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

Summary of IFTR work

- **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**

PROHIPP Project - Summary

IFTR Objectives of WP2.1 & WP2.4:

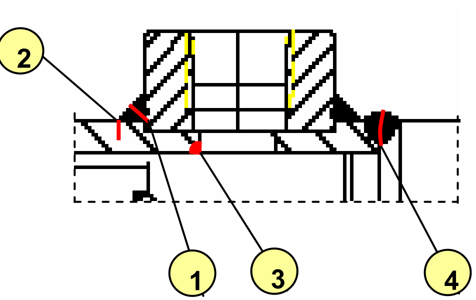
- Develop deterministic fatigue life assessment methodology
- Develop probabilistic design methodology
    - Determine variability of design parameters
    - Develop methods for probabilistic analyses
    - Formulate new design criteria.

Partners involved:

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

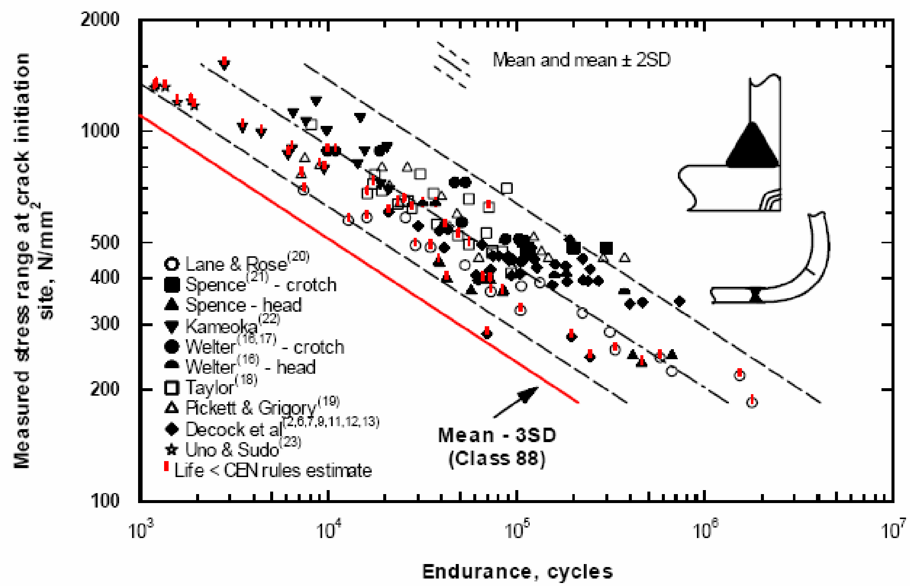
Fatigue Design – Current State

Critical locations (example)



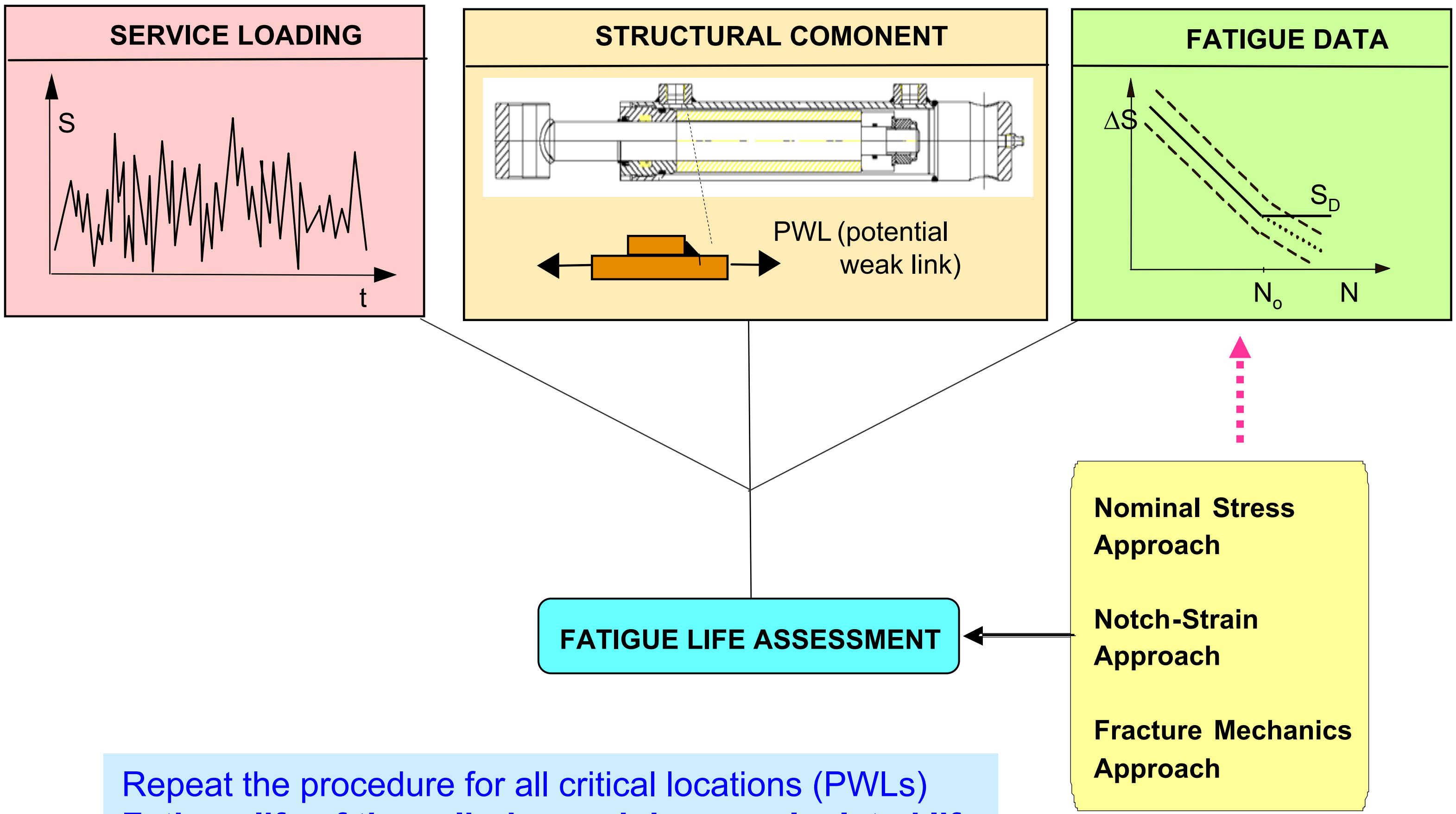
Practical observations

Fatigue data



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

Local Fatigue Life Assessment

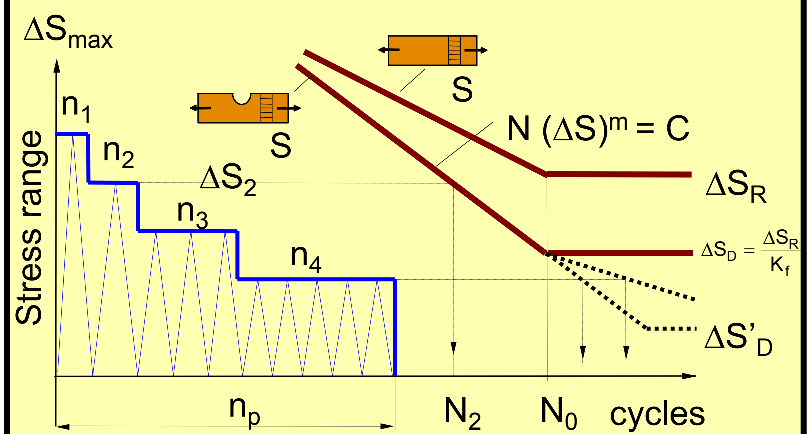


Repeat the procedure for all critical locations (PWLs)

Fatigue life of the cylinder = minimum calculated life

Methods of Local Fatigue Analysis

Nominal Stress Approach (NSA)

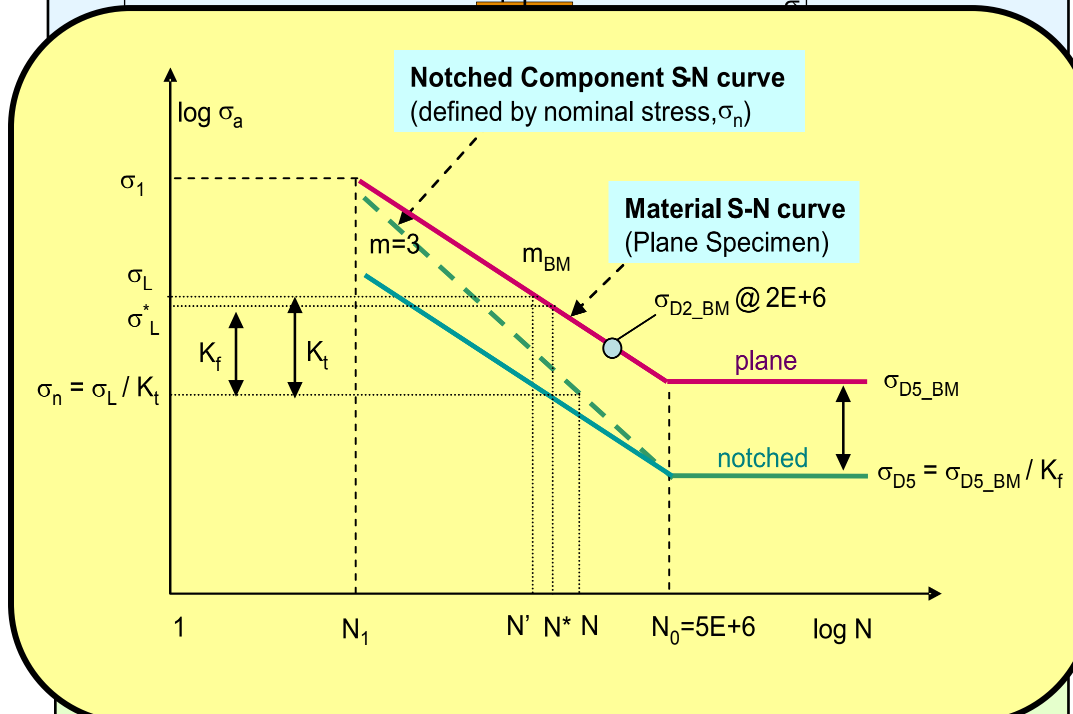


Life: $N = BLK\ n_p$ [cyc] $T = BLK\ t_r$ [h]

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

Notch-strain approach = Low Cycle Fatigue (LCF)

Modified method



- Allows life assessment based on FEA stress
- Accounts for the notch sensitivity

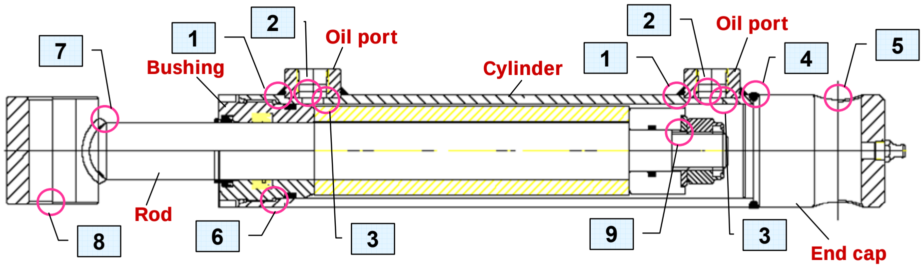
K – stress intensity factor

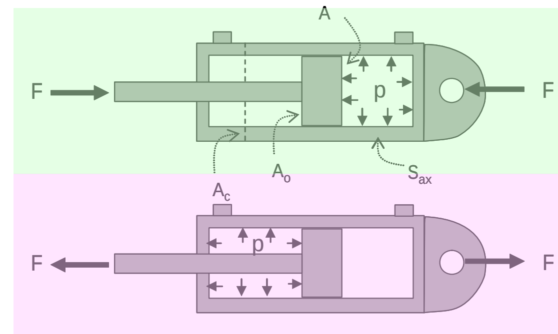
Required: S – nominal (remote) stress

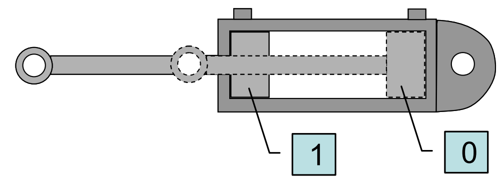
σ(x) – local stress (FE analysis, without crack)

Stress Analysis at PWLs

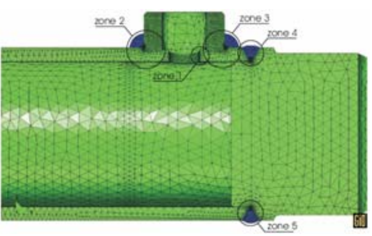
Identification of critical locations (Roquet results)

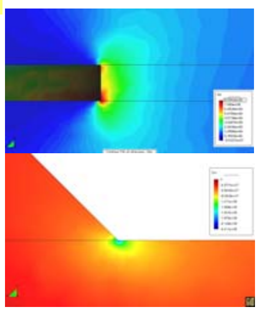




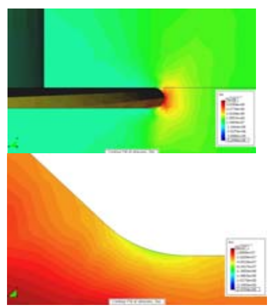


PWL modeling in FE



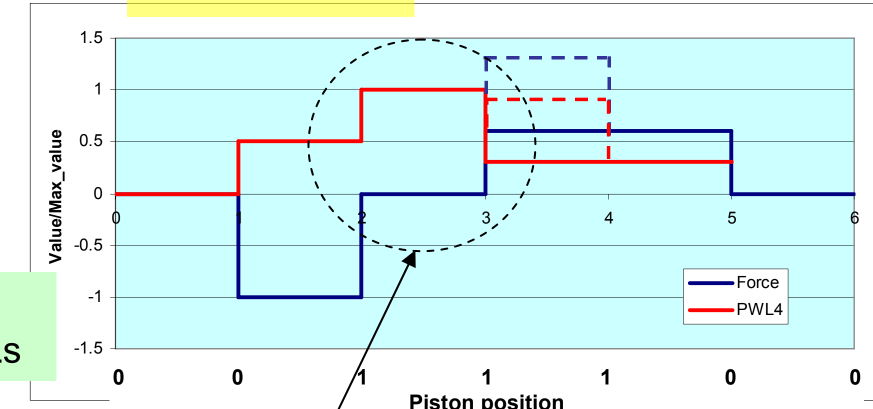


Wrong



Correct

PWL4

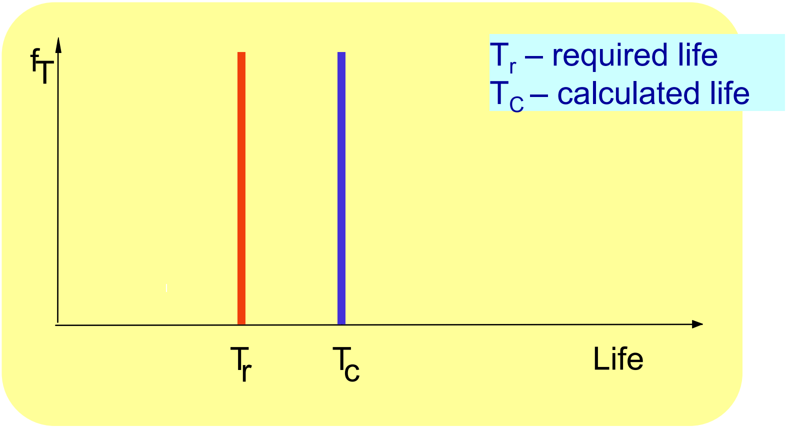


Loading – stress flow diagrams indicate critical cylinder loading for specified PWLs

Avoiding this situation may significantly increase cylinder's life!

Deterministic vs. Probabilistic Design

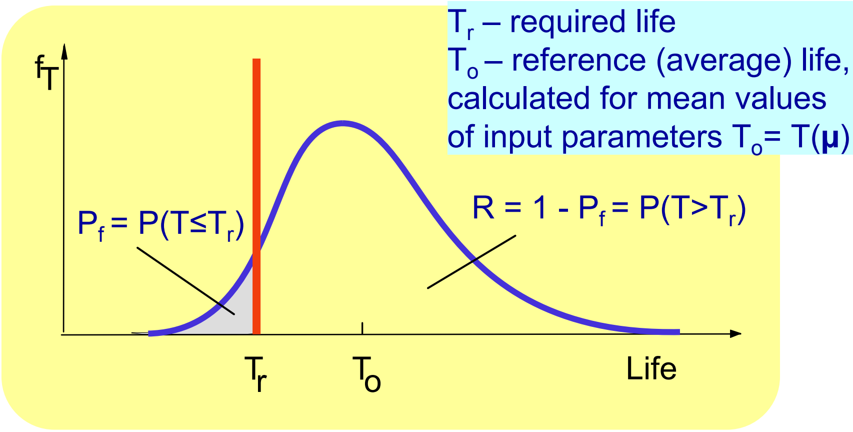
Deterministic fatigue design



Design condition: $T_c > SF*T_r$

(SF = experience based Factor of Safety)

Probabilistic fatigue design



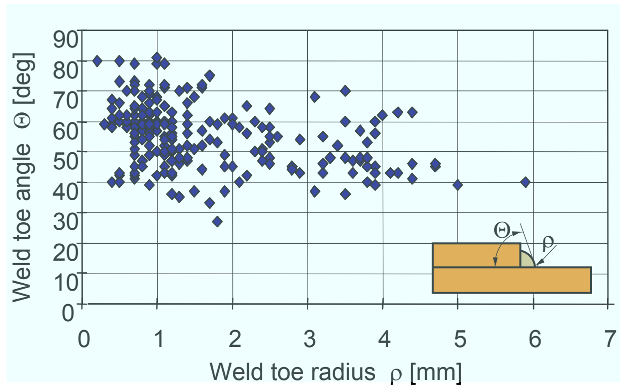
Design condition: ???

What is needed for probabilistic design?

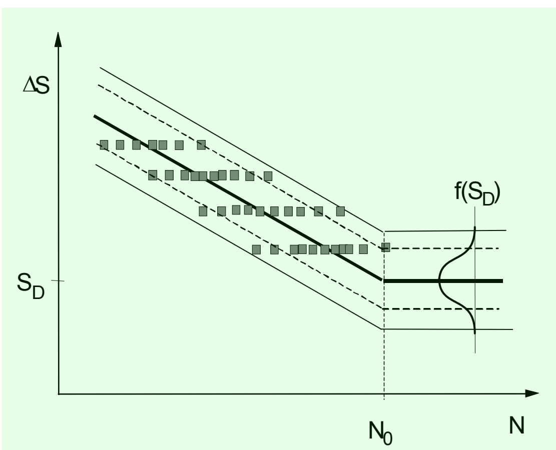
- Variability of design parameters
- Probabilistic analysis method
- Design criteria

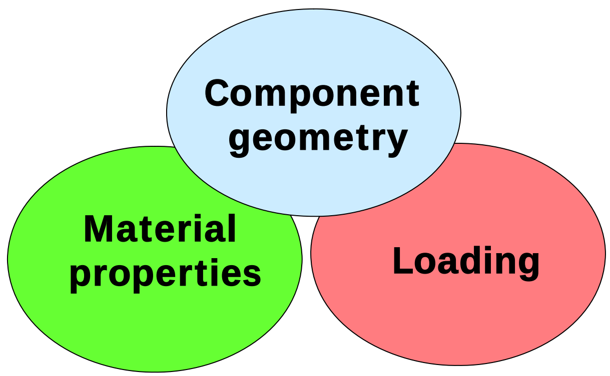
Variability of Design Parameters

Component geometry

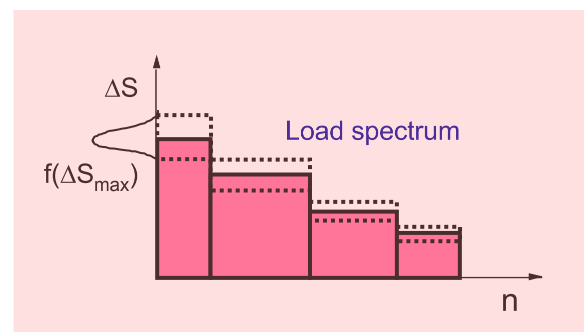


Fatigue data (S-N)



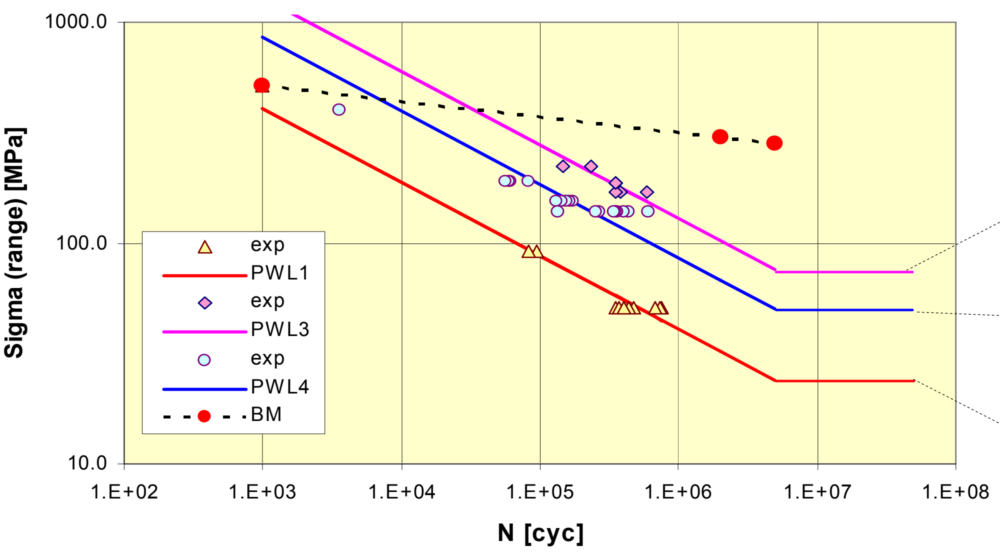


Service loading



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

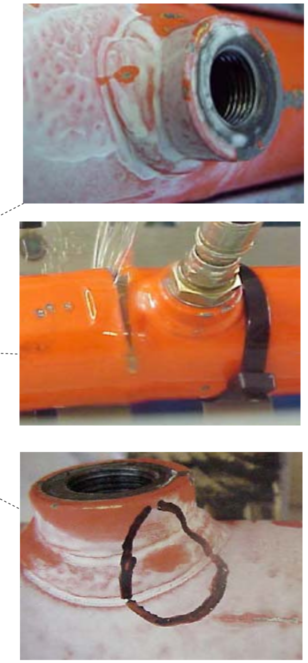
Determination of SN Curves

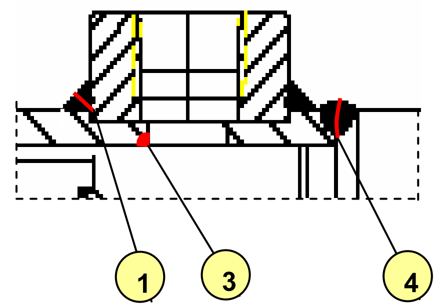


3

4

1



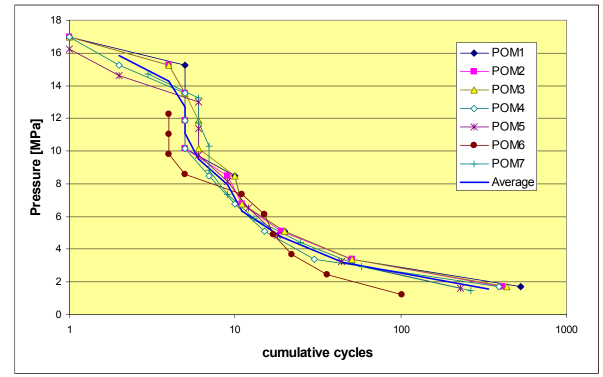


- S-N curves estimated based on full-scale fatigue tests of hydraulic cylinders by Pedro Roquet S.A.
- Estimated S-N curve parameters and their scatter: $COV_x = V_x = \sigma_x / \mu_x$
- Literature studies

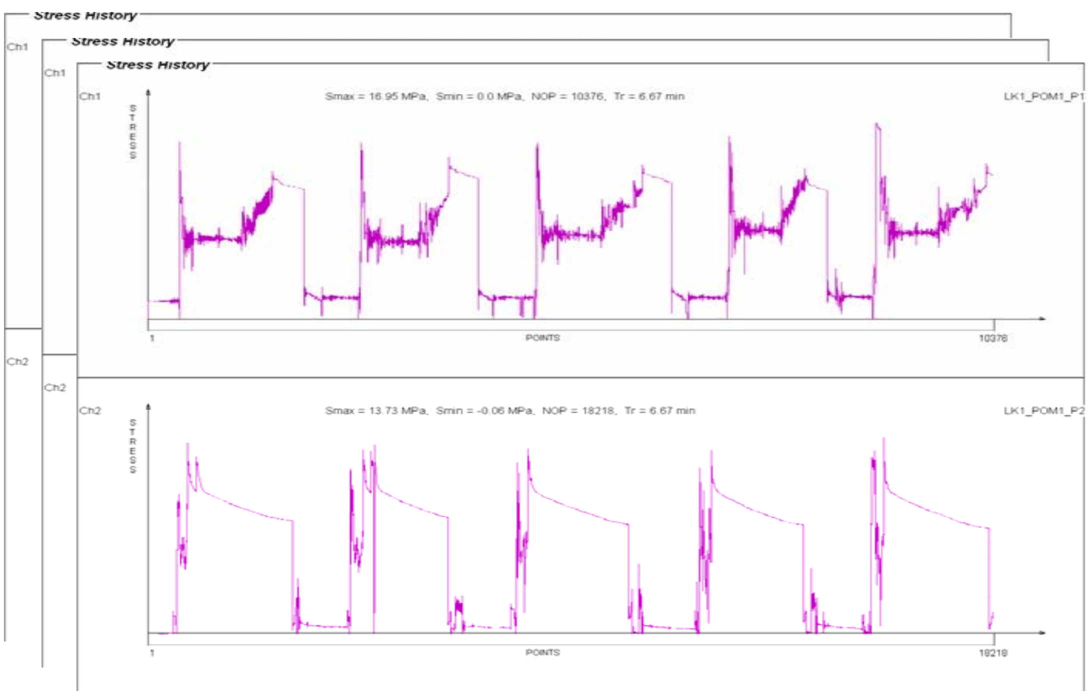
	PWL1	PWL3	PWL4
m	3.0	3.0	3.0
m2	5.0	5.0	5.0
S_{D2} mean	32.3	102.2	67.9
S_{D2} $-3\sigma_R$	24.3	83.2	41.9
S_{D5} mean	23.8	75.3	50.0
S_{D5} $-3\sigma_R$	17.9	61.3	30.9
COV_2	**0.109**	**0.076**	**0.207**
COV_5	**0.082**	**0.062**	**0.128**

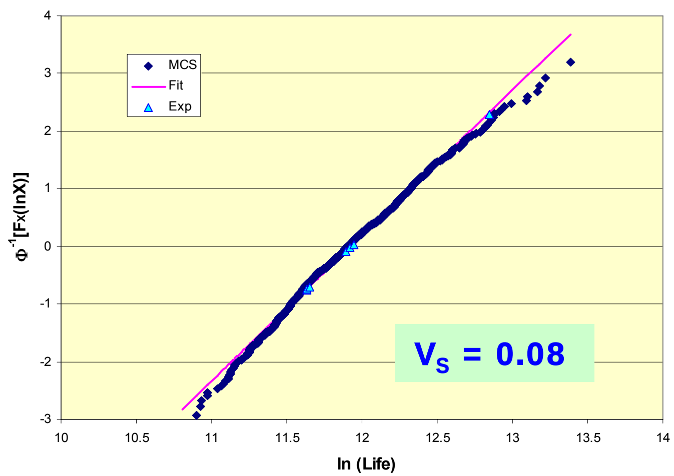
Scatter of Service Loading

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



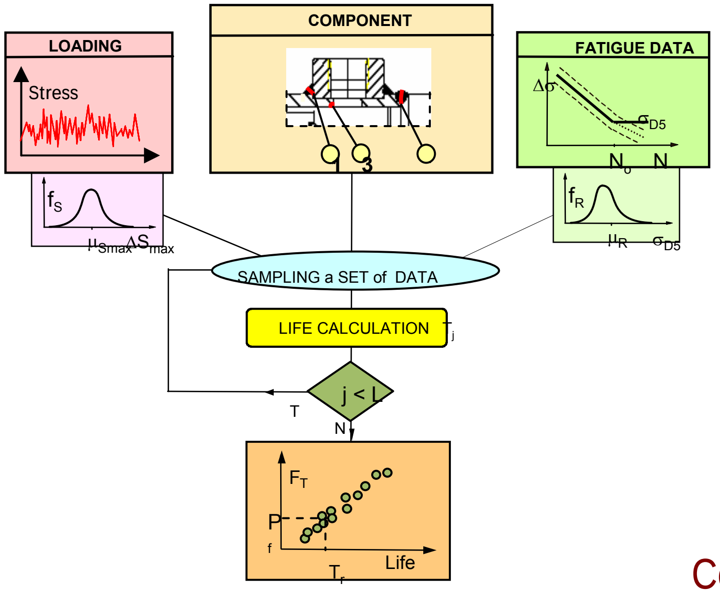
Cylinder P1



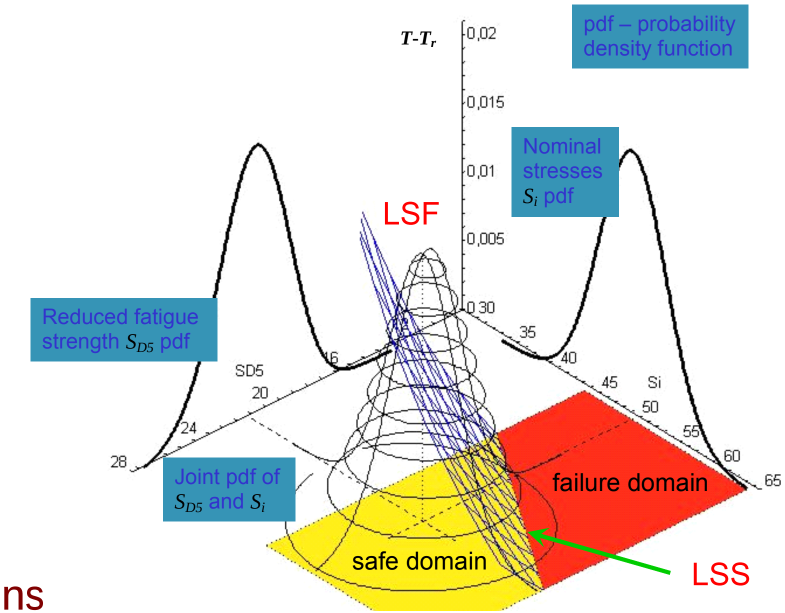


Probabilistic Analysis

Direct Monte Carlo Simulation

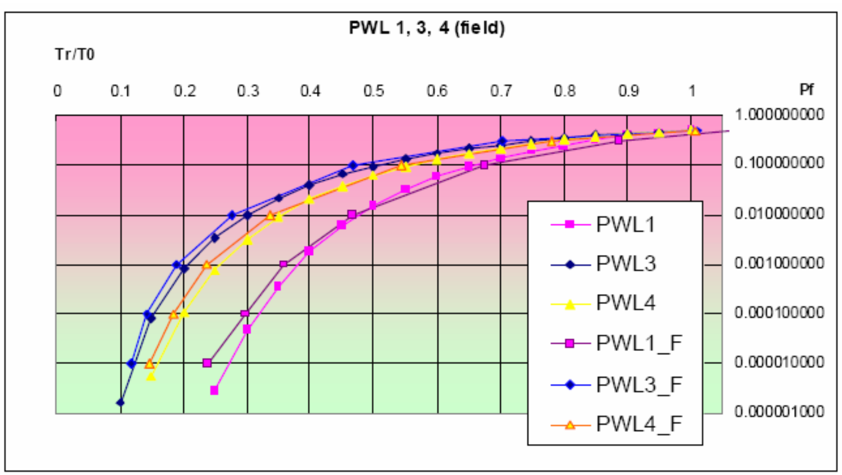


Response Surface Method



Comparisons

Simulations:
L = 100000

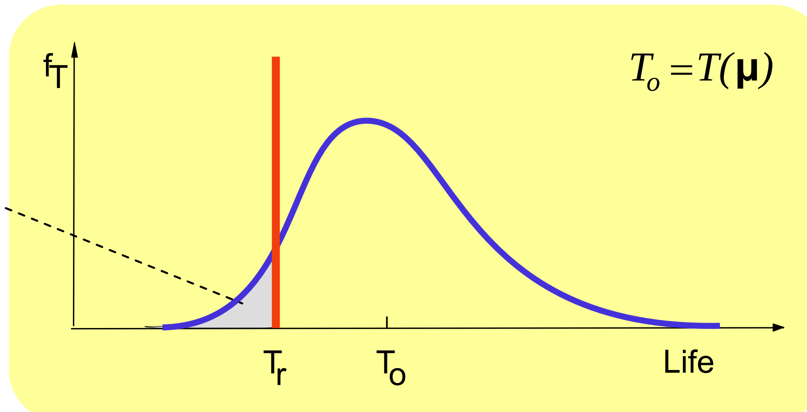


Simulations:
L = 25

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:
$P_f = P(T \le T_r)$
$R = 1 - P_f$



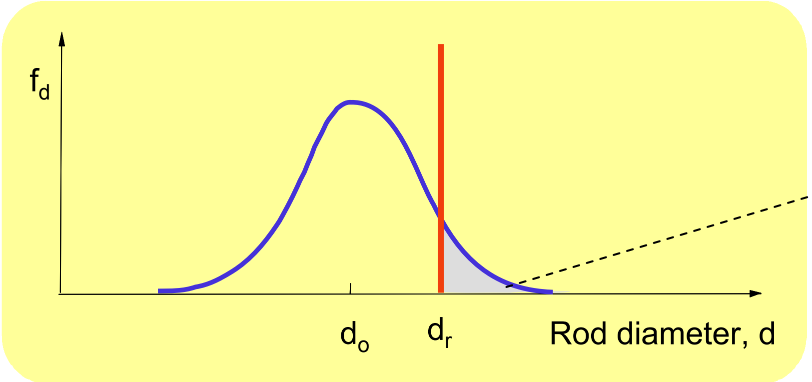
Probabilistic analysis		
Requirement		Response
Life, Tr	→	Reliability, R
Reliability, R	→	Safe life, Tr

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

Probabilistic design criteria	
Reliability requirement	$P_f = P(T \le T_r) \le P_{fr}$
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:

$P_f = P(d > d_r)$

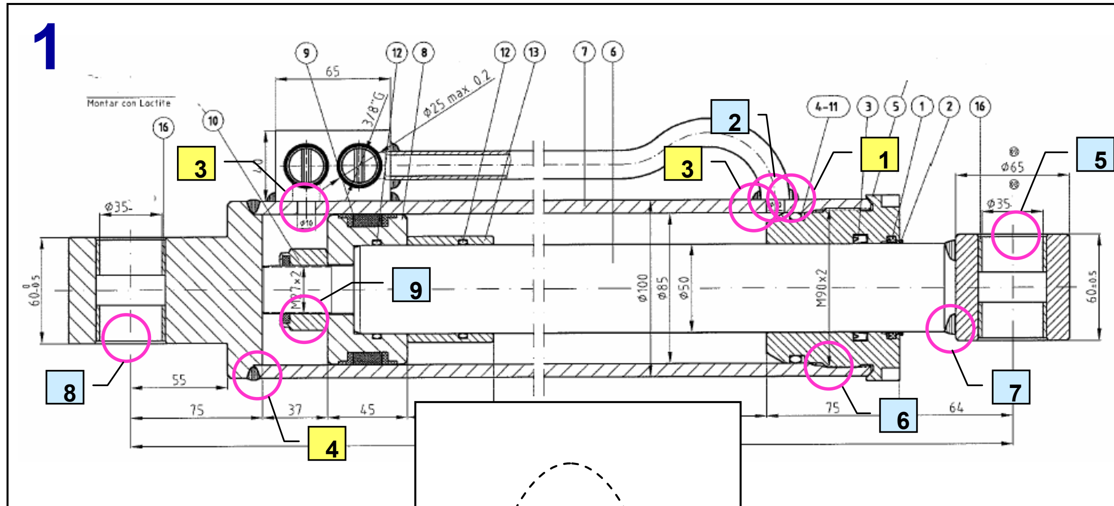
$R = 1 - P_f$

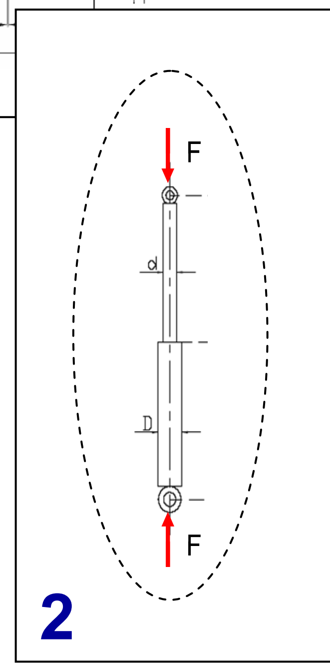
Probabilistic analysis	
Requirement	Response
Rod dia, dr →	Reliability, R
Reliability, R →	Rod dia, dr

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	$d_s = d(P_f = P_{f_r}) > d_r$

Probabilistic Design Example





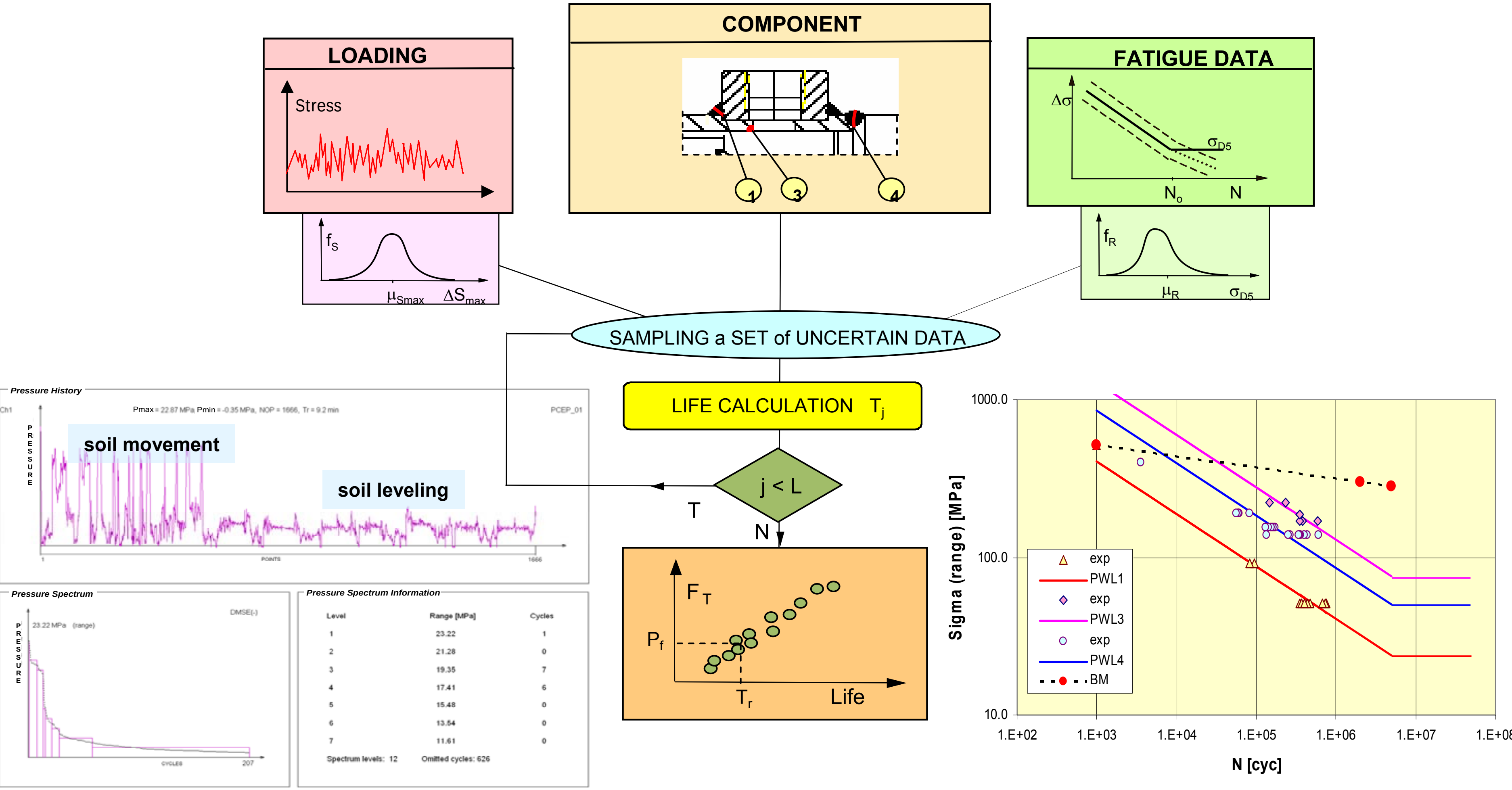
Deere 6420 tractor with a 6000-4 loader work attachment

- **Redesign of the elevation cylinder**

Failure modes:

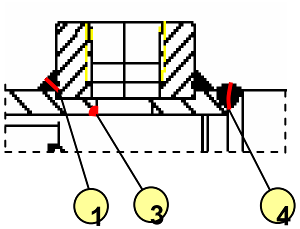
1. **Fatigue failure**
2. **Buckling of cylinder's rod**

Probabilistic Fatigue Design



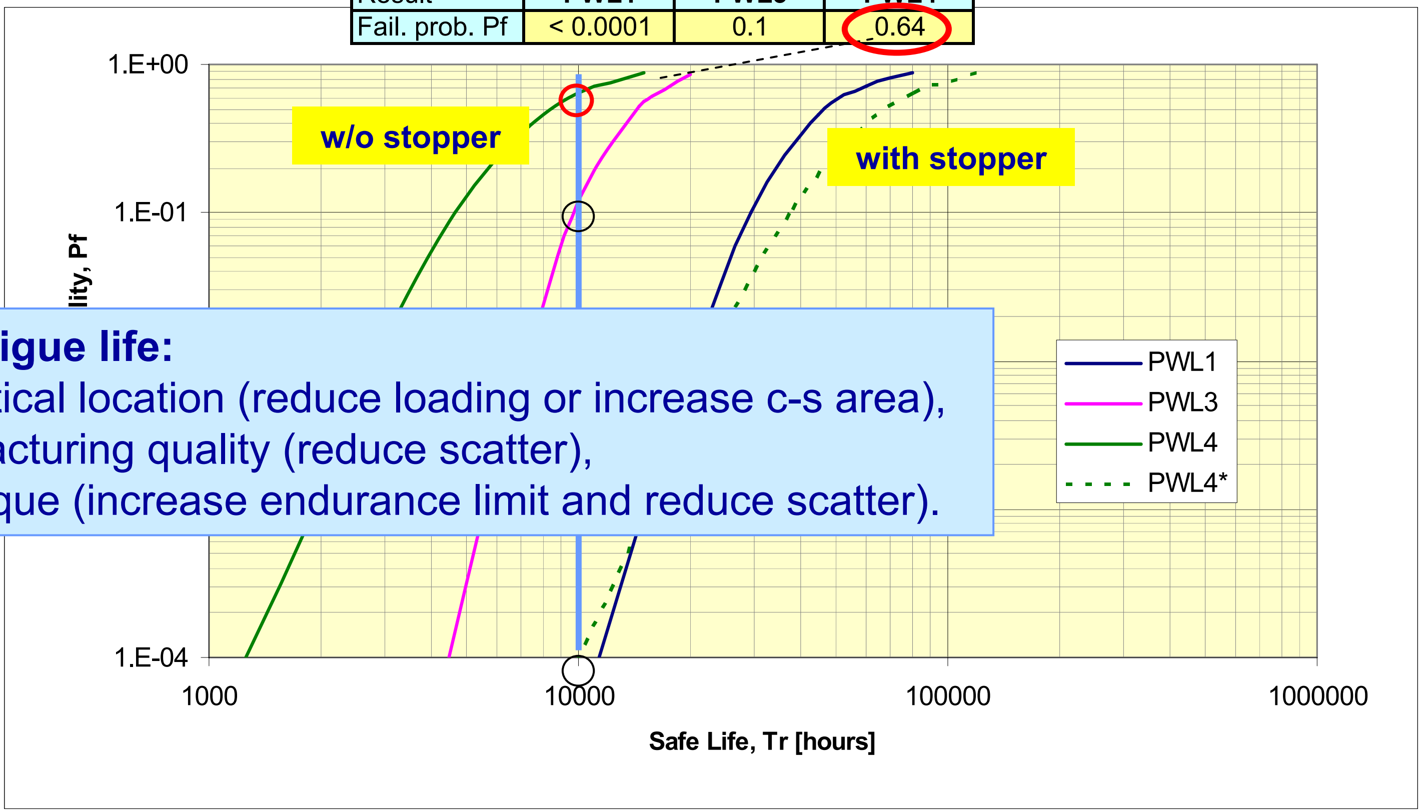
Probabilistic life assessment performed for 3 critical locations

Simulation Result - Baseline



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

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

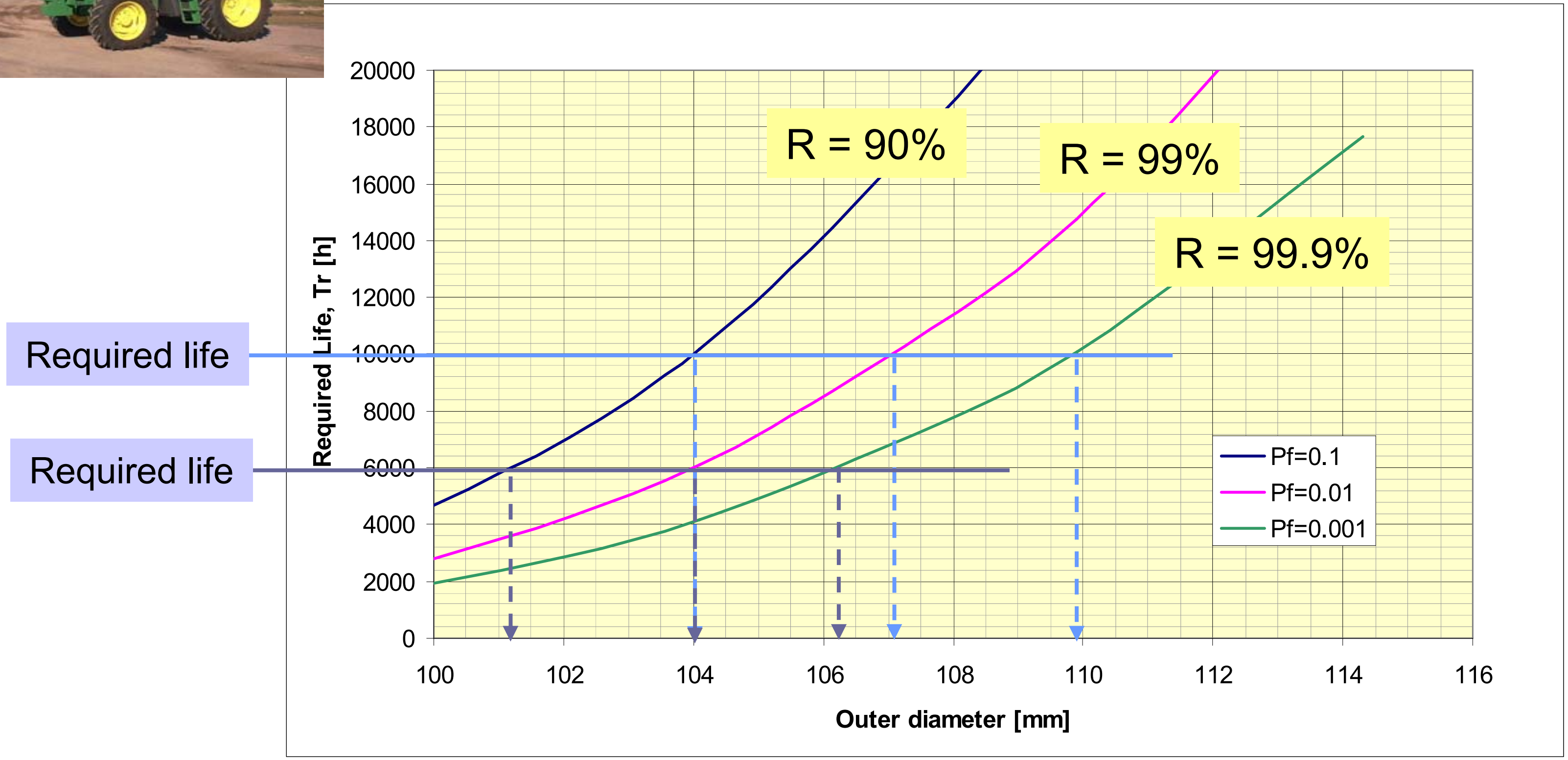


Ways to improve fatigue life:

- 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).

Probabilistic Fatigue Design - Result

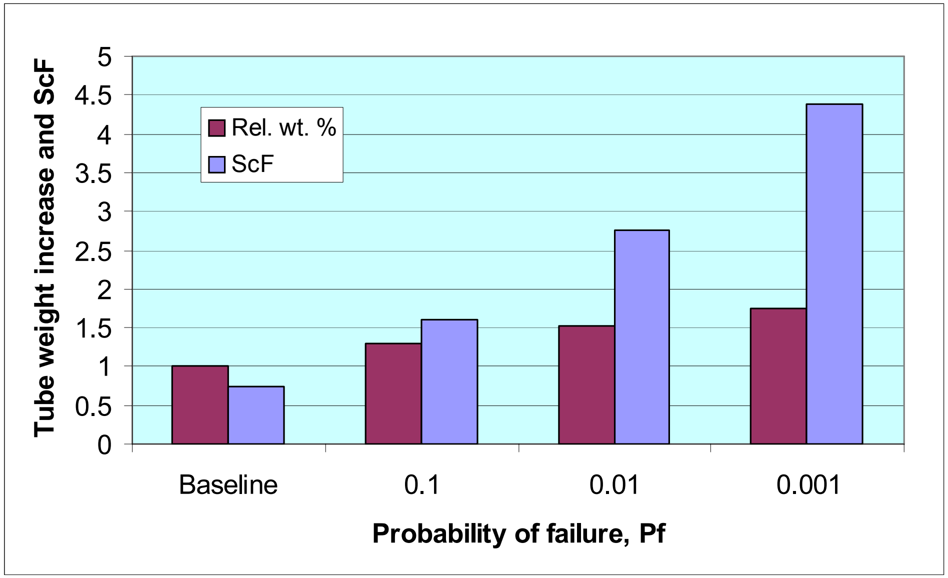
Fit your design to customer's expectations:
Find maximum stress (and cylinder dimensions)
for the required life T_r & reliability $R = 1 - P_f$



Redesign – Changes and Results

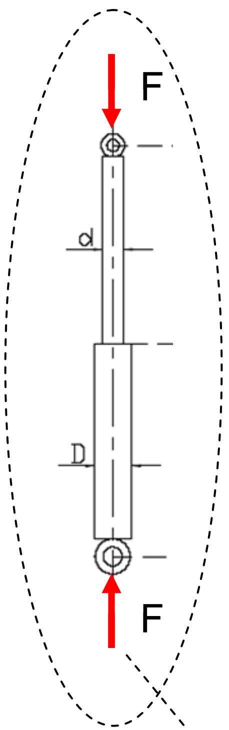
Required change of the outer cylinder diameter
for life T_r = 10000 hrs & reliability R = 1 – P_f

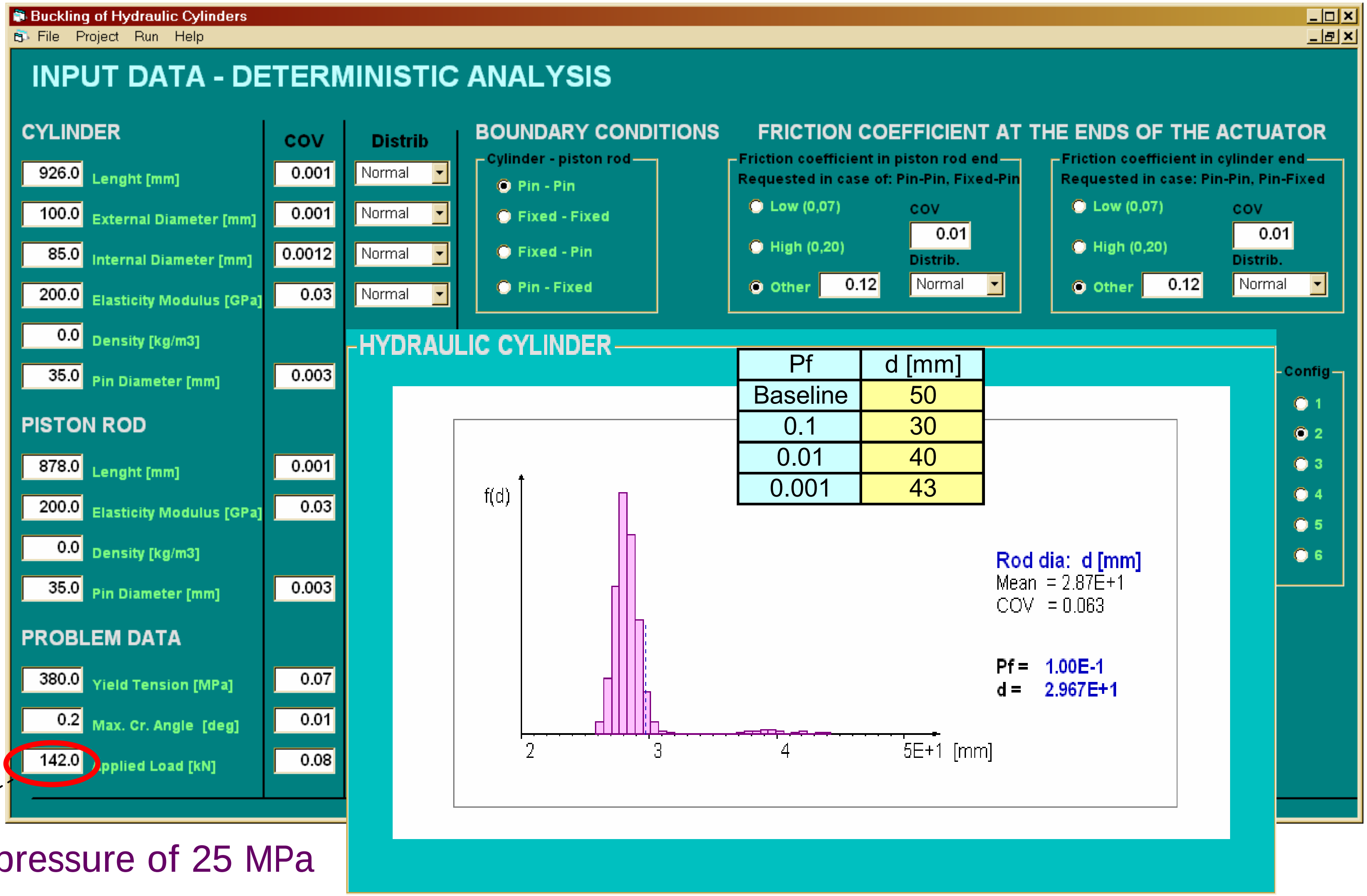
Pf	Sr [MPa]	Do [mm]	S [MPa]	To [h]	ScF	Weight [kg]
Baseline	129.1	100		7320	0.73	15.59
0.1	100.6	104	99.7	16032	1.60	20.17
0.01	85.3	107	85.6	27530	2.75	23.73
0.001	74.3	110	74.5	43910	4.39	27.39



Higher reliability = higher manufacturing cost

Probabilistic Buckling Design



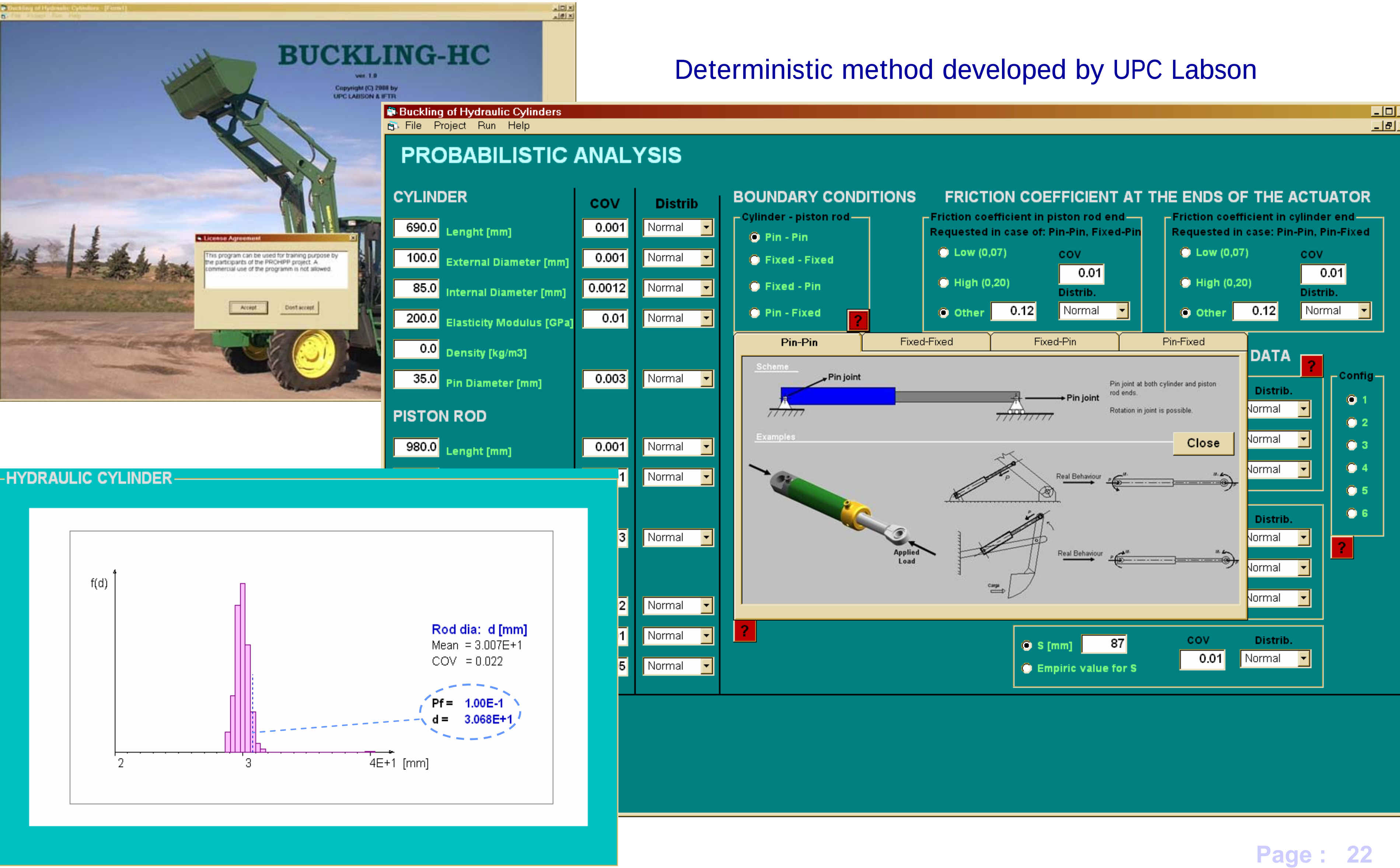


Pf	d [mm]
Baseline	50
0.1	30
0.01	40
0.001	43

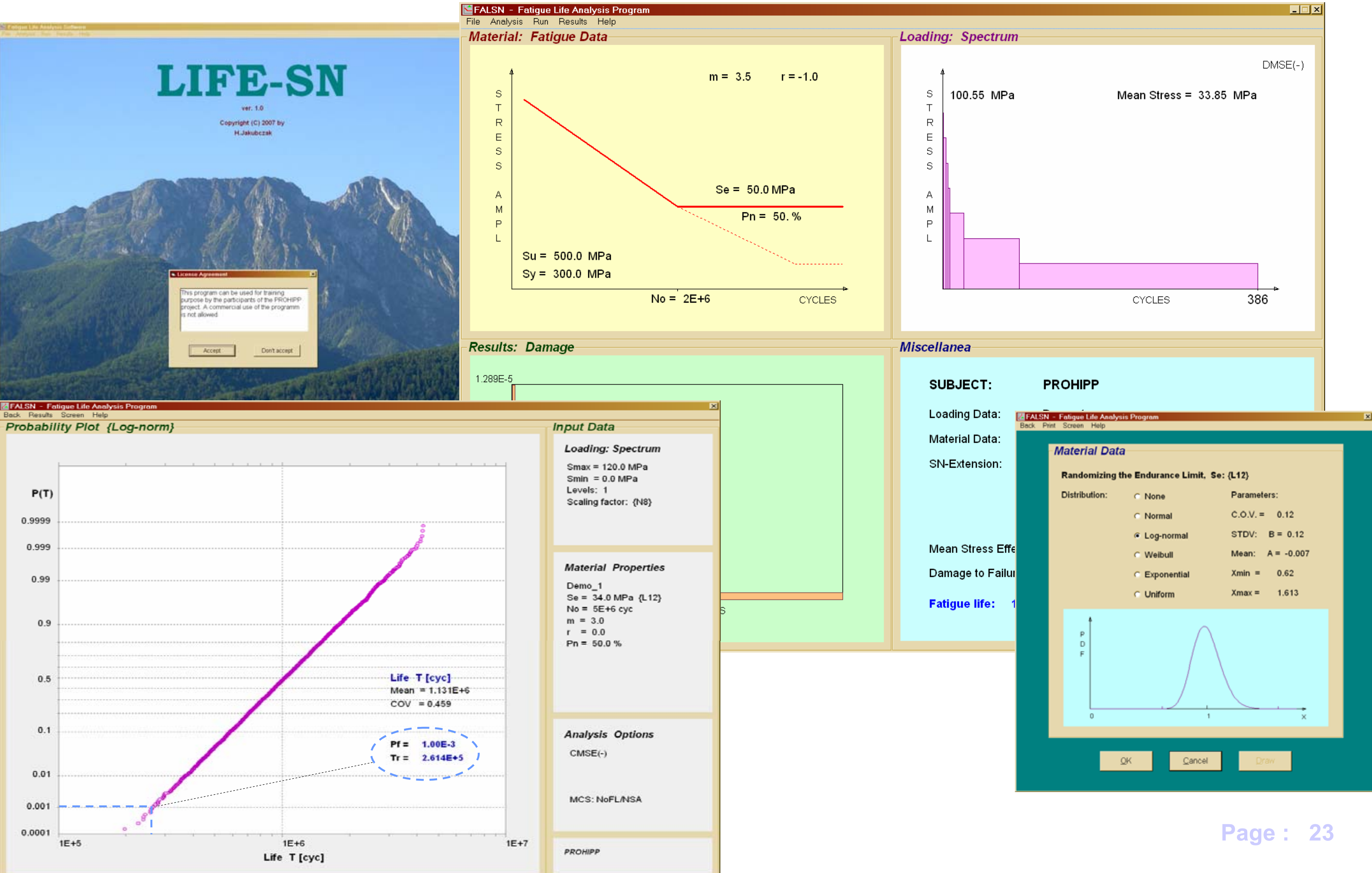
Assumed pressure of 25 MPa

Demonstration Software **Buckling-HC**

Deterministic method developed by UPC Labson



Demonstration Software **Life-SN**



Summary of IFTR work

- **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).

Exploitable results

- 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

IFTR work plan

		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.

Use of resources

		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