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## Numerical simulation of HELICOFLEX<sup>R</sup> metallic gasket ageing mechanism for spent fuel cask

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# Numerical simulation of HELICOFLEX® metallic gasket ageing mechanism for spent fuel cask

Workshop sealing 2016  
October 14<sup>th</sup>, 2016 - Paris

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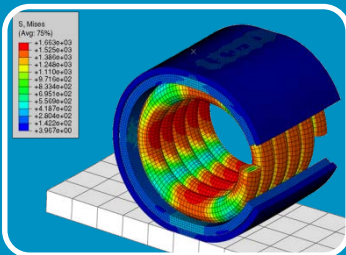
## Introduction

- Context & Objectives
- Ageing tests methodology



## Experimental database

- 100,000 hours ageing tests results
- Analytical processing



## Numerical simulation

- Numerical model presentation
- Results & Discussion



## Cooperation Agreement Relating to Ageing of sealing performances



## Objectives:

Metallic seals ageing tests are carried out since 1999 to assess their behavior for long periods for spent fuel storage casks.

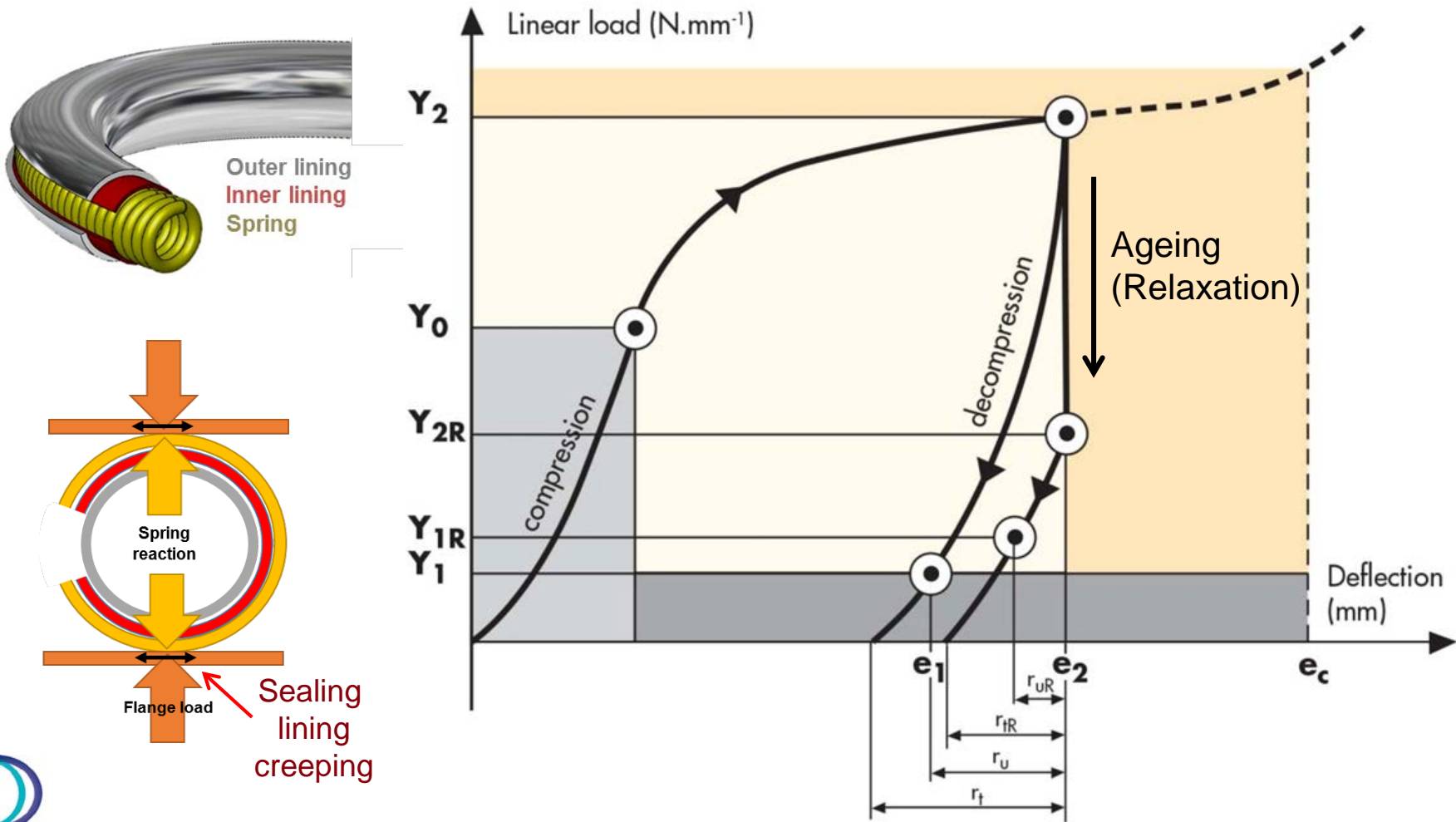
## Method:

Accelerated ageing tests of seals at higher temperature.

- More than **100,000 h** ageing tests at 20, 100 and 200°C
- Residual linear load measurement (Y2R).
- Statistical analysis : 120 mockups used, 444 points.



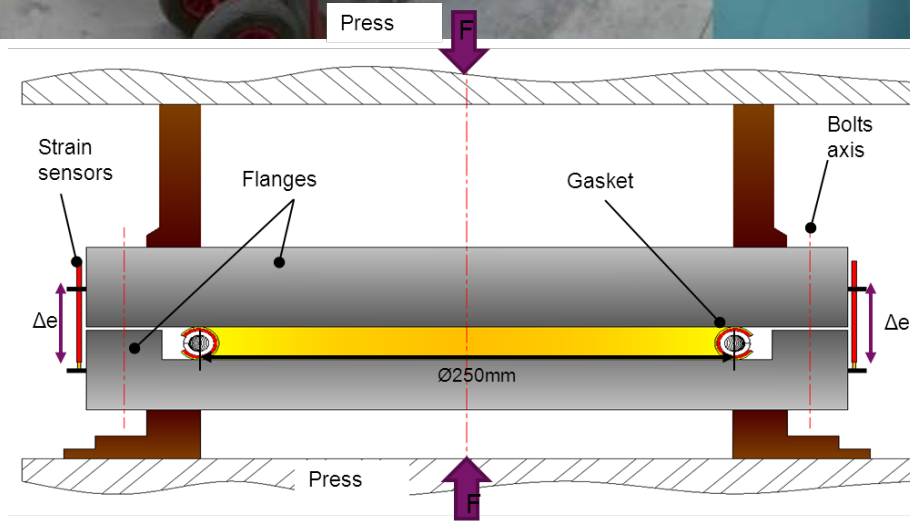
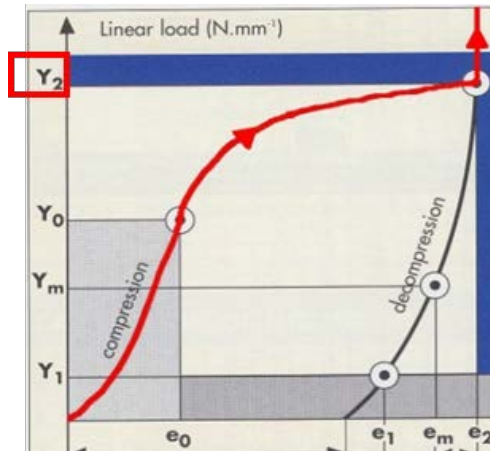
## Metallic seals ageing mechanisms:





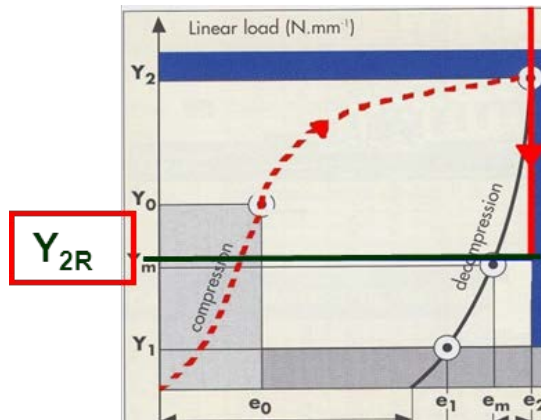


Measurement of the compression curve before ageing.





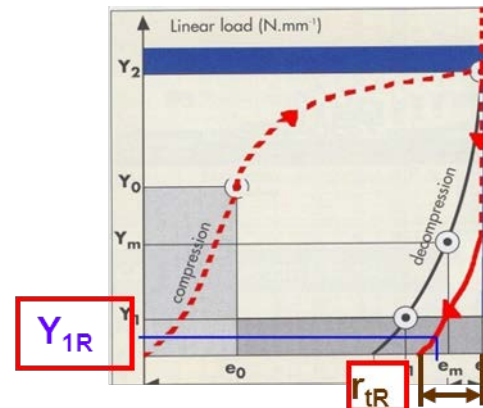
Ageing in ovens at RT, 100 and 200°C  
up to 100,000h.



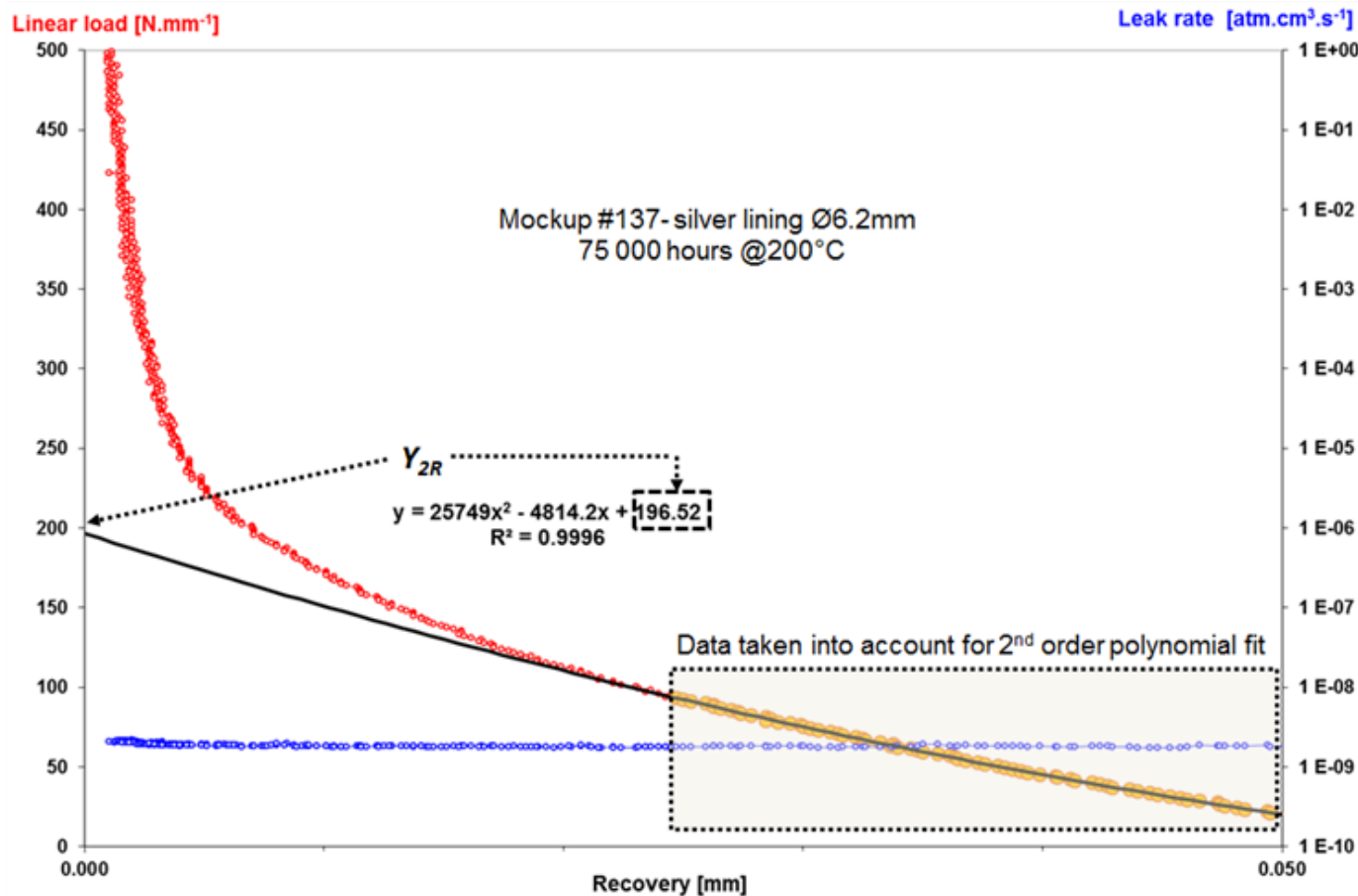




Measurement of the decompression curve after thermal ageing.





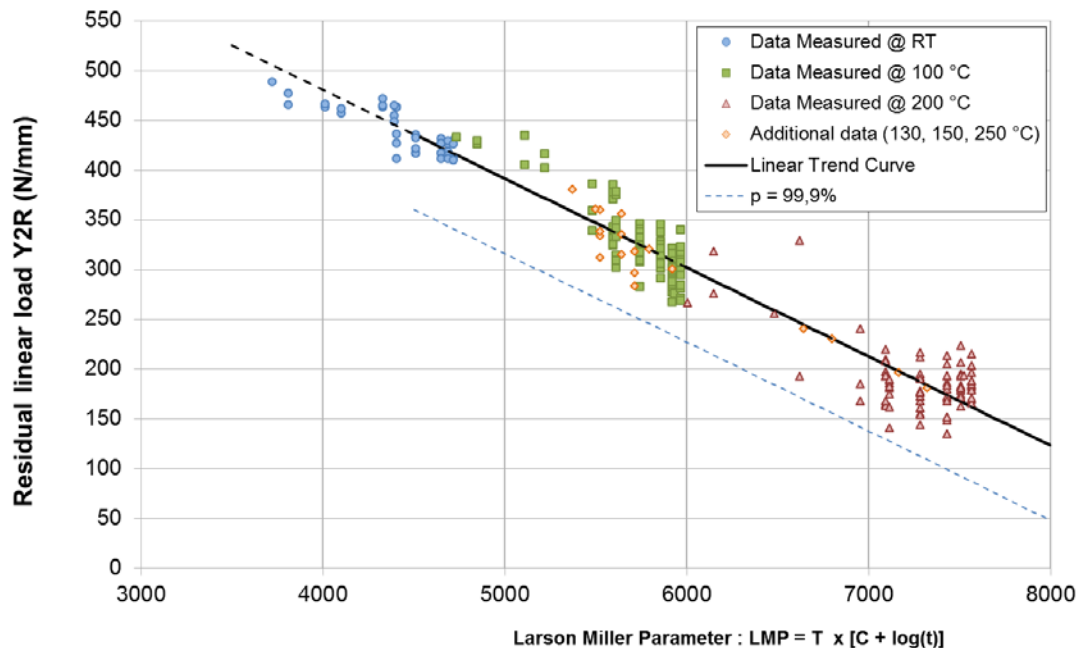


Example of  $Y_{2R}$  determination: mockup#137, Ø6.2 mm section silver lining seal held at 200°C for 75,000 h. Blue curve: leak rate measurement. Red curve: residual seal loading.

## Available database related to 100,000 hours ageing tests

- Mock-up tightening on instrumented press device
- Accelerated ageing in ovens
- Unloading with instrumented press (@ RT, partial opening on regular time base)
- Tightening and further ageing...
- Time & Temperature equivalence suggested using Larson Miler Parameter :

$$\text{LMP} = T \times [C + \log(t)]$$



Ø8.4 mm silver seals tests results

### Ageing Temperatures :

- RT
- 100 °C
- 200 °C

### Ageing durations :

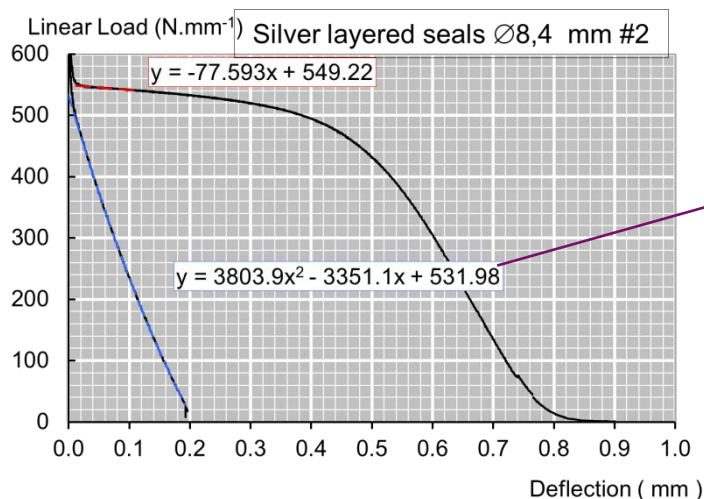
- 10,000 hours
- 25,000 hours
- 50,000 hours
- 75,000 hours
- 100,000 hours

### Facts :

- Metallic seals have a complex behavior during ageing :
- Seal compression is constant → Seals relaxation
- Creep of the silver jacket
- Non-linear spring-back reaction

### Idea : Consider a polynomial spring back

Initial compression/unloading test :



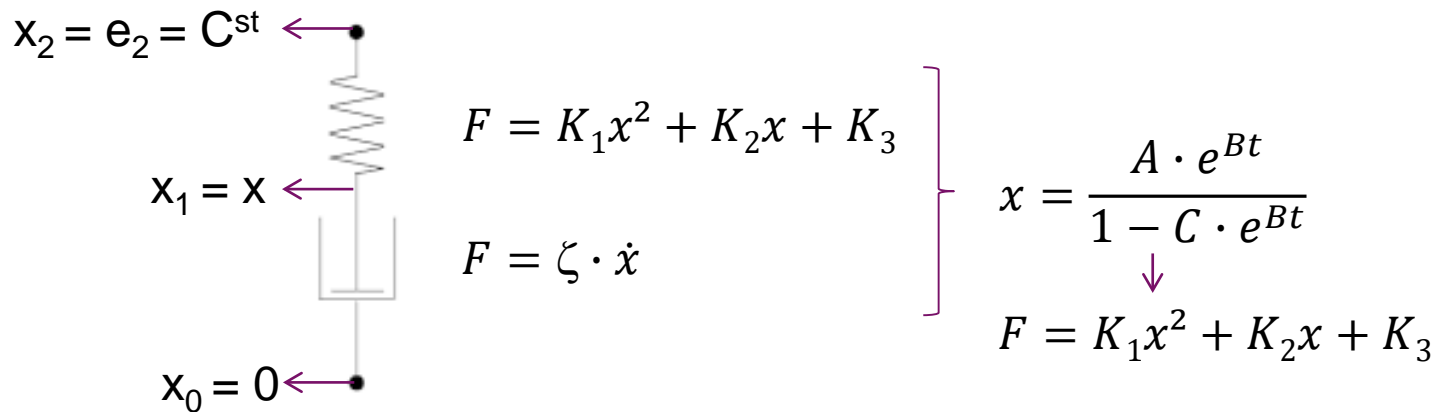
$$F = K_1x^2 + K_2x + K_3$$

$$F = \zeta \cdot \dot{x}$$

$F$  : Linear load  
 $x$  : Displacement  
 $K_1, K_2, K_3$  : Non linear stiffness factors  
 $\zeta$  : Damping coefficient

### Idea : Consider a polynomial spring back

Model presentation :



Coefficients optimization : A, B, C,  $K_1$  &  $K_2$  ( $K_3 = 185$  N/mm)

Use a gradient algorithm (Python)

Result depends on guess parameters

→ Need to apply a genetic algorithm (ongoing)

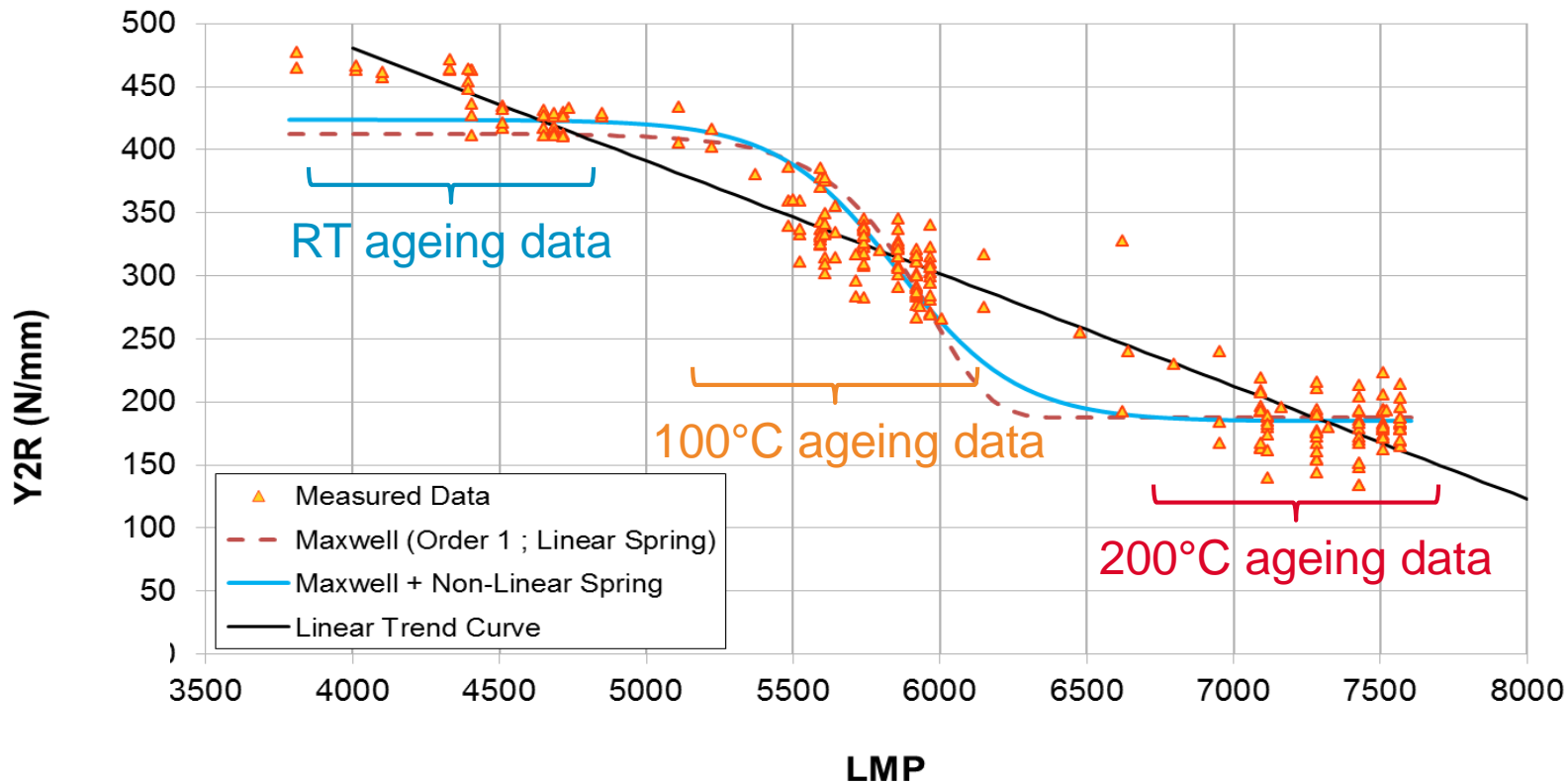


## LMP-Generalized Maxwell relaxation model

Relevant with RT data : increase the database

Standard deviation = 30 N/mm

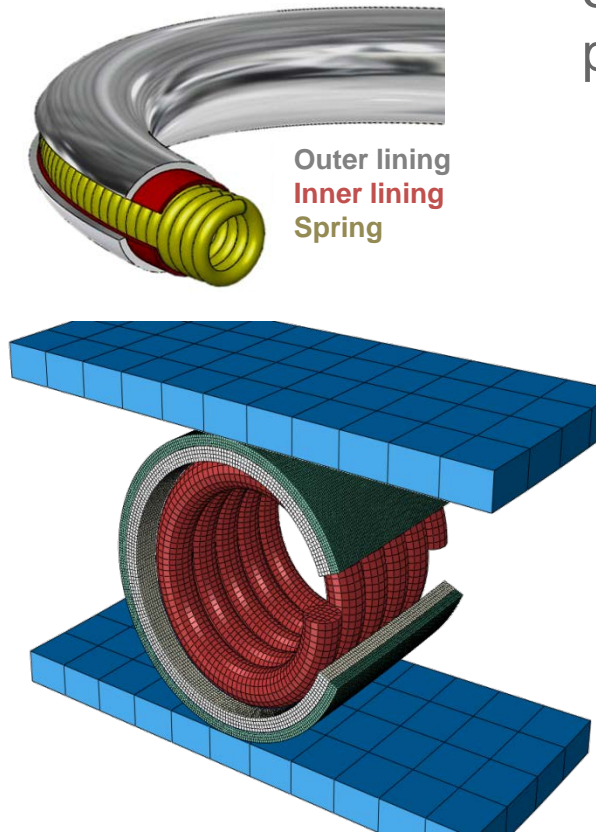
→ Need to increase data @ intermediate steps



## Discussion on tests results :

- Changes in seals designs and materials affect:
    - “C” constant of LMP
    - Linear trend curve of ageing
  - In some cases, linear trend curve does not describe properly behavior at shorter times (data at RT)
- Seal simulations using FEA approaches would be required to assess :
- Behavior in various ageing scenarios
  - Behavior of different seals designs

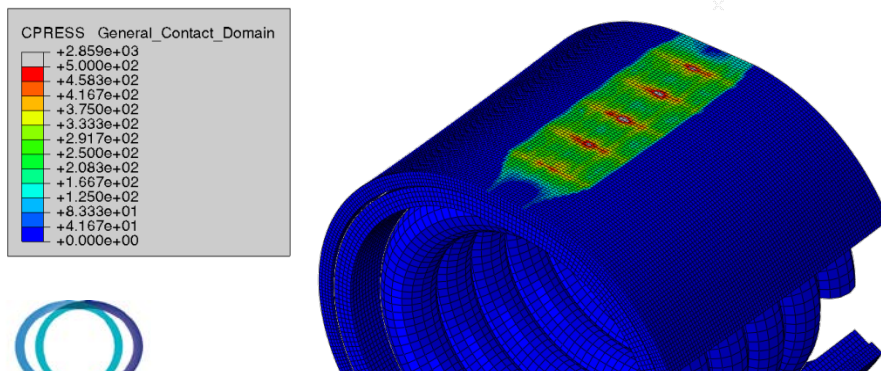
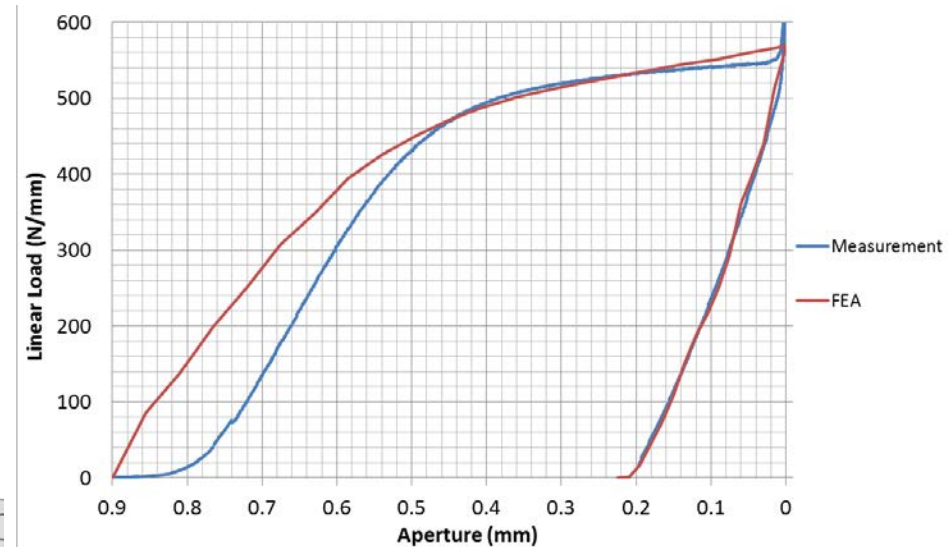
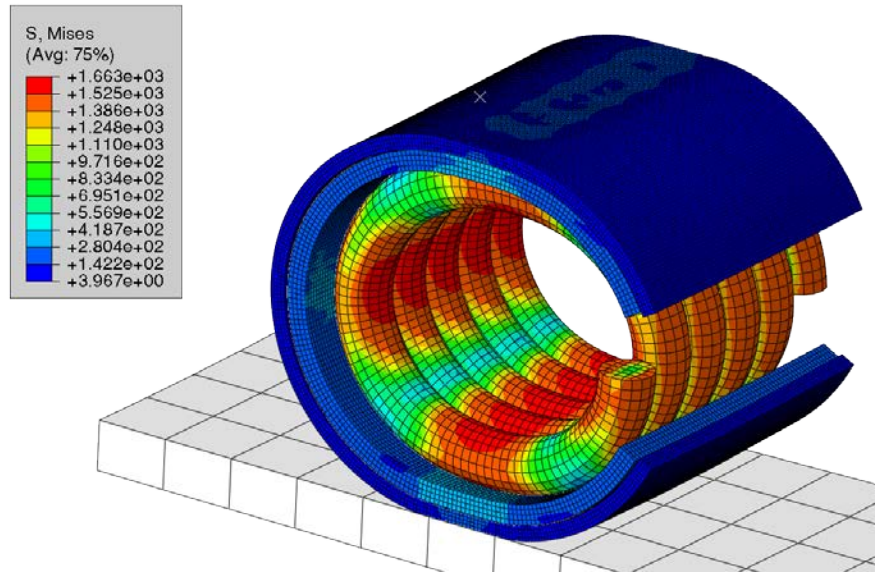
## Seals Tightening simulation



3D Model of HELICOFLEX® is used for a better precision

- Elastic-Plastic behavior for each component
- Perfectly rigid flanges
- Spring made of 5 Coils considered
- Faces of spring coupled  
(reproduce cyclic symmetry)
- Symmetry along r-z plane of jackets
- Contacts between each bodies with Friction
- Explicit simulation help to solve convergence issues related to contacts management

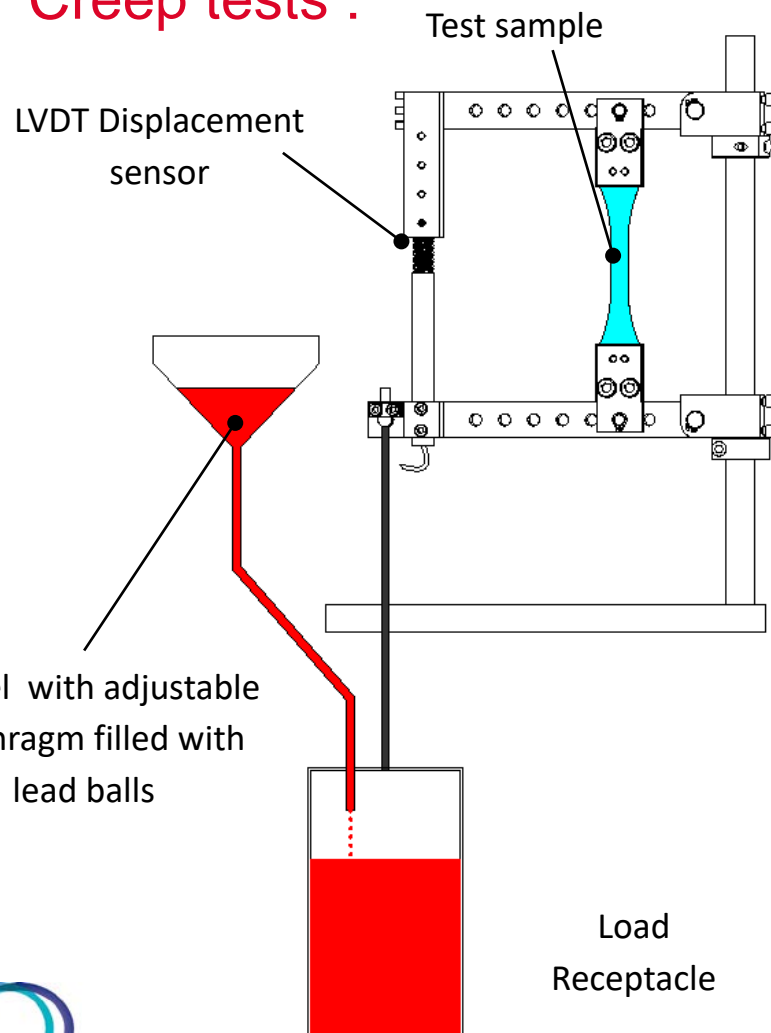
## Seals Tightening simulation



- Good correlation of simulations / tests
- Influence of geometric tolerances & material behavior



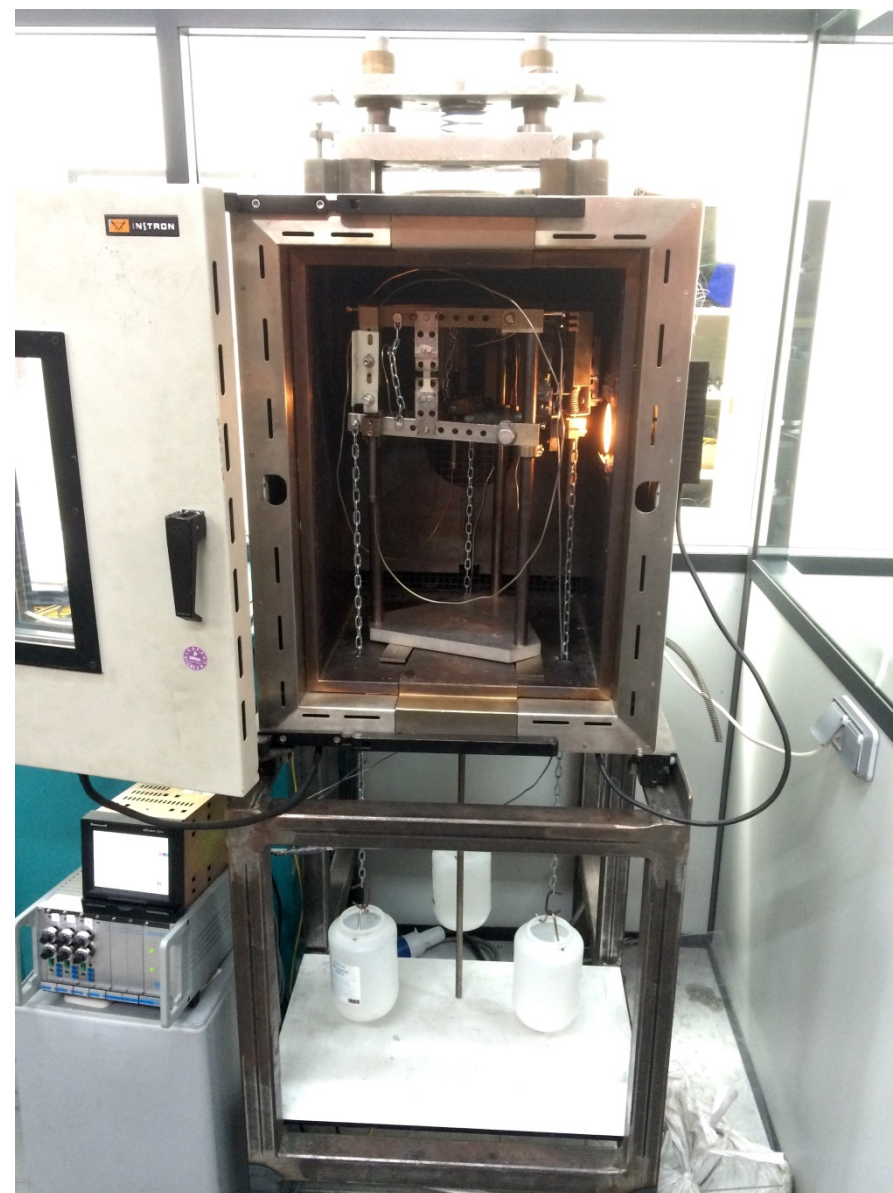
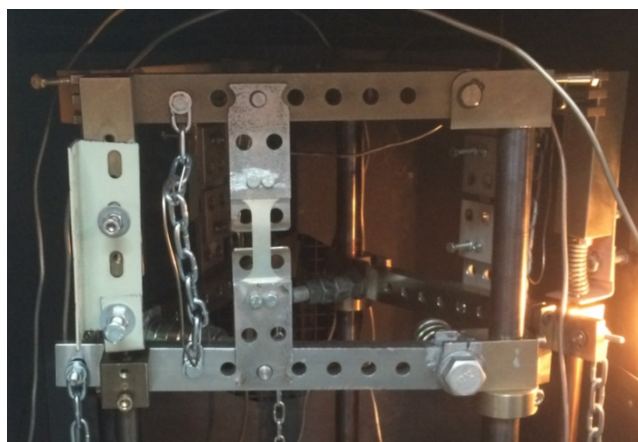
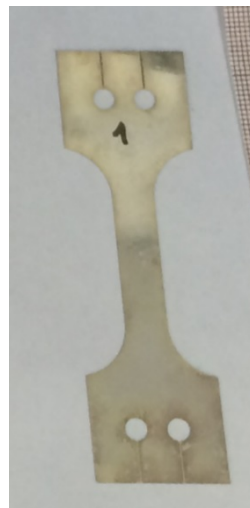
## Creep tests :



- Samples loaded progressively by gravity with  $\varnothing 2\text{mm}$  lead balls
- Sample installation (check LVDT sensor measurement range regarding expected elongation)
- 3 samples are tested simultaneously
- Heating in oven
- Small pre-Loading applied (to suppress initial gaps)
- Loading



Creep tests :

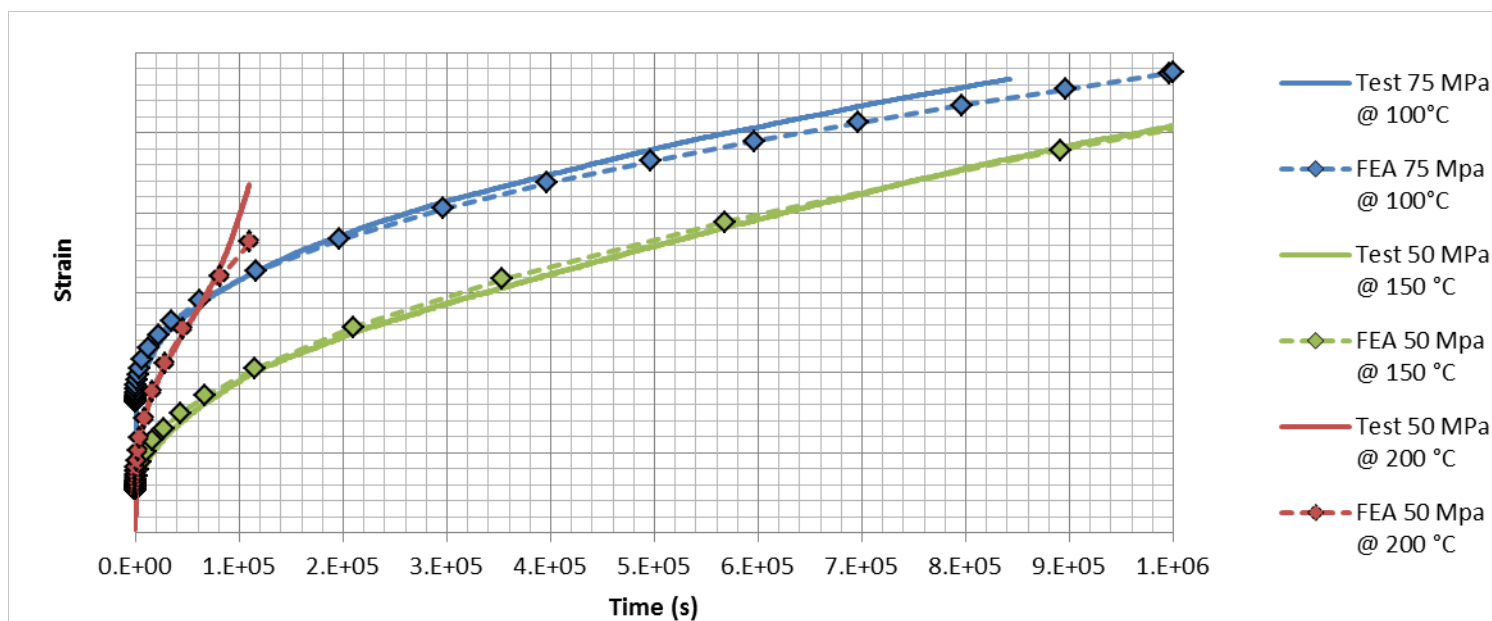


## Tests analysis

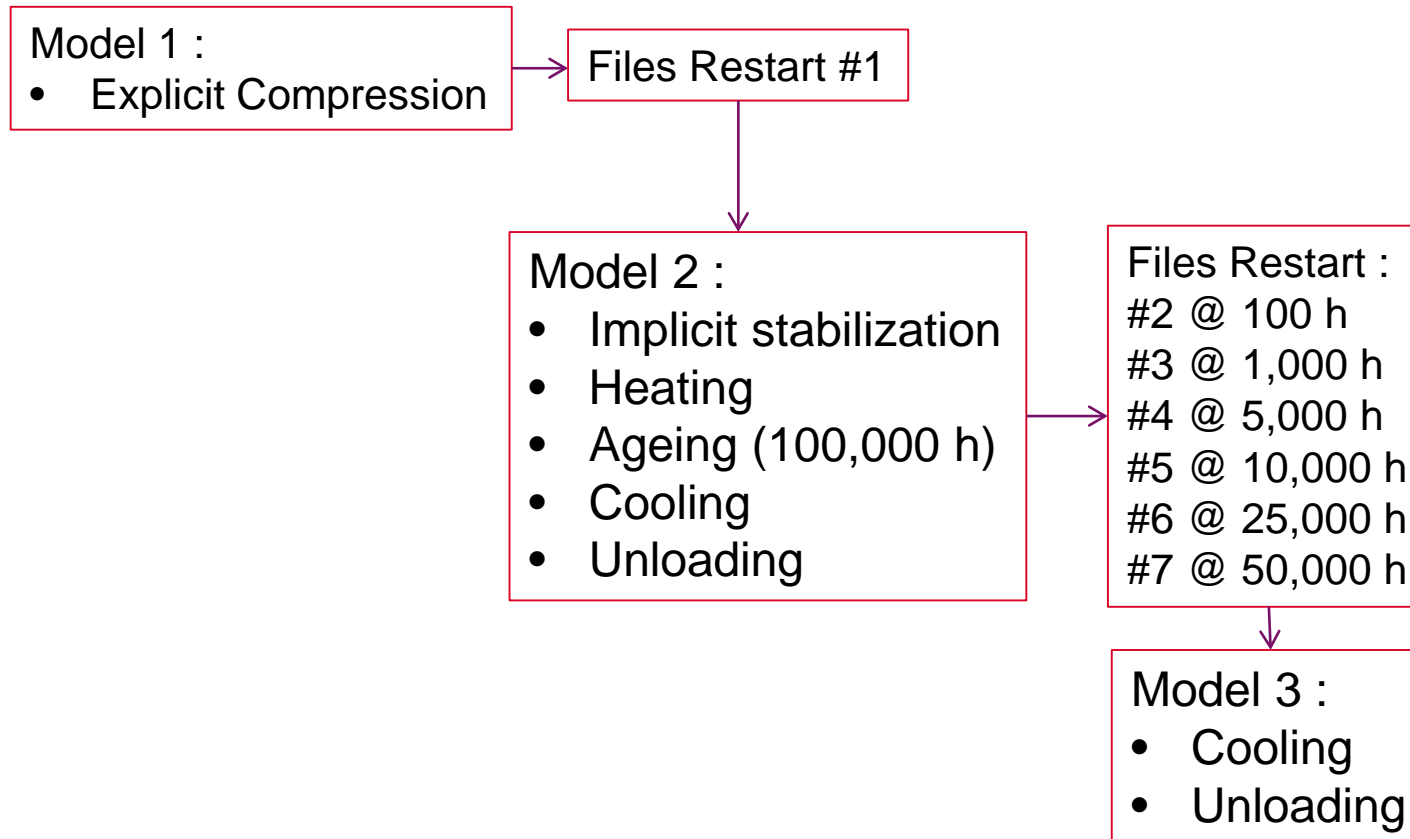
Creep law coefficients ( $C_1$ ,  $C_2$ ,  $C_3$ ) are fitted according to tests data

$$\dot{\varepsilon} = C_1 \cdot \sigma^{C_2} \cdot \varepsilon^{C_3}$$

- 3 Samples / Tests conditions
- 3 Stresses
- 4 Temperatures : 50 °C ; 100 °C ; 150 °C ; 200 °C



## Methodology for Finite Elements Analysis

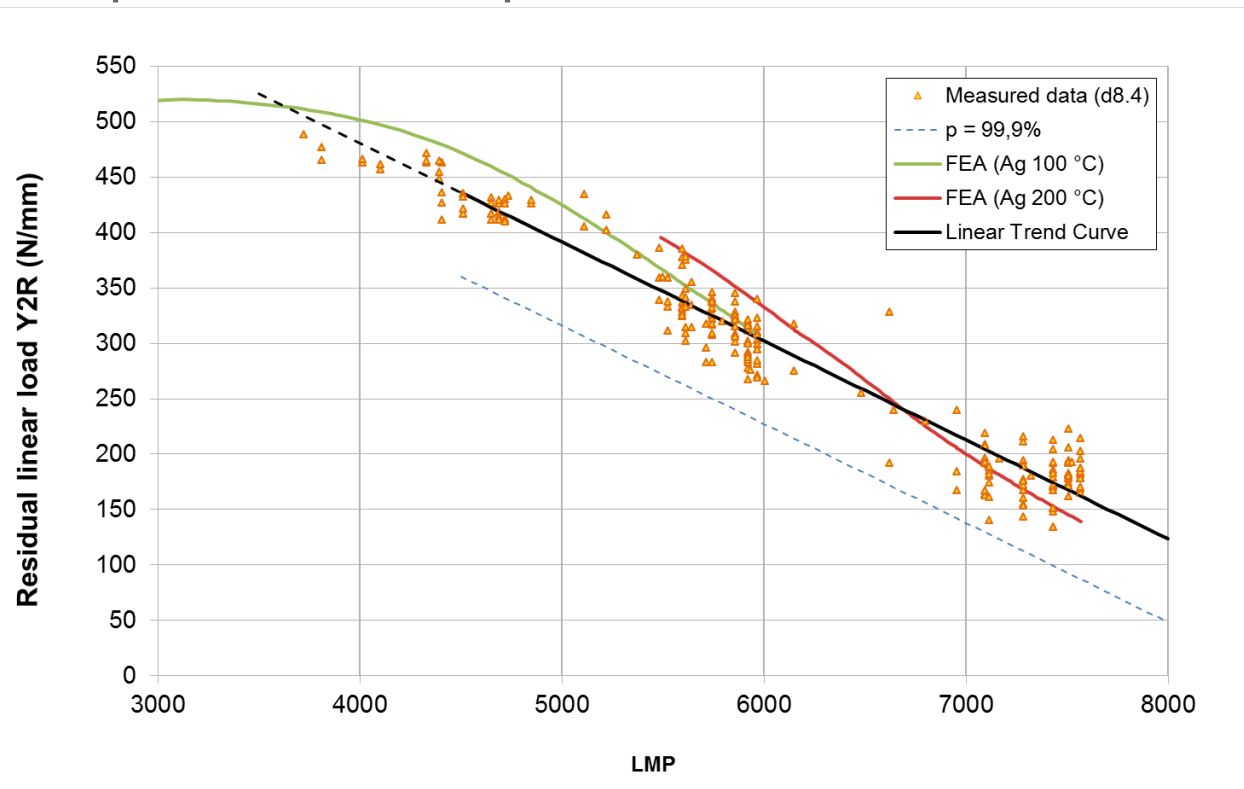




## Results

- Y2R drop as a function of LMP remains convenient  

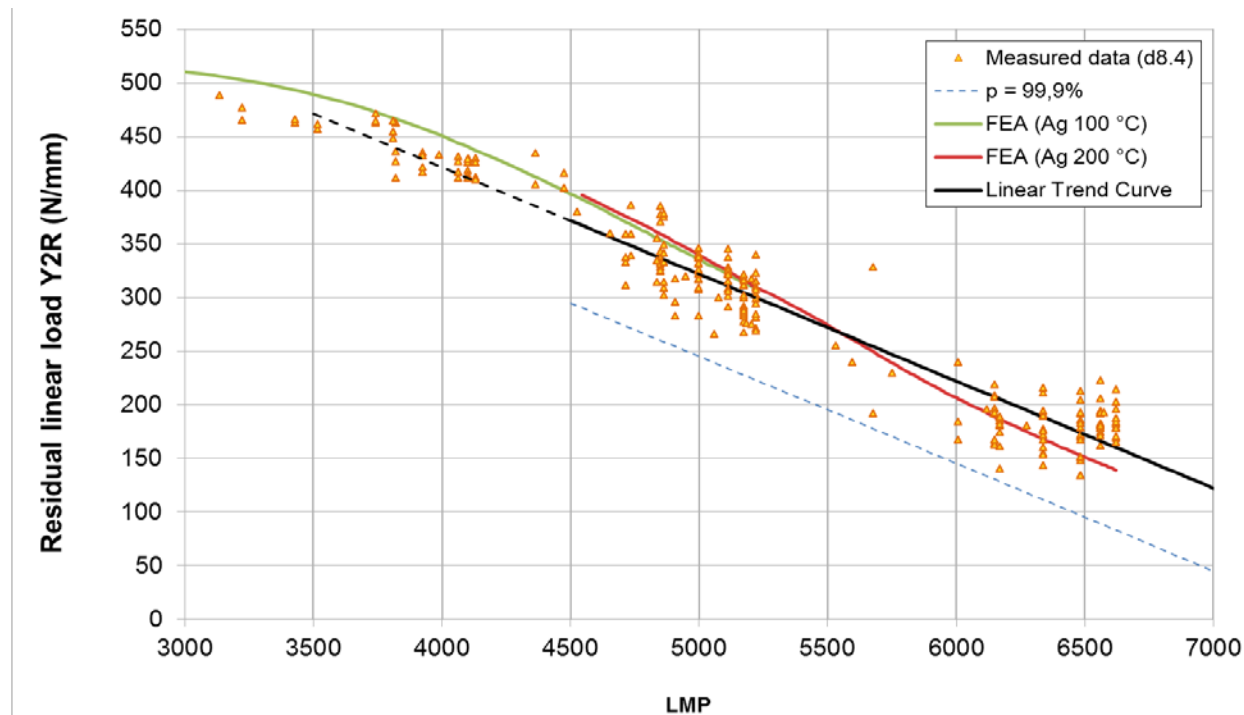
$$LMP = T \times [11 + \log(t)]$$
- Comparison with experimental data is consistent



## Results

- Adjustment on “C” constant improve calculated curve continuity using LMP Time-Temperature equivalence  

$$LMP = T \times [9 + \log(t)]$$
- This adjustment increases maximum ageing temperature



## Results

Maximum ageing temperature to keep Y2R above threshold in 99.9 % cases after **60 years**

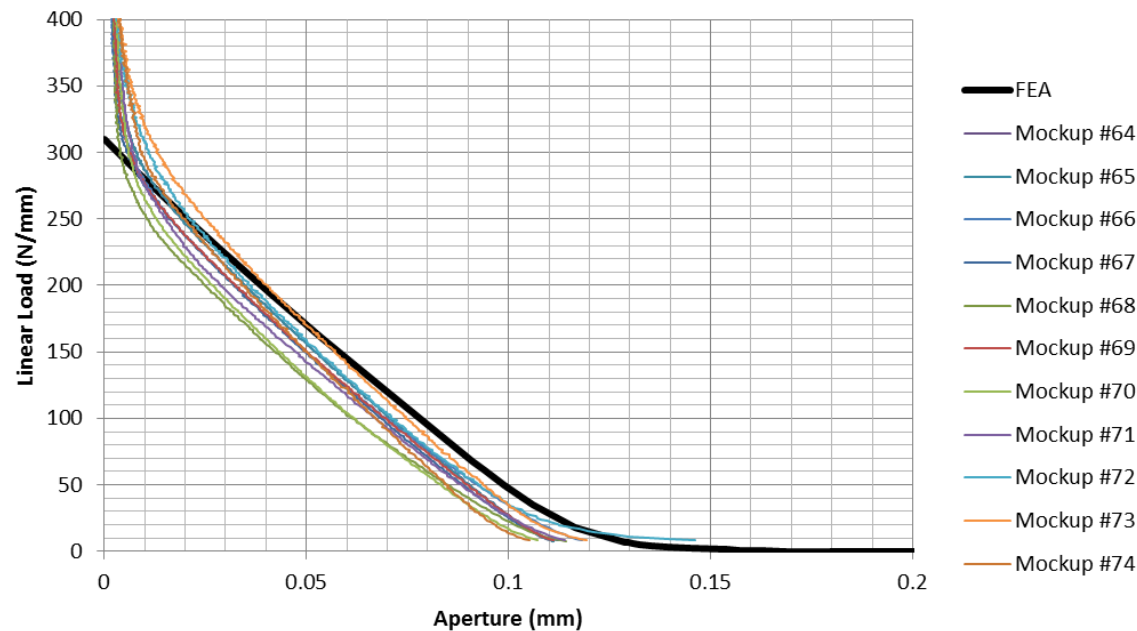
Y2R (N/mm)	C = 9	C = 11
0	233 °C	168 °C
20	219 °C	155 °C
50	199 °C	135 °C

Maximum ageing temperature to keep Y2R above threshold in 99.9 % cases after **100 years**

Y2R (N/mm)	C = 9	C = 11
0	225 °C	162 °C
20	212 °C	149 °C
50	192 °C	130 °C

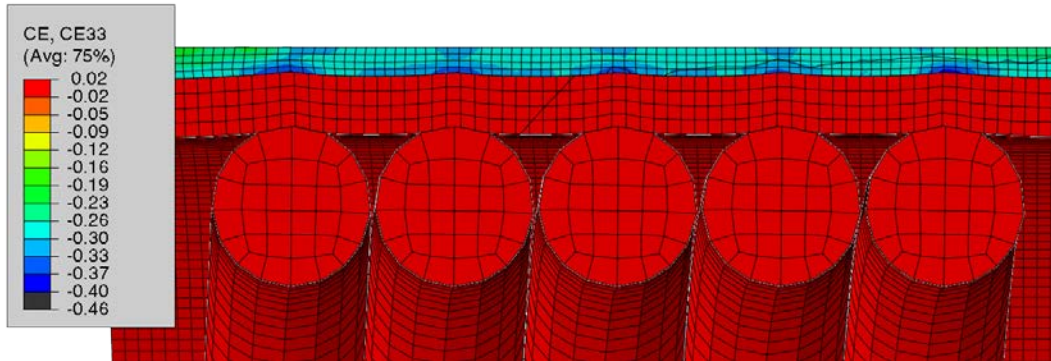
## Results :

- Calculated spring back curve after 100,000 hours ageing is consistent regarding experimental curves
- Mock-up stiffness is not included yet in this model :  
a 15  $\mu\text{m}$  deflection is expected



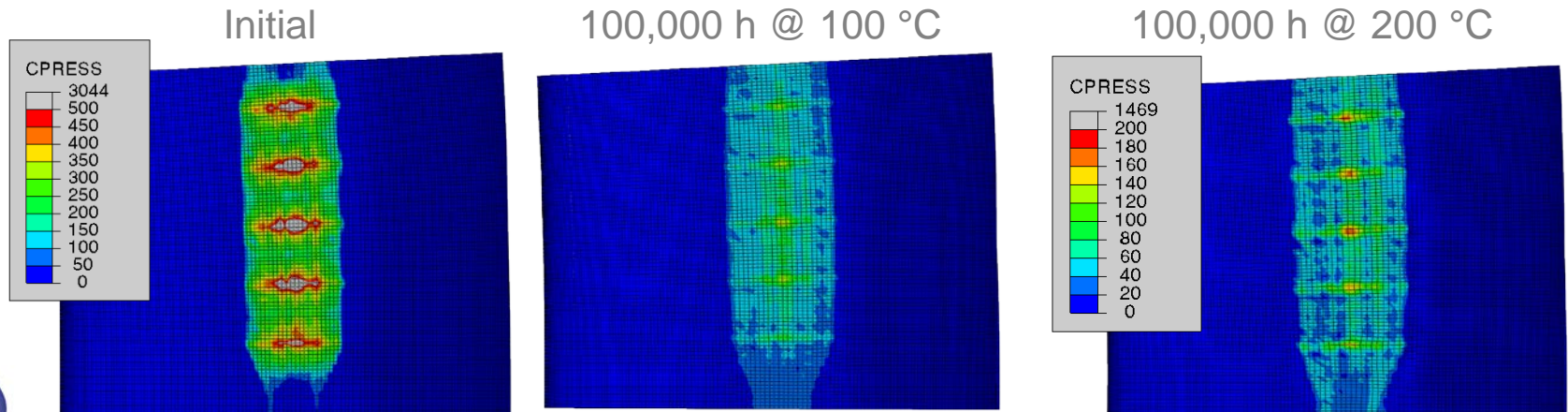
## Results

- Analysis of jackets deformation and contact pressure evolution



Creep strain in axial direction  
after 100,000 h @ 200 °C

## Residual contact pressure (MPa)





## CONCLUSIONS

A numerical model of HELICOFLEX® seals with ageing is available

Comparison with experimental data highlight its relevance to analyze:

- Compression/Spring-back
- Residual Linear Load (Y2R) drop due to ageing
- Residual Spring back (RtR) drop due to ageing
- Influence of ageing scenario (temperature, time...)

This approach provide :

- Possibility to extrapolate experimental results to different seals design and ageing scenarios
- Explanation & Complements on ageing tests procedure and analysis
- New information on aged seals behavior (spring-back, deformations, contact width, contact pressure...)

## Conclusions & Outlooks

- Materials behavior is now the main key to improve the simulation reliability

→ Creep tests are performed

- Simulations results and seals behavior are sensitive to:
  - Manufacturing tolerances
  - Dimensions scattering
  - Material behavior scattering
  - Uncertainties

→ A sensitivity analysis would be required to address reliability using FEA



ありがとうございます

Danke schön !

Merci !

Thank you for your  
attention !

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