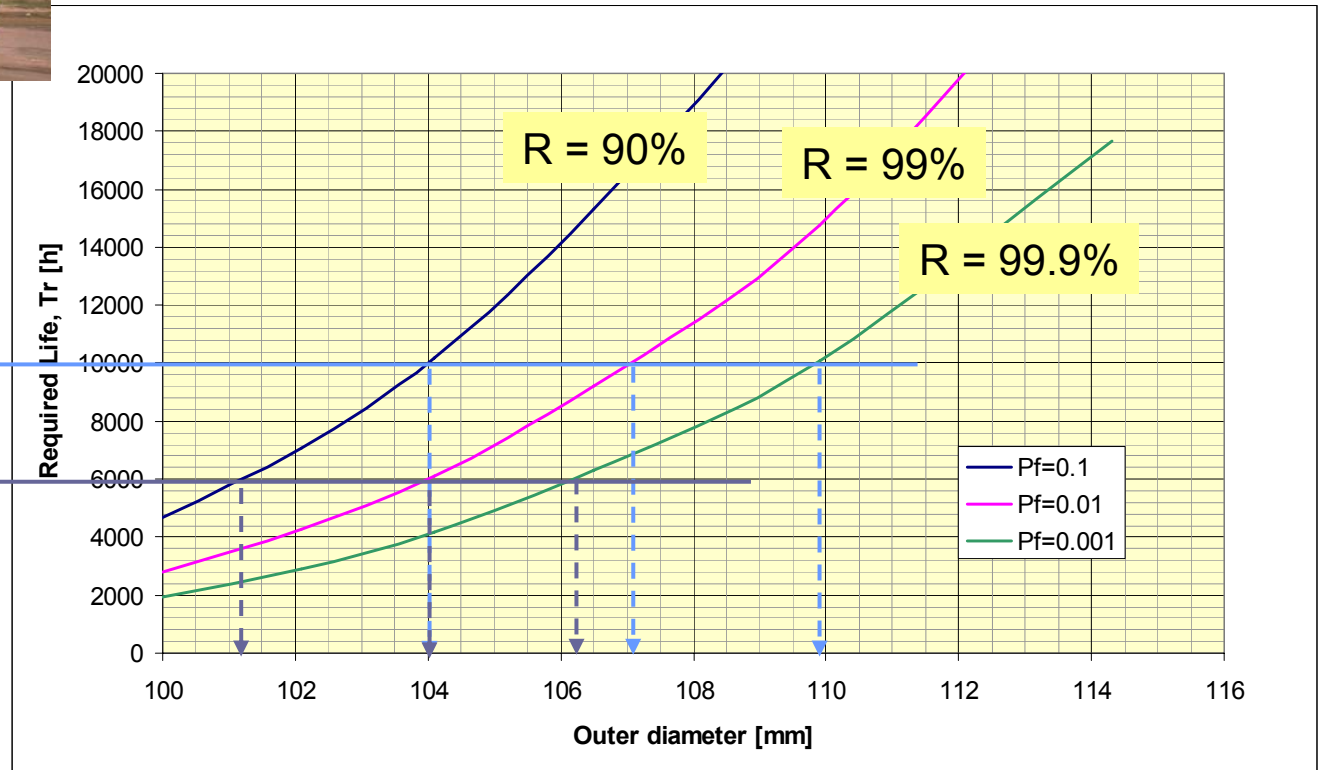


Ways to improve fatigue life:

- reduce stress at critical location (reduce loading or increase c-s area),
- improve the manufacturing quality (reduce scatter),
- new welding technique (increase endurance limit and reduce scatter).



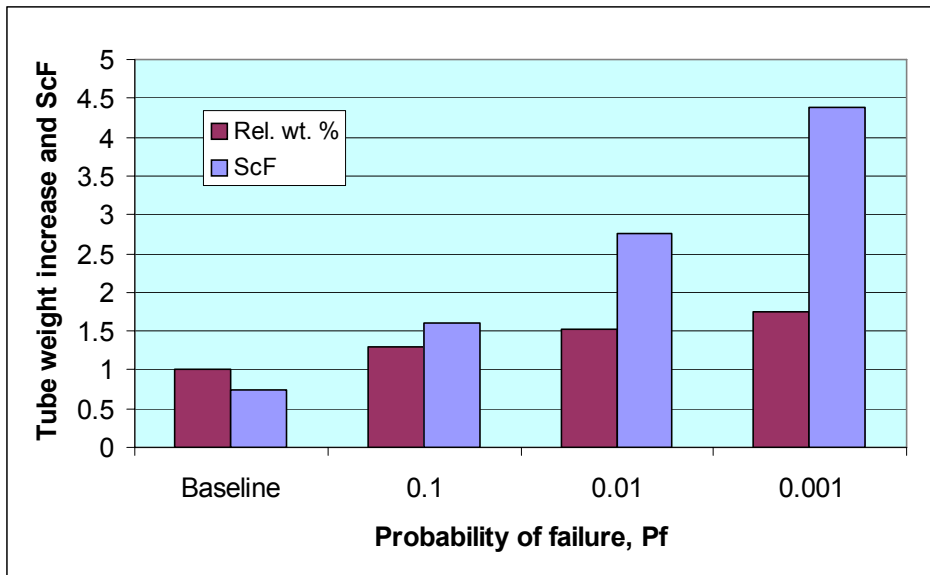
Fit your design to customer's expectations:
 Find maximum stress (and cylinder dimensions)
 for the required life T_r & reliability $R = 1 - P_f$



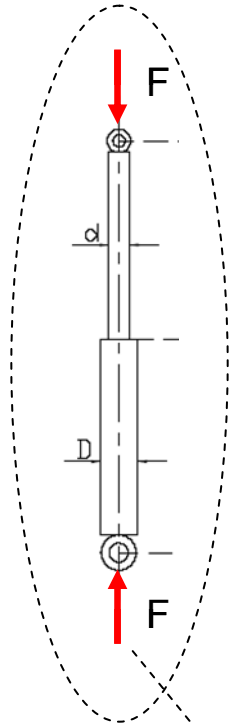
Redesign – Changes and Results

Required change of the outer cylinder diameter
for life $T_r = 10000$ hrs & reliability $R = 1 - P_f$

P_f	S_r [MPa]	D_o [mm]	S [MPa]	T_o [h]	ScF	Weight [kg]
Baseline	129.1	100		7320	0.73	15.59
0.1	100.6	104	99.7	16032	1.60	20.17
0.01	85.3	107	85.6	27530	2.75	23.73
0.001	74.3	110	74.5	43910	4.39	27.39



Higher reliability = higher manufacturing cost



Buckling of Hydraulic Cylinders

File Project Run Help

INPUT DATA - DETERMINISTIC ANALYSIS

CYLINDER		COV	Distrib	BOUNDARY CONDITIONS		FRICTION COEFFICIENT AT THE ENDS OF THE ACTUATOR	
926.0	Length [mm]	0.001	Normal	Cylinder - piston rod		Friction coefficient in piston rod end	
100.0	External Diameter [mm]	0.001	Normal	<input checked="" type="radio"/> Pin - Pin	Requested in case of: Pin-Pin, Fixed-Pin		Friction coefficient in cylinder end
85.0	Internal Diameter [mm]	0.0012	Normal	<input type="radio"/> Fixed - Fixed	Requested in case of: Pin-Pin, Pin-Fixed		Requested in case of: Pin-Pin, Pin-Fixed
200.0	Elasticity Modulus [GPa]	0.03	Normal	<input type="radio"/> Fixed - Pin	Low (0,07)	COV: 0.01	Low (0,07)
0.0	Density [kg/m ³]			<input type="radio"/> Pin - Fixed	High (0,20)	Distrib: Normal	High (0,20)
35.0	Pin Diameter [mm]	0.003			Other: 0.12		Other: 0.12

PISTON ROD		COV	Distrib
878.0	Length [mm]	0.001	Normal
200.0	Elasticity Modulus [GPa]	0.03	Normal
0.0	Density [kg/m ³]		
35.0	Pin Diameter [mm]	0.003	

PROBLEM DATA		COV	Distrib
380.0	Yield Tension [MPa]	0.07	Normal
0.2	Max. Cr. Angle [deg]	0.01	Normal
142.0	Applied Load [kN]	0.08	Normal

HYDRAULIC CYLINDER

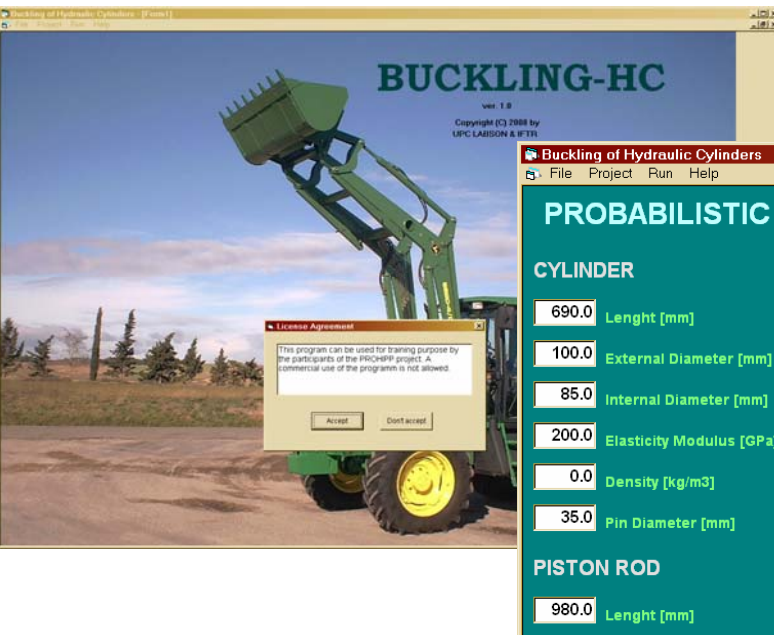
Pf	d [mm]
Baseline	50
0.1	30
0.01	40
0.001	43

Rod dia: d [mm]
 Mean = 2.87E+1
 COV = 0.063

Pf = 1.00E-1
d = 2.967E+1

Assumed pressure of 25 MPa

Deterministic method developed by UPC Labson



Buckling of Hydraulic Cylinders
File Project Run Help

PROBABILISTIC ANALYSIS

CYLINDER	COV	Distrib
690.0 Length [mm]	0.001	Normal
100.0 External Diameter [mm]	0.001	Normal
85.0 Internal Diameter [mm]	0.0012	Normal
200.0 Elasticity Modulus [GPa]	0.01	Normal
0.0 Density [kg/m3]		
35.0 Pin Diameter [mm]	0.003	Normal

PISTON ROD	COV	Distrib
980.0 Length [mm]	0.001	Normal

BOUNDARY CONDITIONS

Cylinder - piston rod

- Pin - Pin
- Fixed - Fixed
- Fixed - Pin
- Pin - Fixed

FRICITION COEFFICIENT AT THE ENDS OF THE ACTUATOR

Friction coefficient in piston rod end
Requested in case of: Pin-Pin, Fixed-Pin

- Low (0,07) COV: 0.01, Distrib: Normal
- High (0,20)
- Other 0.12, Distrib: Normal

Friction coefficient in cylinder end
Requested in case: Pin-Pin, Pin-Fixed

- Low (0,07) COV: 0.01, Distrib: Normal
- High (0,20)
- Other 0.12, Distrib: Normal

Pin-Pin | Fixed-Fixed | Fixed-Pin | Pin-Fixed

Scheme: Pin joint at both cylinder and piston rod ends. Rotation in joint is possible.

Examples: Real Behaviour

Close

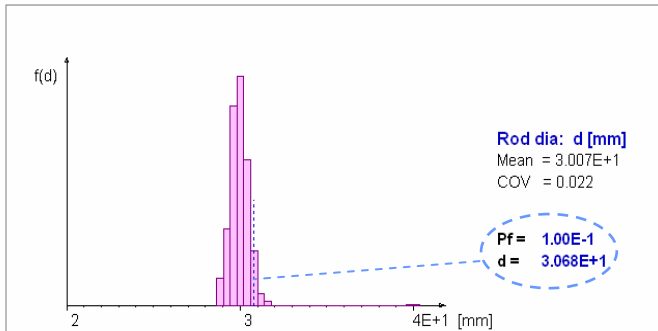
S [mm] 87 COV: 0.01, Distrib: Normal
 Empiric value for S

DATA

Distrib. Normal

Config: 1, 2, 3, 4, 5, 6

HYDRAULIC CYLINDER





Demonstration Software Life-SN



LIFE-SN
ver. 1.0
Copyright (C) 2007 by H.Jakubczak

License Agreement
This program can be used for training purpose by the participants of the PROHIP project. A commercial use of the program is not allowed.

Accept Don't accept

FALSIN - Fatigue Life Analysis Program
File Analysis Run Results Help

Material: Fatigue Data

$m = 3.5$ $r = -1.0$

STRESS
AMPL

$S_e = 50.0$ MPa
 $P_n = 50.0\%$

$S_u = 500.0$ MPa
 $S_y = 300.0$ MPa

$N_0 = 2E+6$ CYCLES

Loading: Spectrum

DMSE(-)

100.55 MPa Mean Stress = 33.85 MPa

STRESS
AMPL

CYCLES 386

Results: Damage

1.289E-5

Miscellanea

SUBJECT: PROHIP

Loading Data:
Material Data:
SN-Extension:
Mean Stress Effect:
Damage to Failure:
Fatigue life:

Probability Plot {Log-norm}

P(T)

Life T [cyc]
Mean = 1.131E+6
COV = 0.459

$P_f = 1.00E-3$
 $T_r = 2.614E+5$

1E+5 1E+6 1E+7

Life T [cyc]

Input Data

Loading: Spectrum
 $S_{max} = 120.0$ MPa
 $S_{min} = 0.0$ MPa
Levels: 1
Scaling factor: (N8)

Material Properties
Demo_1
 $S_e = 34.0$ MPa (L12)
 $N_0 = 5E+6$ cyc
 $m = 3.0$
 $r = 0.0$
 $P_n = 50.0\%$

Analysis Options
CMSE(-)
MCS: NoFLINSA

PROHIP

Material Data

Randomizing the Endurance Limit, S_e : (L12)

Distribution: None Parameters:
 Normal C.O.V. = 0.12
 Log-normal STDV: B = 0.12
 Weibull Mean: A = -0.007
 Exponential Xmin = 0.62
 Uniform Xmax = 1.613

PDF

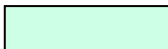
OK Cancel Draw

- **Main achievements**

- Development of fatigue life assessment methodology for hydraulic cylinders
 - Improvement of method for fatigue life prediction
 - Classification of fatigue failure modes of HC
 - Guidelines to stress calculation for critical locations
- Development of probabilistic design methodology
 - Formulation of new design criteria
 - Estimation of scatter of design parameters
 - Development of methods for efficient failure probability calculation in probabilistic analyses (Response Surface Method).

- Methodology of fatigue life assessment of real structures
- Methodology of probabilistic design
- Database of probabilistic distributions of design parameters
- Computer programs for:
 - Loading data acquisition (Rainflow counting)
 - Fatigue life calculation (deterministic and probabilistic)
 - Probabilistic buckling analysis

		months 1-12	months 13-18	months 19-24	months 25-30	months 31-36	months 37-42	months 43-48
WP1	T1.1							
	T1.3							
WP2	T2.1							
	T2.3							
	T2.4							
WP3	T3.2							
WP6	T6.1							
WP7	T7.2							
WP8	T8.1							
WP9	T9.2.2-public							
WP12	T12.1							
WP12 & 13	T13.1							
	T13.2							

 active tasks

IFTR work done according to the work programme.

		1-12 justified	13-24 planned	13-24 justified	25-36 justified	25-36 planned	37-48 justified	37-48 planned	1-48 justified	1-48 planned	%used
WP1	T1.1	0	0	0	0,5	0,5	0	0	0,50	0,5	100,00
	T1.3	2,93	1,5	1,5	0	0,5	0	0	4,43	4,93	89,86
WP2	T2.1	4	6	5,3	5,5	6	3	3	17,80	19	93,68
	T2.2									0	
	T2.3	4	4	4,58	7,28	8	4,5	5	20,36	21	96,95
	T2.4	4,03	5	5,5	6,21	7	4,5	3	20,24	19,03	106,36
WP3	T3.2		1	1	1	2	0	1	2,00	4	50,00
WP6	T6.1	1,17							1,17	1,17	100,00
WP7	T7.1									0	
	T7.2				0,76	0,5	1,1	0,5	1,86	1	186,00
WP8	T8.1					1	1,5	1	1,50	2	75,00
WP9	T9.2.2-public		1	1	1,5	2	2	1	4,50	4	112,50
WP12	T12.1		0	0	0	0	0	0	0,00	0	
WP13	T13.1	3,47	1	1,4	4,18	3	2	2	11,05	9,47	116,68
	T13.2	0	1	0	0	1	2,8	2	2,80	4	70,00
All WPs		19,6	20,5	20,28	26,93	31,5	21,4	18,5	88,21	90,1	97,90

Resources are used nearly as planned