Influence of the storage conditions on the reliability of overpacks for high level radioactive waste

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Context of the thesis

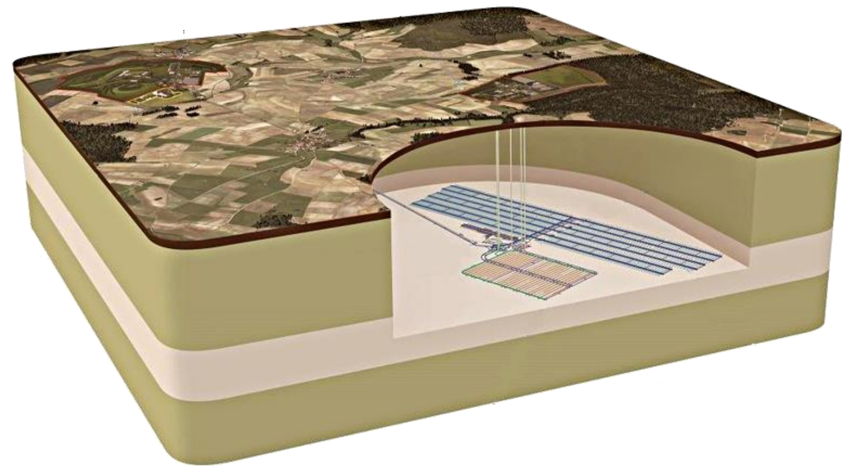
- Early stage of a French industrial project for radioactive waste long-term management
- The lack of data from similar projects and the time scales involved (several centuries) induce a lot of uncertainties

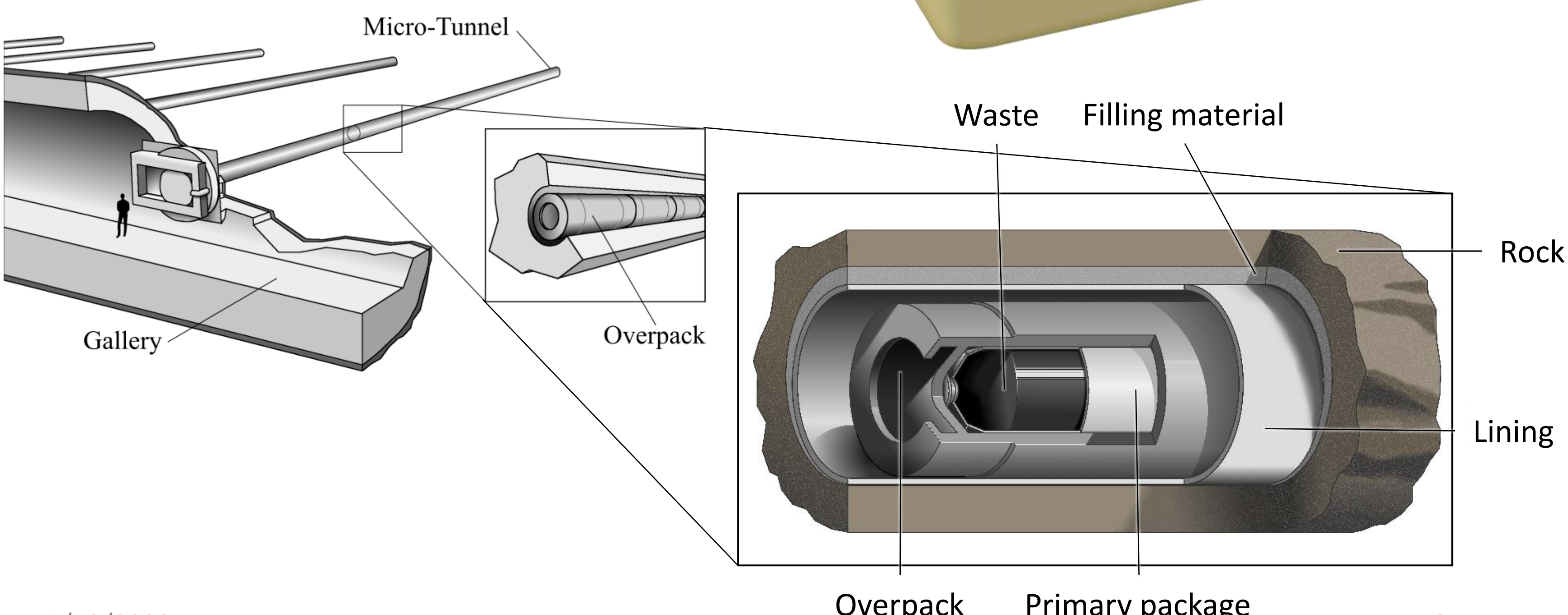
- The thesis is focused on high level radioactive waste facilities
- It aims at:
  - taking into account the uncertainties associated with the system studied
  - estimating the reliability over time
  - finding the critical parameters (sensitivity analysis)

- It requires the complete deployment of the reliability approach:
  - definition of the probability distributions of the uncertain input parameters
  - development of a dedicated finite element model
  - choice of a failure criterion
  - implementation of a suitable reliability method
  - Sensitivity analysis

Framework and system

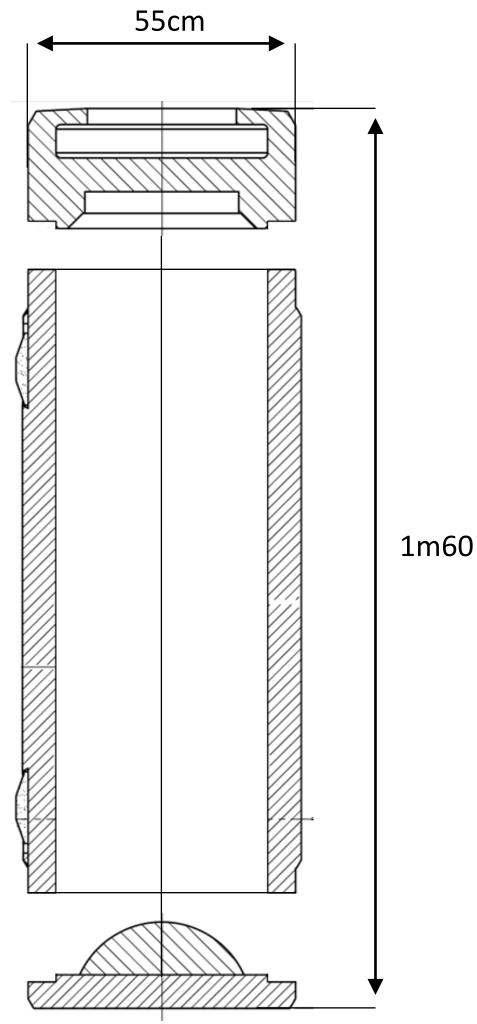
- French deep geological repository project (Cigéo)
- Facilities 500 m below ground
- Argillaceous rock





The overpack

- Purpose: Isolate the waste from the environment at least 500 years
- Non-alloy steel
- 3 forged parts welded



I. General modelling

II. Failure by crack propagation

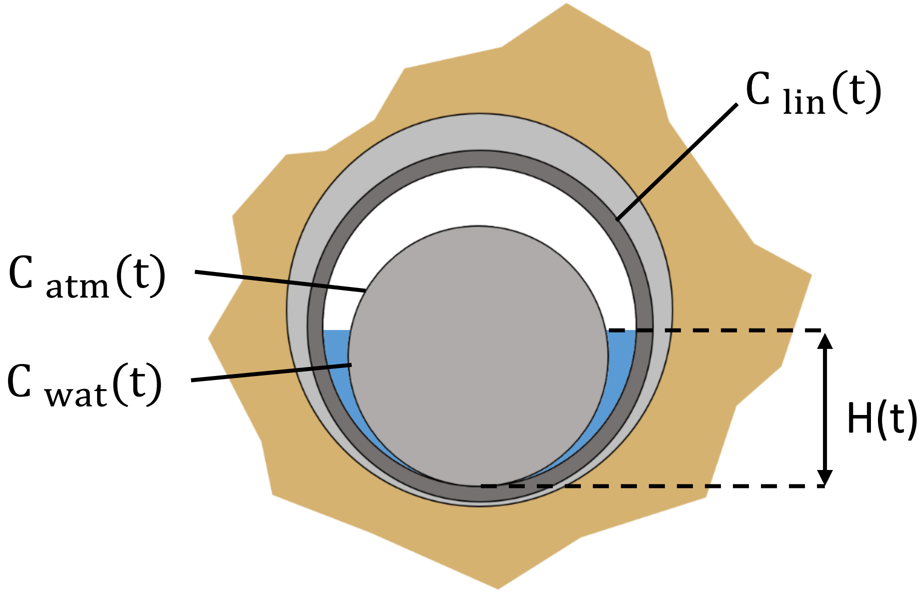
III. Failure by ductile fracture

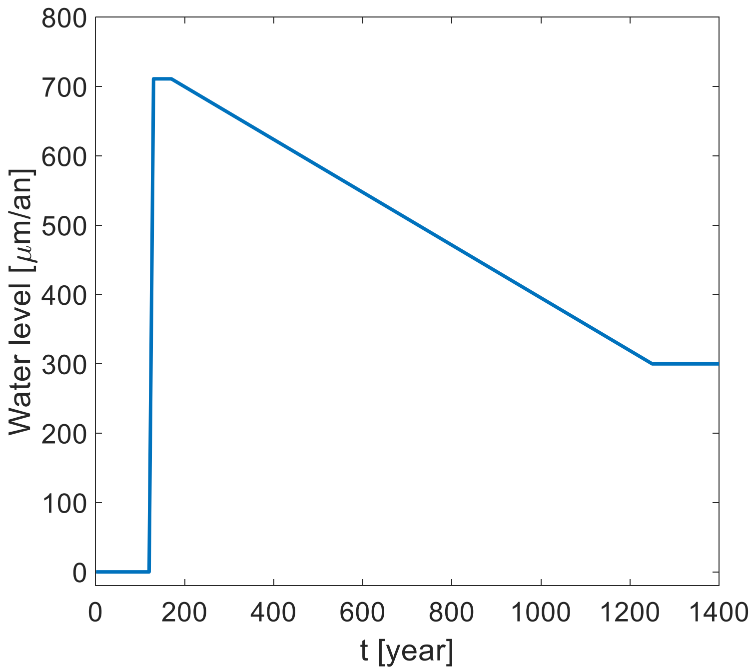
IV. Comparison of the two approaches

V. Conclusions

Modelling the corrosion

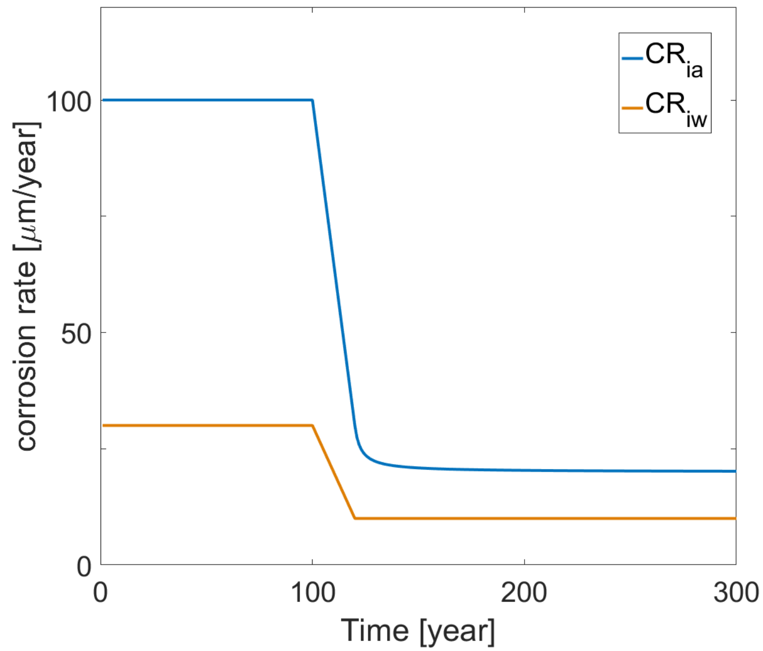
- Water diffusion through the rock
- Water level is time-dependent
- The corrosion rate depends, on the environment (water, atmosphere and saturated rock), and the time

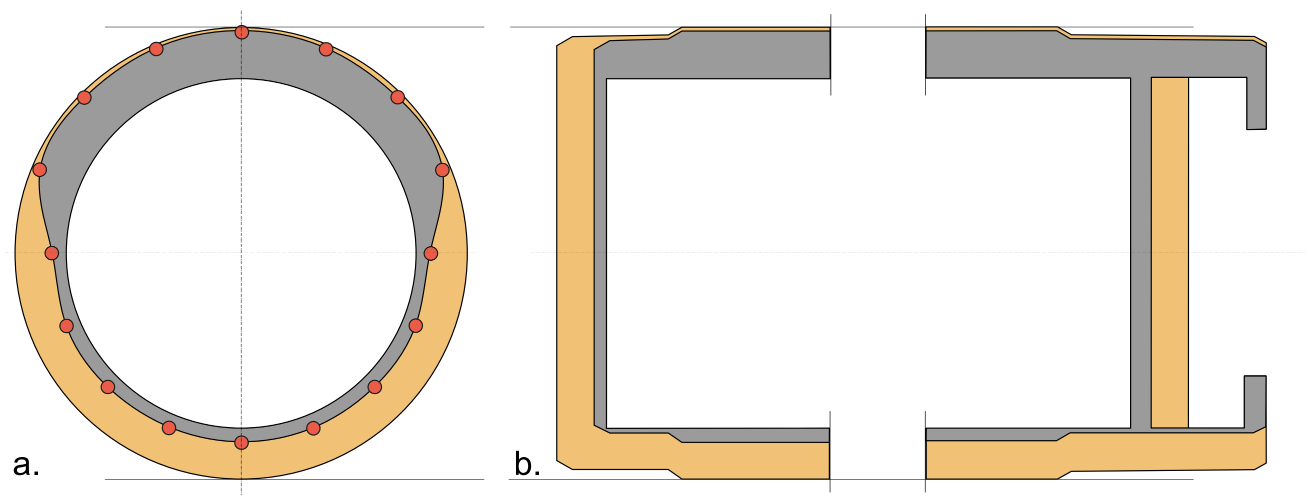




Modelling the corrosion

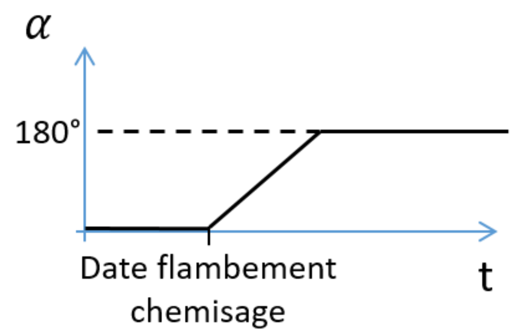
- The corrosion process is taken as a reduction of the thickness of the overpack
- The corrosion rate is time and environment dependent and is uncertain
- The geometry depends on the time and the corrosion rates

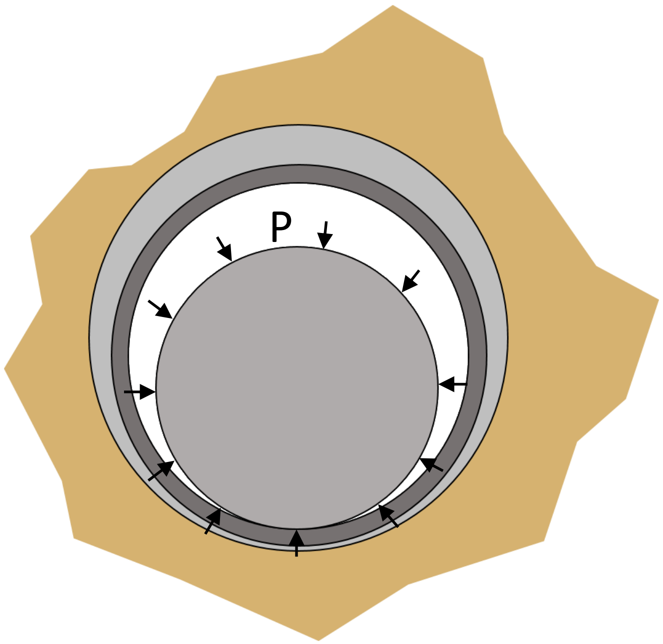




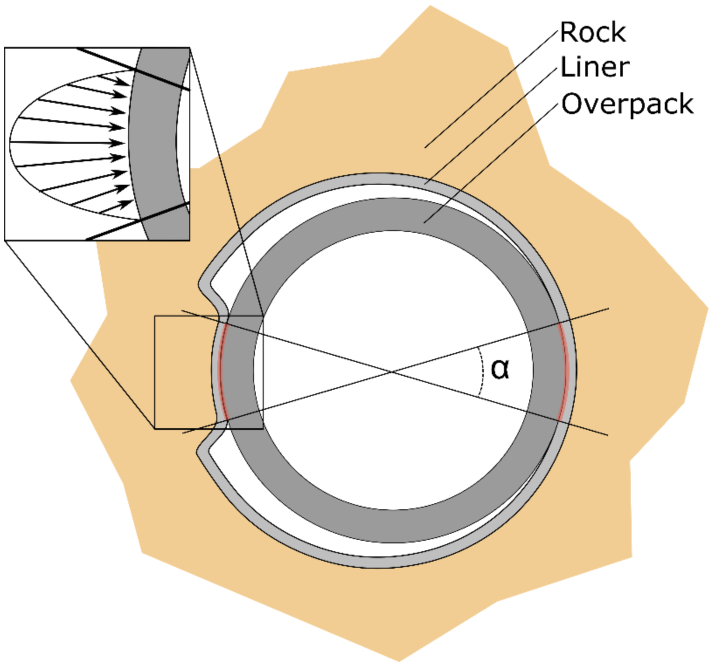
Modelling the mechanical loading

- Deterministic and steady fluid pressure
- The date of buckling of the lining depends on the corrosion rates and the rock pressure
- The contact areas between the buckled lining and the overpack are time dependent (contact angle α)
- The pressure transmitted to the overpack is uncertain





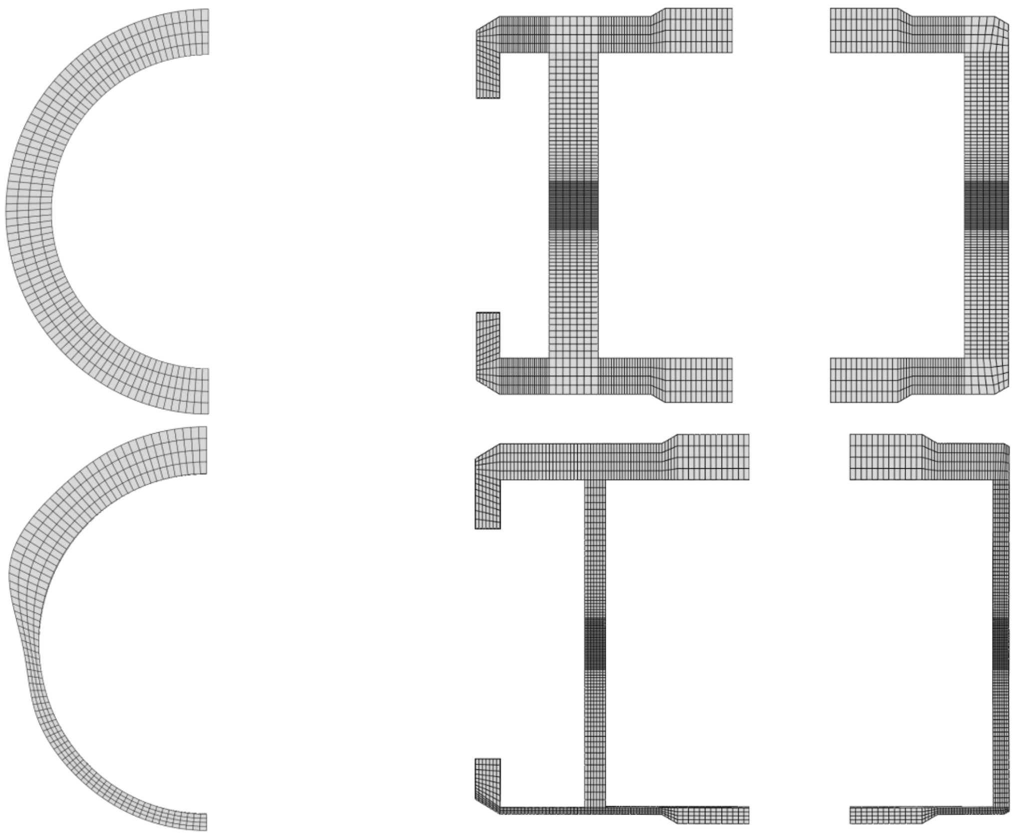
Fluid pressure



Contact pressure

Definition of the finite element model

- The system is time dependent and subjected to uncertainties
- Uncertainties affect the corrosion process and the mechanical loading
- The lifetime is discretized into a finite number of static analyses (every 100 years)
- The geometry and mechanical loading of each analysis are representative of state of the system at a given date



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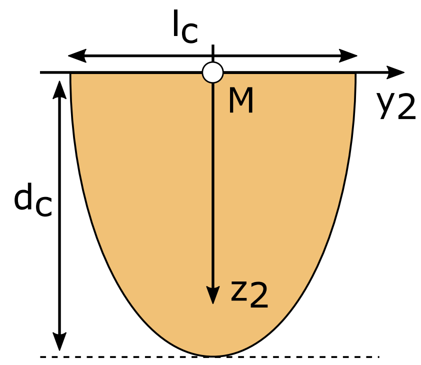
Failure criterion

- Model limited to the elastic behavior of the material
- The iterative analyses (one every 100 years) are all independent and can be evaluated individually
- A geometrical defect is considered at the surface of the model
- It is modelled as a surface semi-elliptical crack

- Two failure modes are considered:
  - Failure by corrosion : $d_{corr} \geq d_{ini}$
  - Failure by crack propagation: $K_1 \geq K_{1c}$

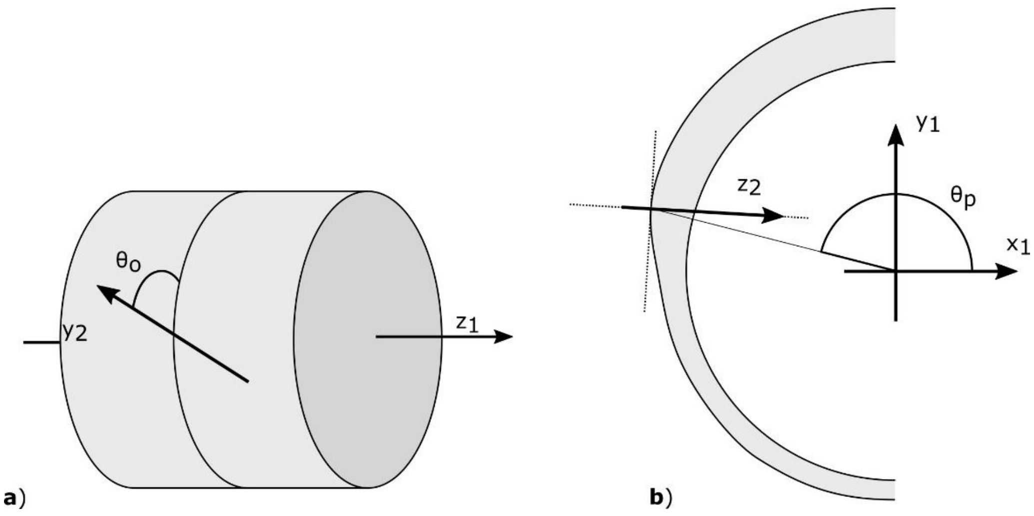


Simulation of an initial crack

- The crack is not included in the finite element model
- It is simulated by post-processing the results of the un-cracked model
- K_1 is estimated by empirical equations using the stress field around the crack location (Pommier et Al., 1999)

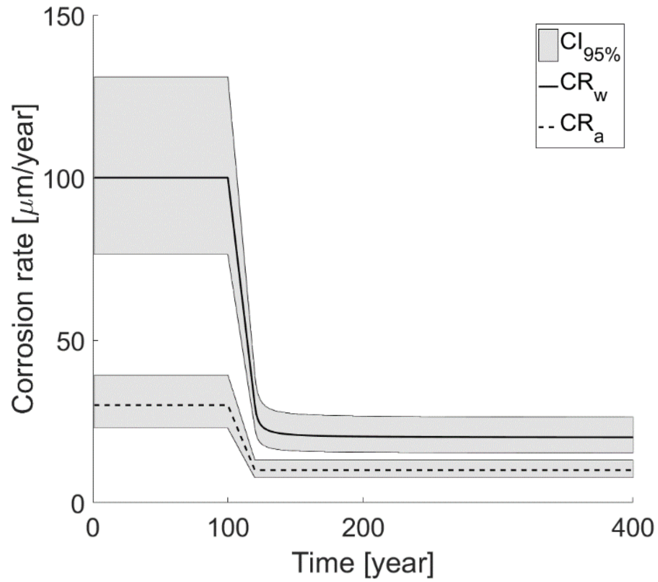
Deterministic parameters:
- Crack dimensions
- Longitudinal position

Random variables:
- Circumferential position (θ_p)
- Orientation (θ_o)
- K_{1c}



Definition of the probability distributions

- The corrosion rates are considered fully correlated in all environments and at all times
- The corrosion process is then associated with a unique random variable affecting all corrosion rates



- The uncertainties associated with the corrosion process and the mechanical loading are estimated by expert's judgement
- The experts provided a nominal evolution of the corrosion rates and intervals "containing" the uncertainty

Definition of the probability distributions

- The corrosion variable is chosen following a lognormal distribution such that 99,7% of the realizations fall in the elicitated interval
- The random variable associated with the rock pressure is defined using the same method (lognormal)
- The position and orientation angles of the crack have no privileged value
- They are defined following uniform distributions with an amplitude of 180°
- Not enough data is available for the fracture toughness, it is chosen by default following a normal distribution

Corrosion rate ~ log-normal
Contact pressure ~ log-normal
Crack position angle ~ uniform
Crack orientation angle ~ uniform
Fracture toughness ~ normal

Reliability methods

- The 5 random variables are divided into two sets based on the computing time required by their evaluation, $\boldsymbol{X} = (\boldsymbol{X_1}, \boldsymbol{X_2})$:
  - $\boldsymbol{X_1}$ the ones affecting the finite element model (corrosion, rock pressure)
  - $\boldsymbol{X_2}$ the ones affecting only the crack simulation (position, orientation, K_{1c})

- Monte Carlo simulations are carried out on two levels involving two different numbers of simulations:

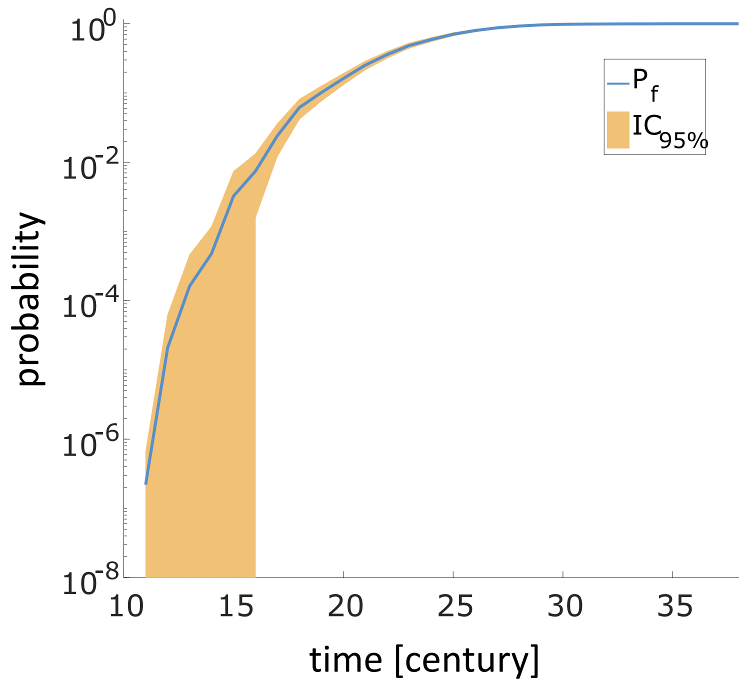
$$P_\mathrm{f} \approx \frac{1}{N_1 N_2} \sum_{j=1}^{N_1} \left(\sum_{k=1}^{N_2} I\left(\boldsymbol{X}_1{}^{(j)}, \boldsymbol{X}_2{}^{(k)}\right) \right)$$

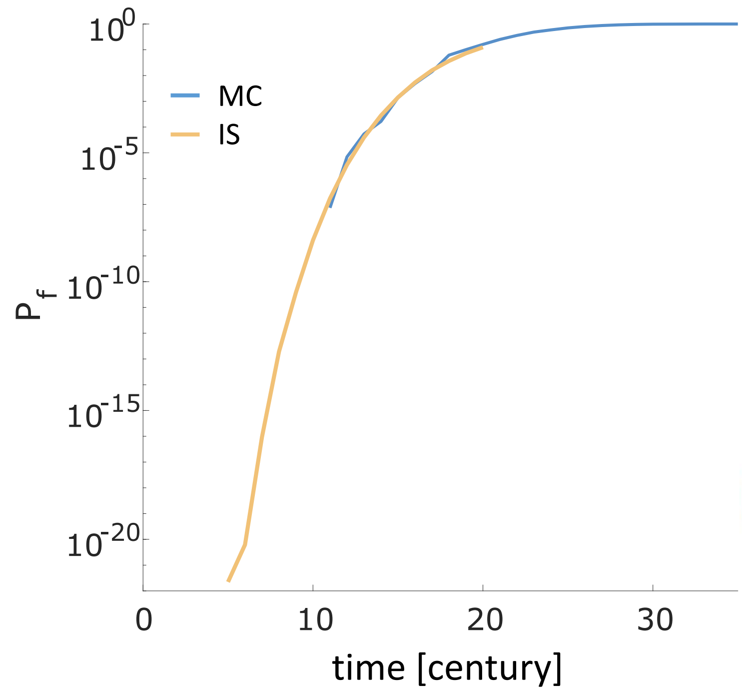
  - With 500 evaluations of the finite element model N_1
  - And for each one 100.000 crack simulation N_2

- The importance sampling method is also implemented to estimate the failure probability at 500 years (100 evaluations)

Estimation of the failure probability

- Failure probability at 500 years is too small to be estimated by the Monte Carlo simulations
- It is estimated around 10^{-22} with the importance sampling method
- A failure before 500 years is very unlikely





Sensitivity analysis

The sensitivity of the time to failure with respect to the input parameters is first investigated using a graphical Scatterplot method:

- plot the output as a function of each input individually
- In order to free one level of simulation from the second, the values for one level are averaged following the second one:

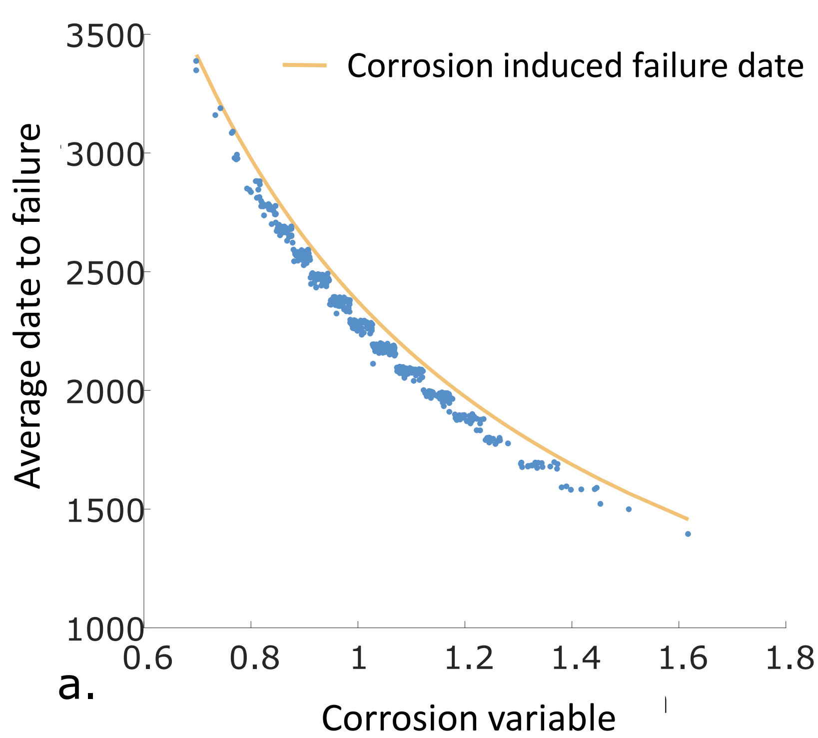
$$\bar{Y}(\mathbf{X}_1) = \int_{-\infty}^{+\infty} Y(\mathbf{X}_1, \mathbf{X}_2) \mathrm{f}(\mathbf{X}_2) \mathrm{d}\mathbf{X}_2$$

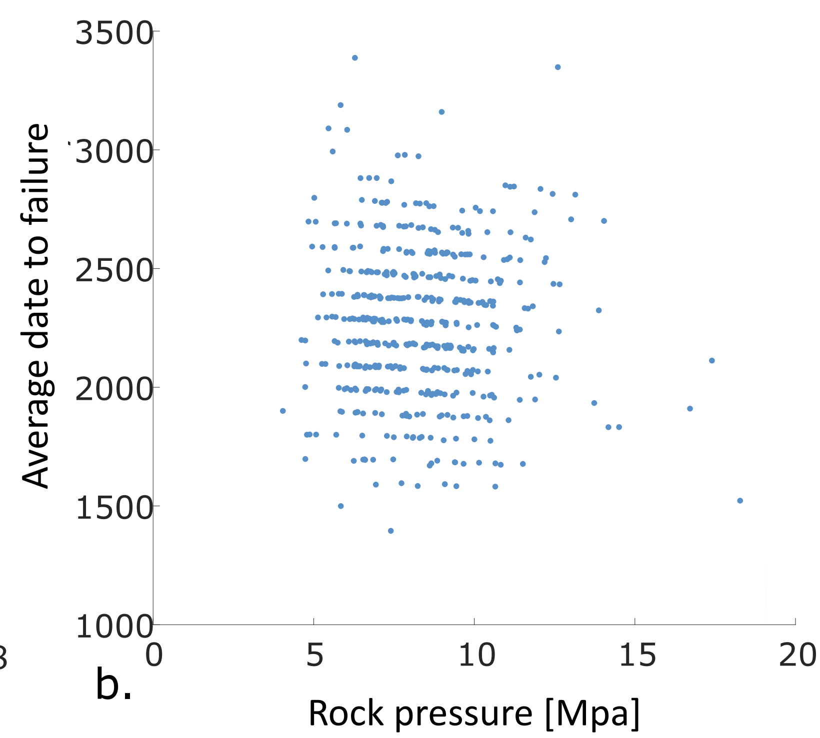
$$\bar{Y}(\mathbf{X}_2) = \int_{-\infty}^{+\infty} Y(\mathbf{X}_1, \mathbf{X}_2) \mathrm{f}(\mathbf{X}_1) \mathrm{d}\mathbf{X}_1$$

The first order Sobol’ indices are also calculated in order to get a quantitative evaluation of the sensitivity (double loop reordering method)

Sensitivity analysis

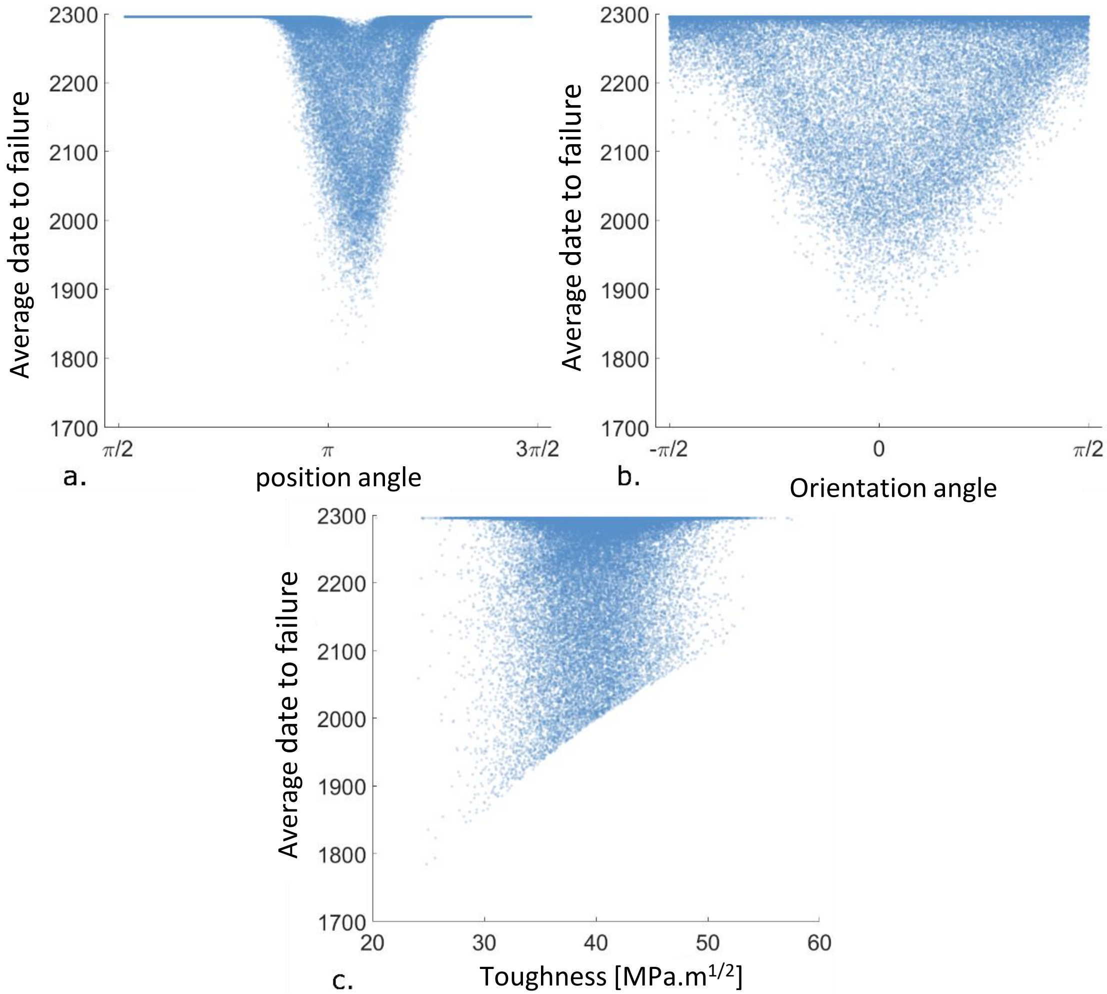
- The failure is mostly driven by the corrosion rate
- Considering only the corrosion gives a rather good but overestimated value of the lifetime





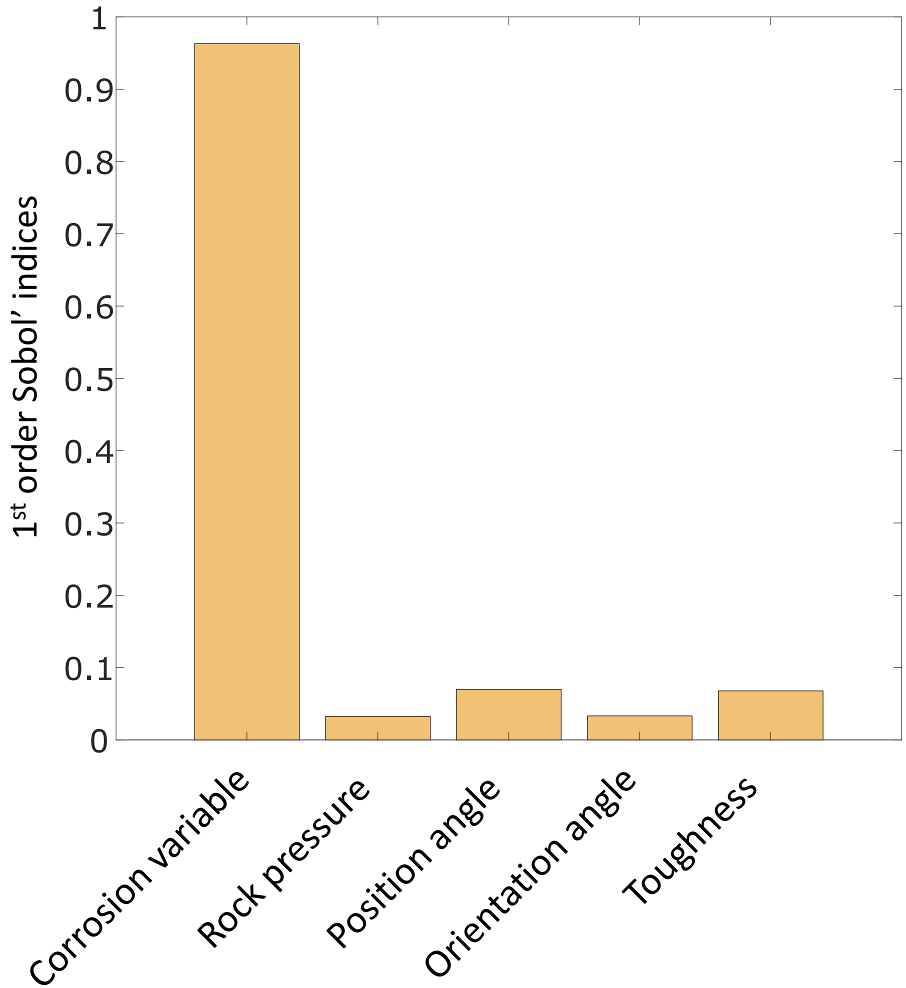
Sensitivity analysis

- Identification of a critical crack position and orientation
- Boundaries can be identified in figure c. but they depend on the variables of the finite element model



Sensitivity analysis

- Sobol’ indices (double loop reordering method)
- Failure is mostly driven by the corrosion process



Sensitivity analysis

- The sensitivity of the failure probability is also investigated with respect to the choice of the distribution (for the corrosion and pressure variables)
- The results of the Monte-Carlo simulations are reused to simulate the results associated with different distributions
  - The methods associate weights to each simulation in the calculation of the failure probability :

$$P_{\bar{f}} \approx \frac{1}{N} \sum_{j=1}^{N} I\left(\mathbf{X}_f{}^{(j)}\right) \frac{\bar{f}\left(\mathbf{X}_f{}^{(j)}\right)}{f\left(\mathbf{X}_f{}^{(j)}\right)}$$

  - Same principle as the importance sampling method
  - 3 Alternative distributions : Beta, triangular, log-triangular
  - 2 Alternative standard deviation for the reference log-normal distribution

Sensitivity analysis

- Influence of the choice of distributions:
  - Significant influence on the failure probability
  - The influence doesn’t seem to be strong enough to contradict the conclusions about the reliability at 500 years

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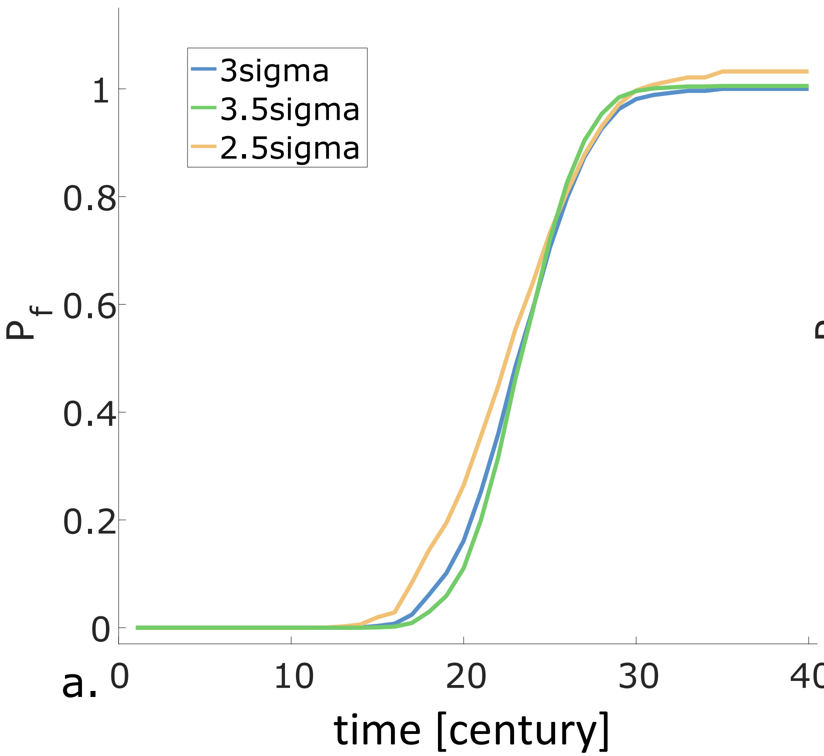
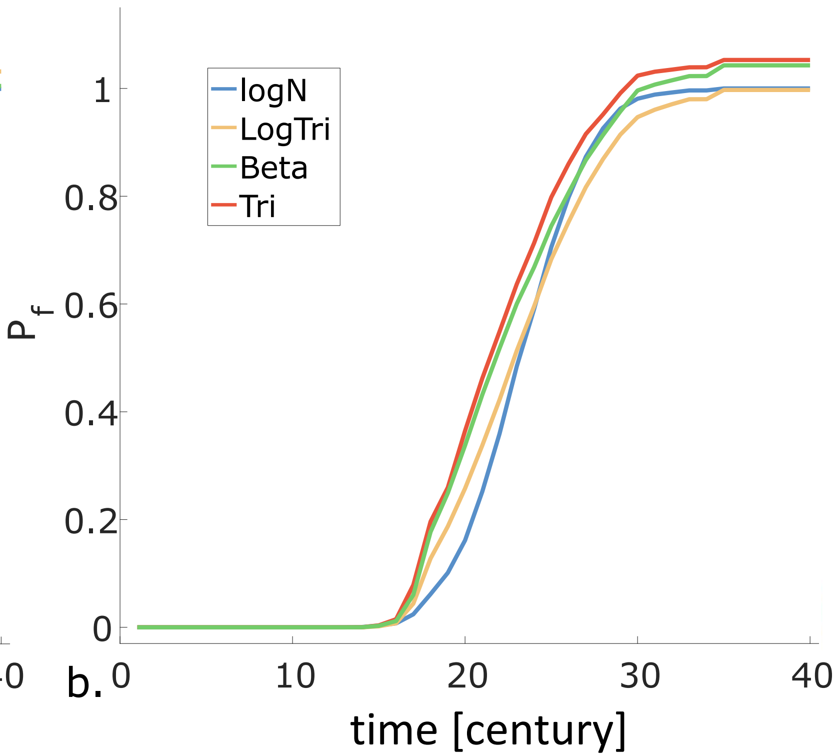


b.



I. General modelling

II. Failure by crack propagation

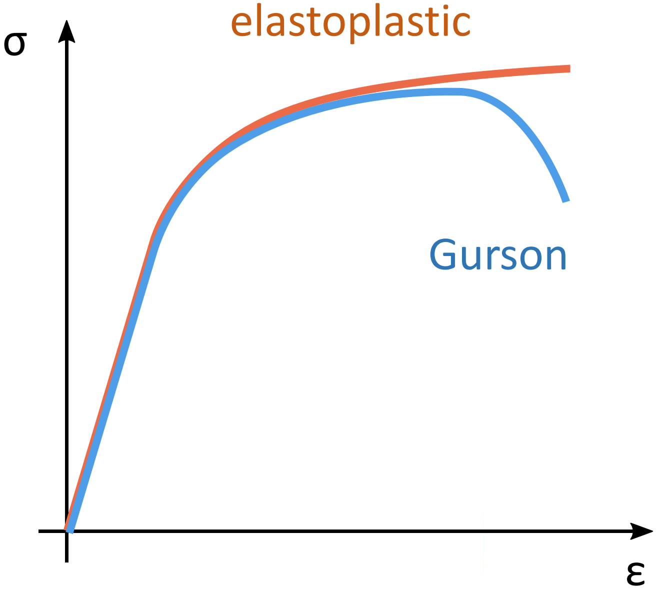
III. **Failure by ductile fracture**

IV. Comparison of the two approaches

V. Conclusions

Modelling the behaviour

- Gurson's damage model
- Ductile fracture criterion
- Lifetime is discretized into a finite number of static analysis
- Problem: dependency on the loading history



The model proceeds as follow:

- Apply a loading/unloading cycle
- Recover the plastically deformed mesh
- Apply the corrosion process to the deformed mesh
- Project the residual fields (stress, strain, damage, …) on the deformed and corroded mesh
- Apply the next loading cycle

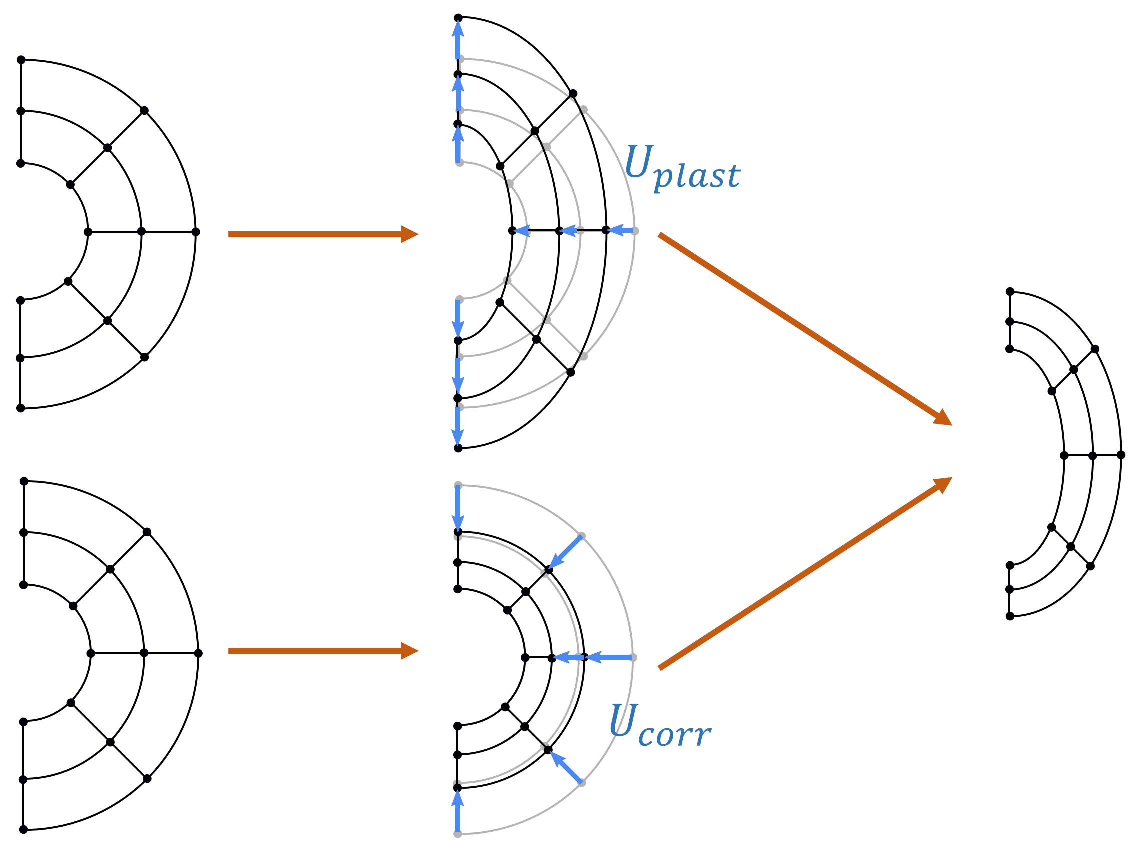
Applying the corrosion

- The nodal displacement between two time steps is defined as:

$$U = U_{plast} + U_{corr}$$

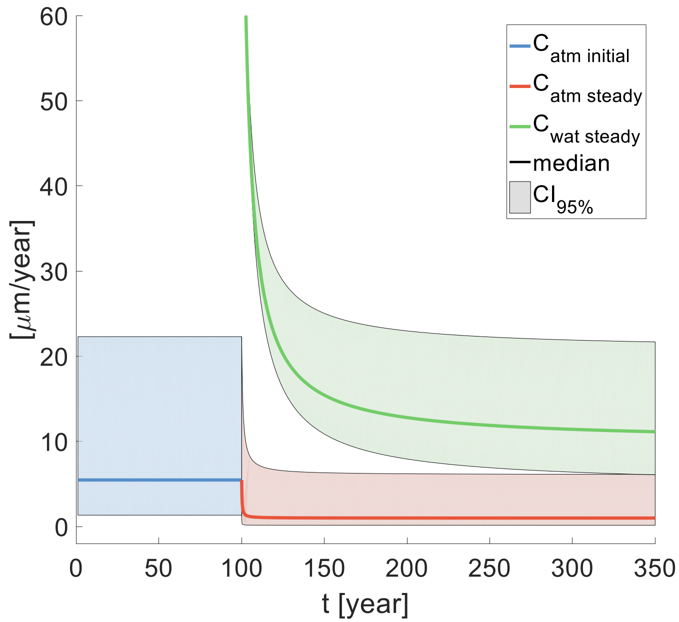
Contribution of the mechanical loading

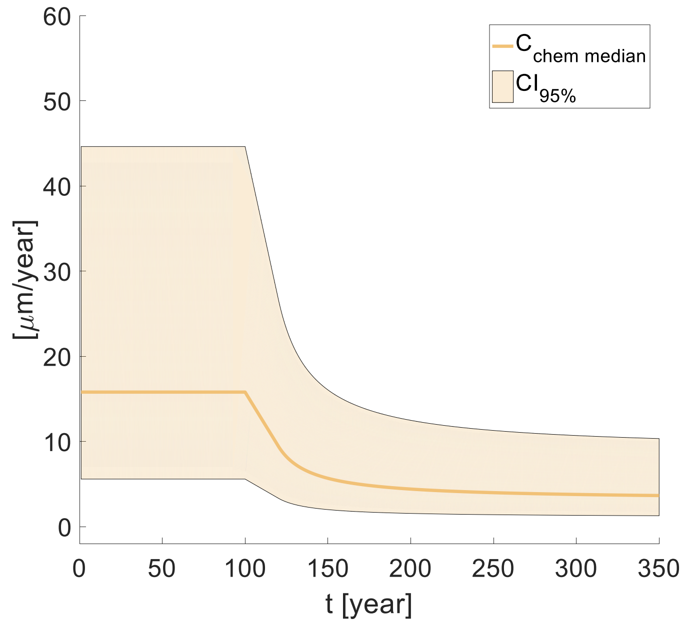
Contribution of the corrosion



Definition of the probability distributions

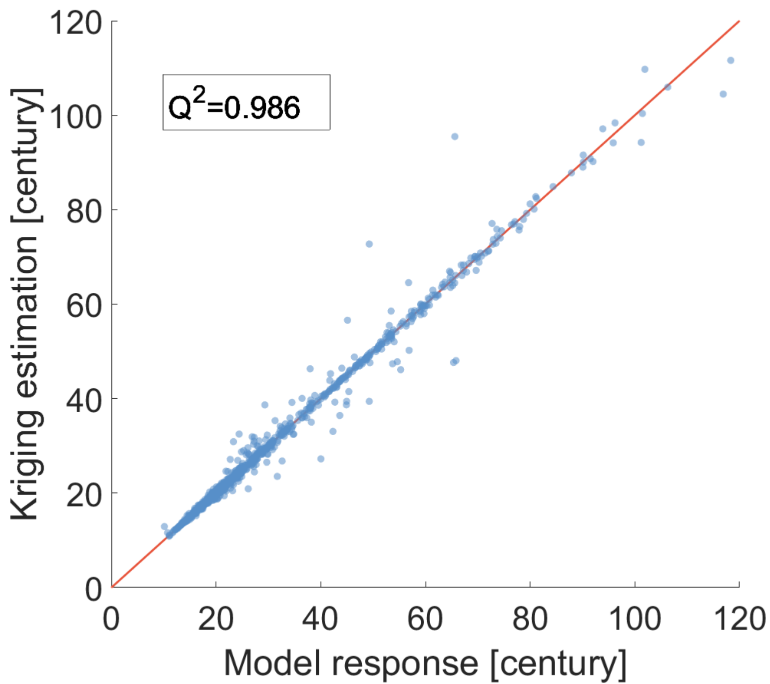
- The first analysis proved that the failure is mostly driven by the corrosion process
- The modelling of the corrosion refined in this second study
  - The corrosion rates (depending on environment and time) are associated with independent random variables
  - 4 variables are considered modelling the corrosion rates:
    - In the atmosphere at early stage
    - In the atmosphere at late stage
    - In the water (late stage)
    - In the saturated rock





Estimation of the failure probability

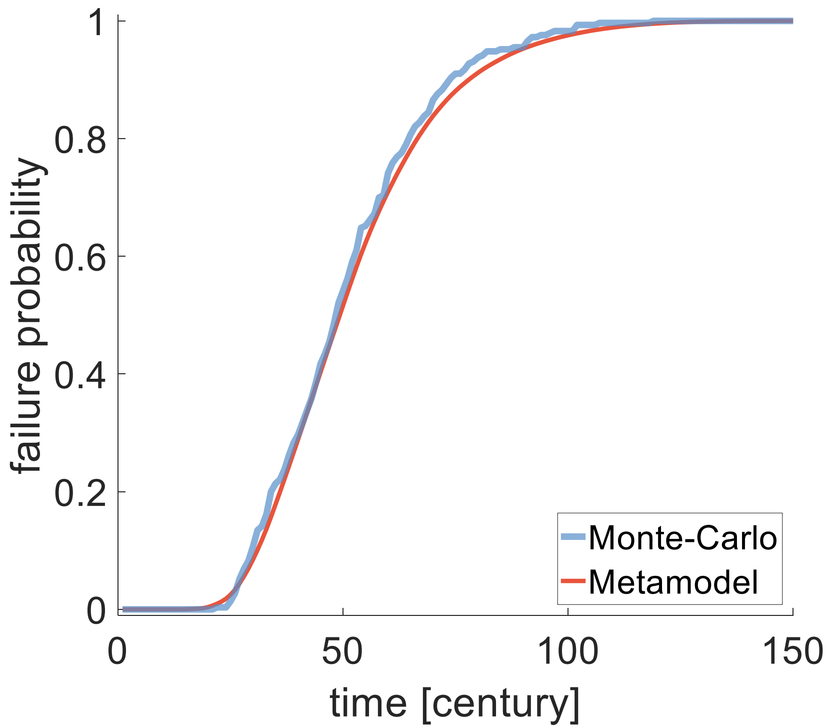
- 5 random variables are considered: 4 corrosion rates and the rock pressure
- A first estimation is carried out using 300 Monte Carlo simulations of the finite element model
- A Kriging meta-model of the system is calibrated using:
  - The 300 Monte-Carlo simulations (≈ 4h each)
  - 400 iterations an adaptive Kriging method AK-MCS:
    - Iteratively enriched design of experiment
    - Evaluate points with the highest probability of misclassification

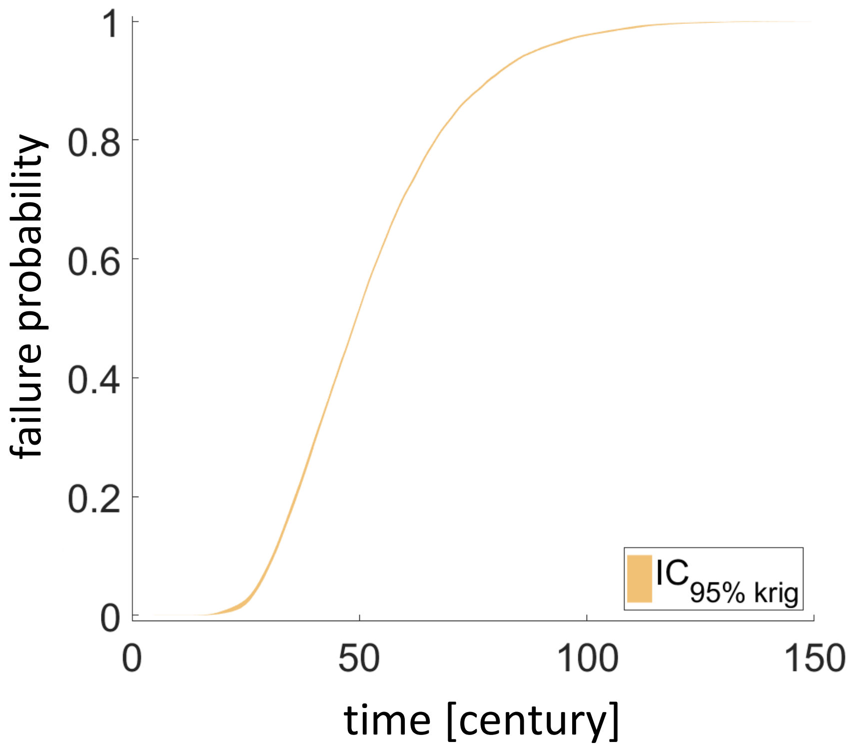


The failure probability is then estimated with 1.000.000 Monte-Carlo evaluations of the meta-model

Estimation of the failure probability

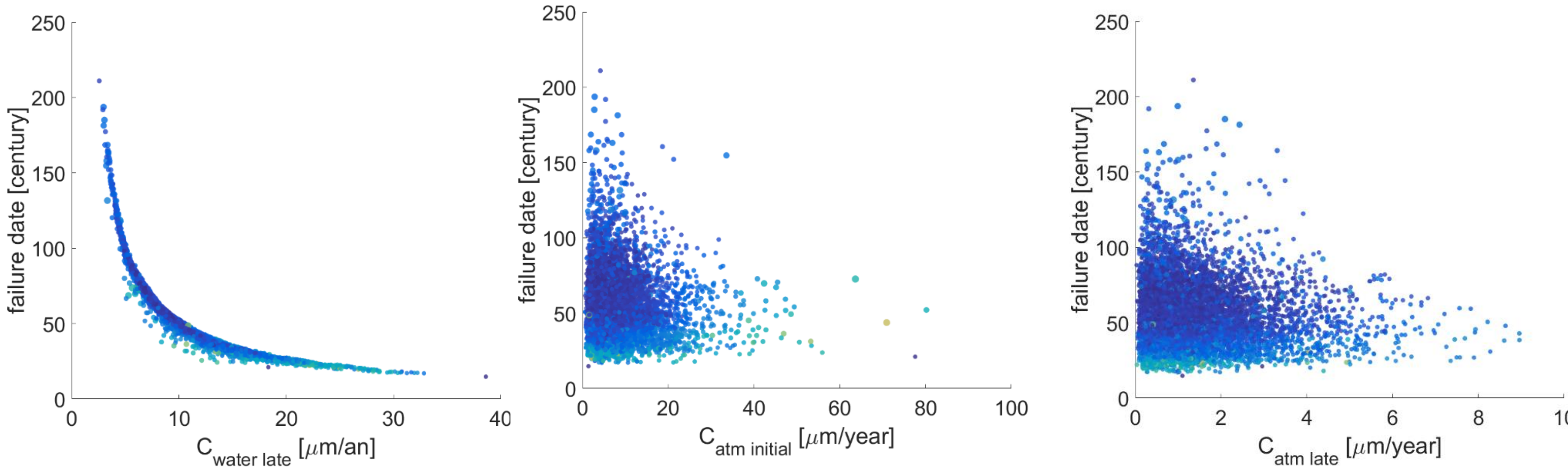
- The two estimations are very close
- No failure observed before 1100 years
- Estimation of the Monte-Carlo error (too small to plot) and the Kriging error (considering the correlation of the Kriging output variables)

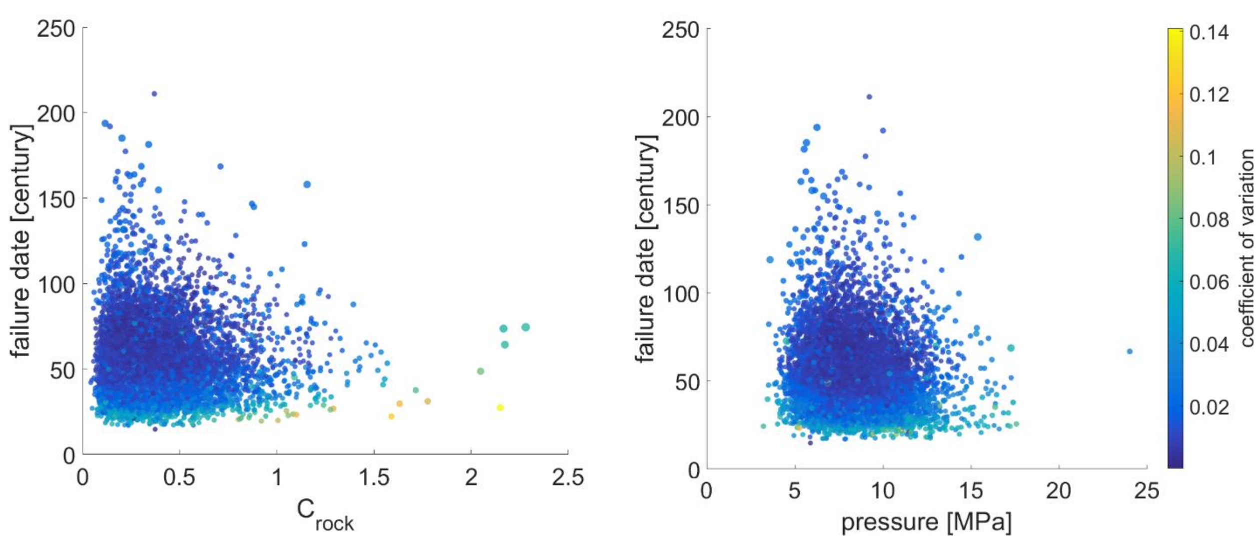




Sensitivity analysis

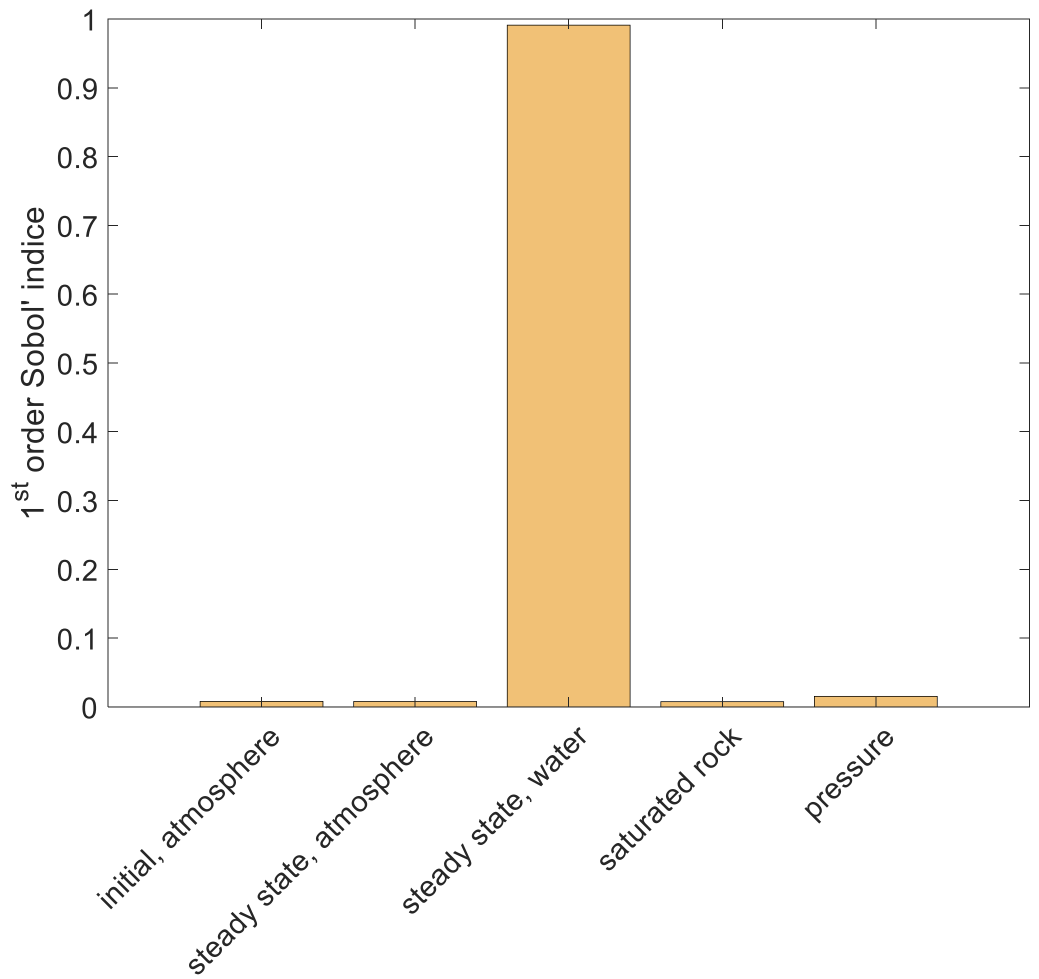
- Scatterplot method: drawing the output as a function of each of the input to reveal correlation patterns





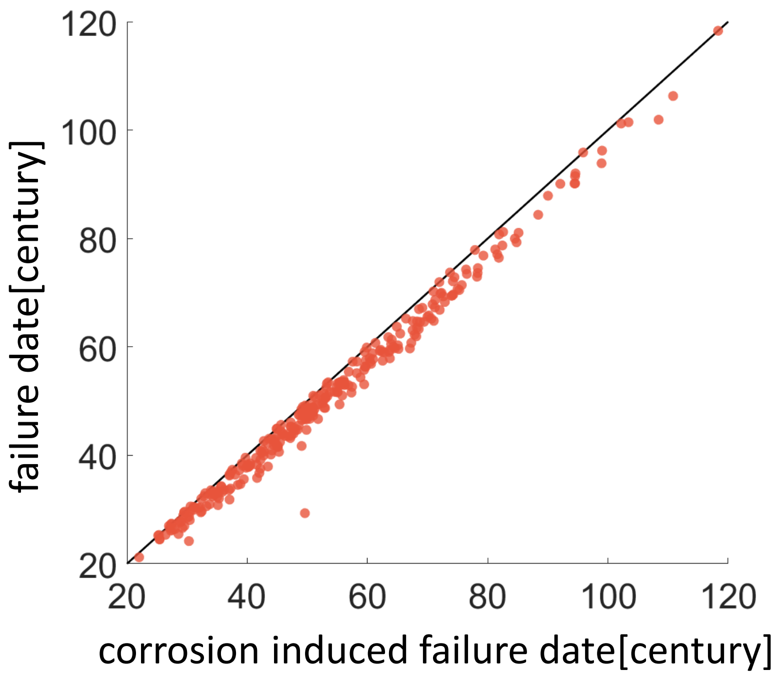
Sensitivity analysis

- Calculation of the 1st order Sobol' Indices using the "pick and freeze" method (from results of the meta-model)



Sensitivity analysis

- The results seem to show that a model taking only into account the corrosion process would give nearly the same results
- However, for a given corrosion rate, the variance of the failure date (due to the mechanical behavior) is not negligible
- The failure by corrosion is the upper bound of the failure date and such a model wouldn't be conservative



I. General modelling
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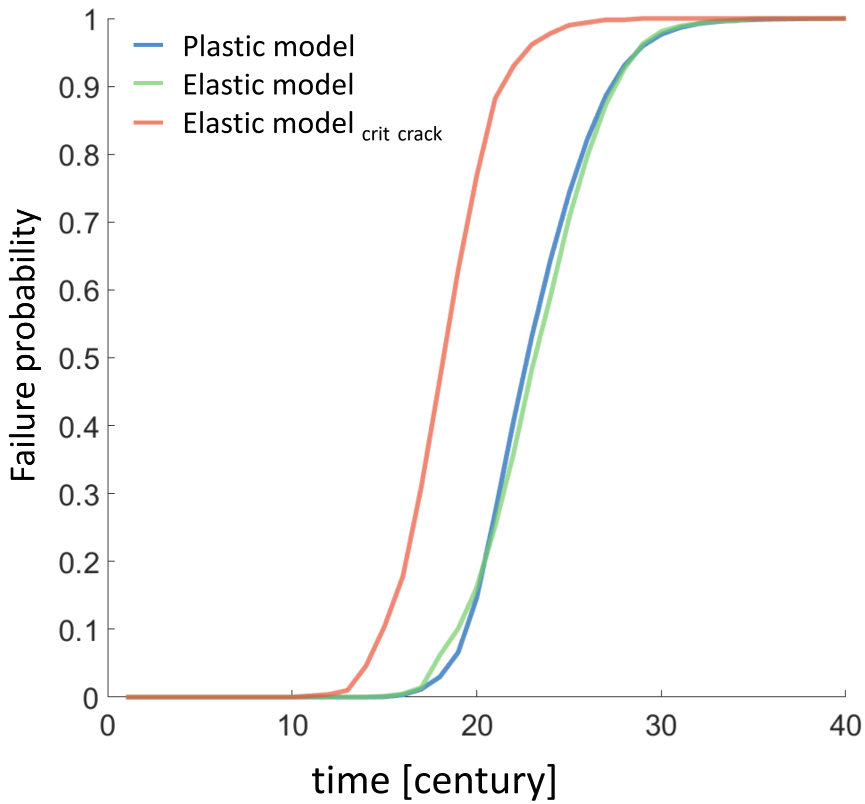
Comparison of the two approaches

- Goal: compare the failure probability curves given by the two models
- Issues :
  - The Kriging metamodel is calibrated using independent corrosion variables
  - In the model considering crack propagation, the mechanical failure can only occur form a limited range of crack positions and orientations

- Therefore:
  - 50 additional iterations of the AK-MCS procedure are carried out considering fully correlated corrosion variables (the same as the 1st model)
  - An additional failure probability curve is drawn, considering only the “worst“ crack for each evaluation of the finite element model

Comparison of the two approaches

- The curves associated with the two models are very close
- The curve considering only critical cracks is significantly shifted
  - The contribution to failure of both of the mechanical behavior is equivalent
  - This result happens to be a coincidence and is very sensitive to the distributions chosen and the initial conditions



Conclusions

- The failure probability at 500 years is expected to be very small for both of the two failure modes considered
- The failure is mostly driven by the corrosion process
- Considering only the corrosion process gives an overestimated value of the lifetime
- If a more precise value of the failure probability is judged relevant, the best way would be to improve the modelling of the corrosion and its uncertainties
- The kriging metamodel is well calibrated and could be used as a practical tool compiling the results of the second study
- Some work has been done to find a reduced analytical model taking into account the corrosion and the mechanical loading
- However no simple explicit relationship between the output and the inputs have been found yet