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# Updating the Reliability of cracked timber beams by using experimental results and numerical fracture model

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# Context of the study

- Use of wood-based materials in sustainable constructions aims to reduce the environmental impact of buildings.
- Timber resistance capacity is affected by the load duration, moisture content and biological activity.
- The mechanical and physical properties of timber structures are strongly affected by the combination of humidity, temperature variation and biological attack.
- Humid exposure and larger wood moisture content **induce** high risk for bio deterioration of unprotected timber (mould and fungal decay).
- Decay: reduces the strength of timber and is the main factor to be considered in assessing the durability of wooden structures [Foliente et al. 2002].

1. Context of the study
2. Time effects
3. Reliability and time-variant reliability analysis
4. Timber decay model
5. Probabilistic climate change model
6. Timber roof application
7. Conclusion

# Context of the study

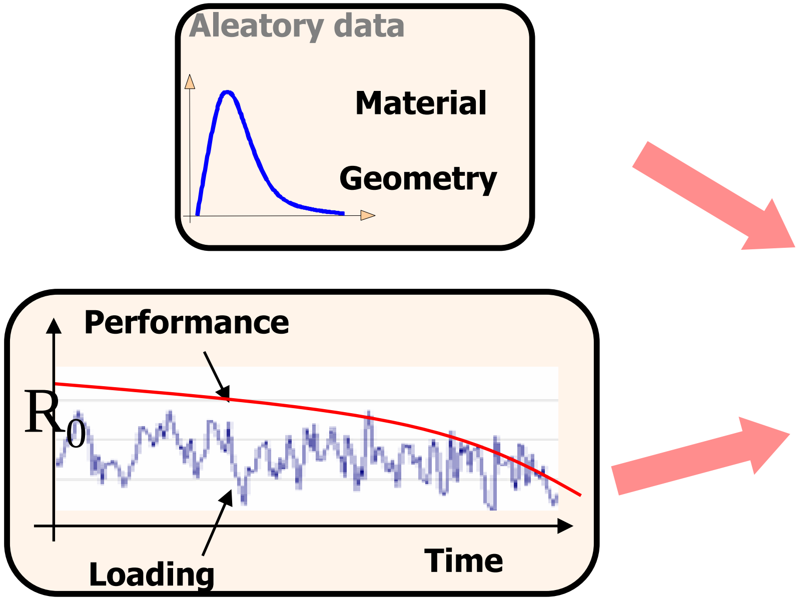
- Climate change with considering temperature and humidity variation may be modelled with a probabilistic tools.
- Take into account **uncertainties** in material properties and actions and increase the structural reliability of timber trusses **subjected to decay**.
- The **partial safety factors** recommended in codes of practice (Eurocodes 5) are not calibrated with considering decay.

Time variant Reliability offers a suitable framework for the consideration of the uncertainties in the design of timber structures and to study the influence of climate uncertainties in the structural behavior.

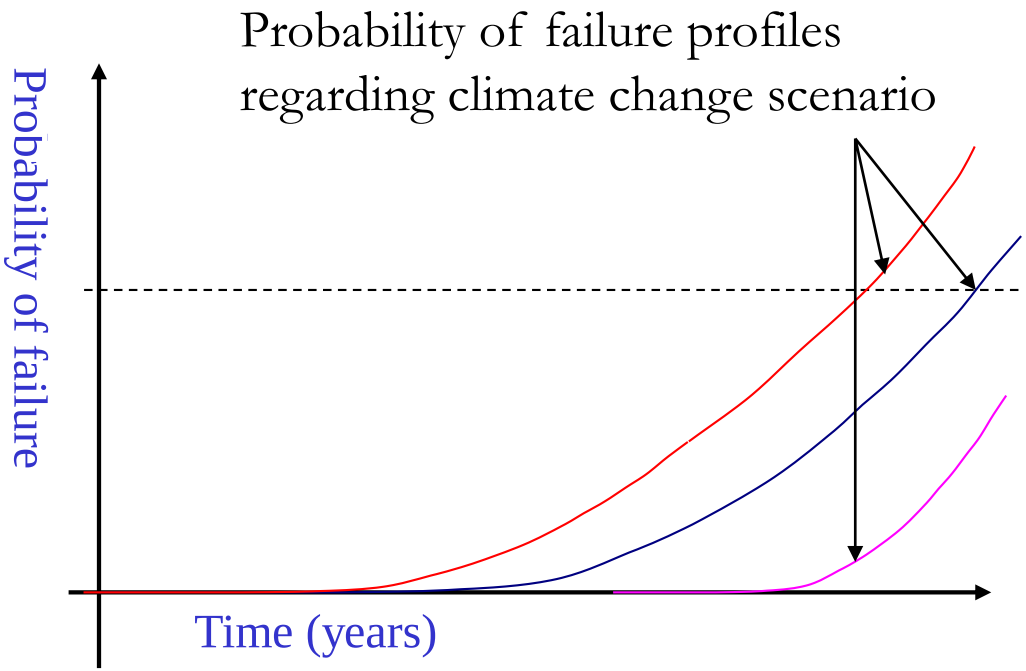
The assessment of reliability of existing timber truss subjected to degradation is an important task for taking decisions on inspection, maintenance and repair actions

# Time effects

- Several kinds of uncertainties related to wood properties, structural dimensions, and load fluctuations are involved.
- Imperfect knowledge of the structural and material degradation.
- Strong fluctuation of the climate parameters (temperature and humidity) that influence the mechanical performance.



Time dependent reliability index of DDO


Probability of failure profiles regarding climate change scenario

Time dependent reliability index of RBDO solution

# Reliability Analysis

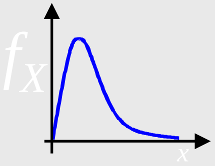
- Probabilistic modelling of the input data (material properties, geometrical dimensions, loading)
- Reliability analysis is based in the evaluation of a limit state function, where in case of timber truss decay leading to failure of performance, requires an understanding of the structure environment, the mechanical model, the environmental action and effects that may result in failure.
- Several methods are developed to perform the reliability analysis, all require the probabilistic-mechanical coupling

Time dependent reliability index of DDO

Time dependent reliability index of RBDO solution

# Reliability Analysis

## Prbabilistic model

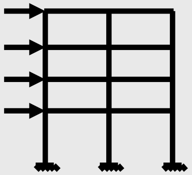


- material prop.
- Geometry
- Laoding

Limite state function

$G(\mathbf{X}) = R - S$

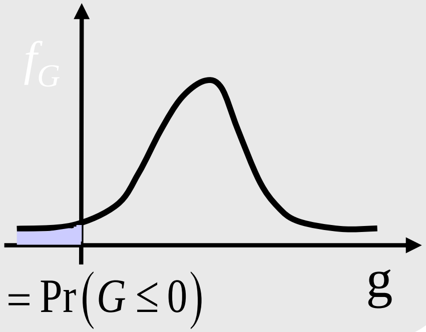
## Mechanical model



- Analytique
- FEM
- degradation models

**Probabilistic-mechanical coupling**

## Reliability analysis



$P_f = \Pr(G \le 0)$

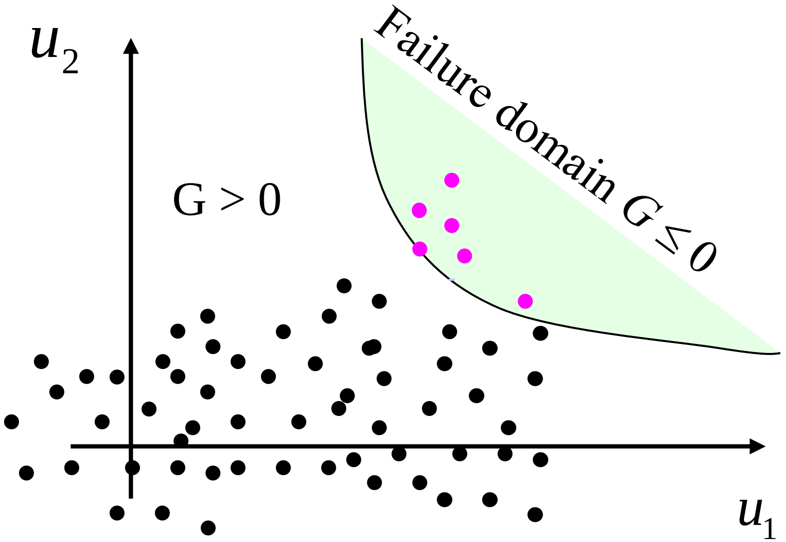
$$P_f = Prob\{G(\mathbf{d},\ X) \le 0\} = \int \dots \int_{G(\mathbf{d},\ x)\le 0} f_X(\mathbf{d}, x)\, dx$$

# Reliability Analysis

## Monte-Carlo Simulation

- Generating a great number of simulation

$$P_f = \frac{N_{G<0}}{N}$$



## Approximation methods

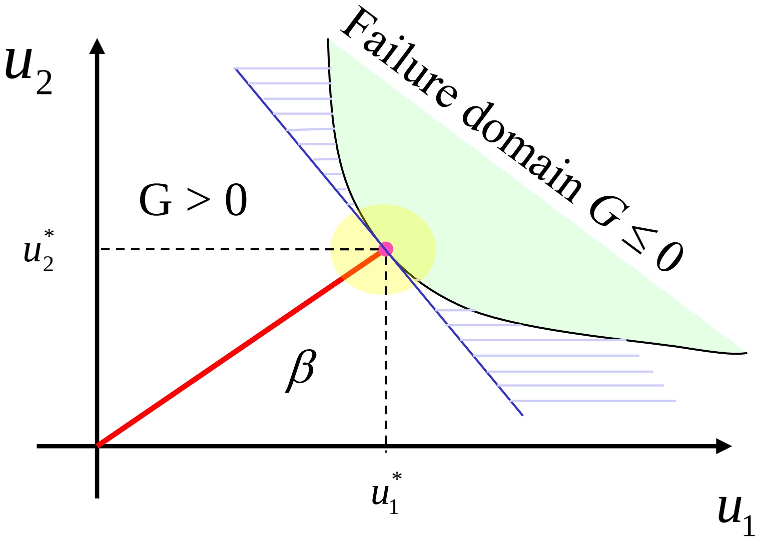
-FORM/SORM

$$\min_{\mathrm{u}} \quad \beta = \|\mathrm{u}\|$$

$$sous:\ G(\mathrm{u}) \le 0$$

The probability of failure is approched by

$$P_f = \Phi(-\beta)$$



# Time-variant reliability Analysis

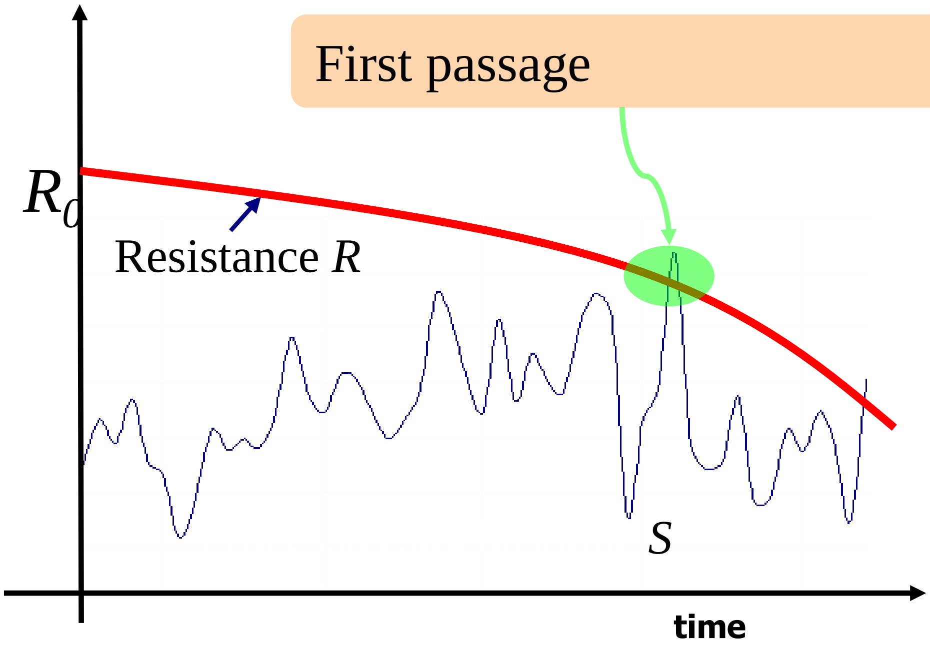
- Probabilistic modelling of the input data (material properties, geometrical dimensions, loading)
- Reliability analysis is based in the evaluation of a limit state function, where in case of timber truss decay leading to failure of performance, requires an understanding of the structure environment, the mechanical model, the environmental action and effects that may result in failure.
- Several methods are developed to perform the reliability analysis, all require the probabilistic-mechanical coupling

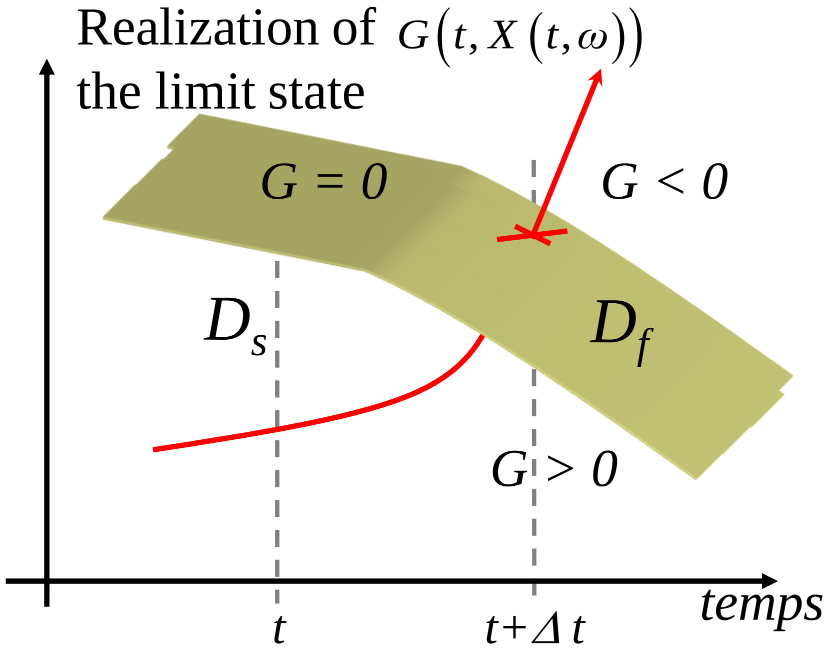
# Time-variant reliability Analysis

## Outcrossing rate

- The probability of the first passage of the limit state in the failure domain at $t+\Delta t$

$$\nu(t) = \lim_{\Delta t \to 0} \frac{P\left[\left(G\left(t, X(t,\omega)\right) \in D_s\right) \bigcap \left(G\left(t+\Delta t, X(t+\Delta t,\omega)\right) \in D_f\right)\right]}{\Delta t}$$





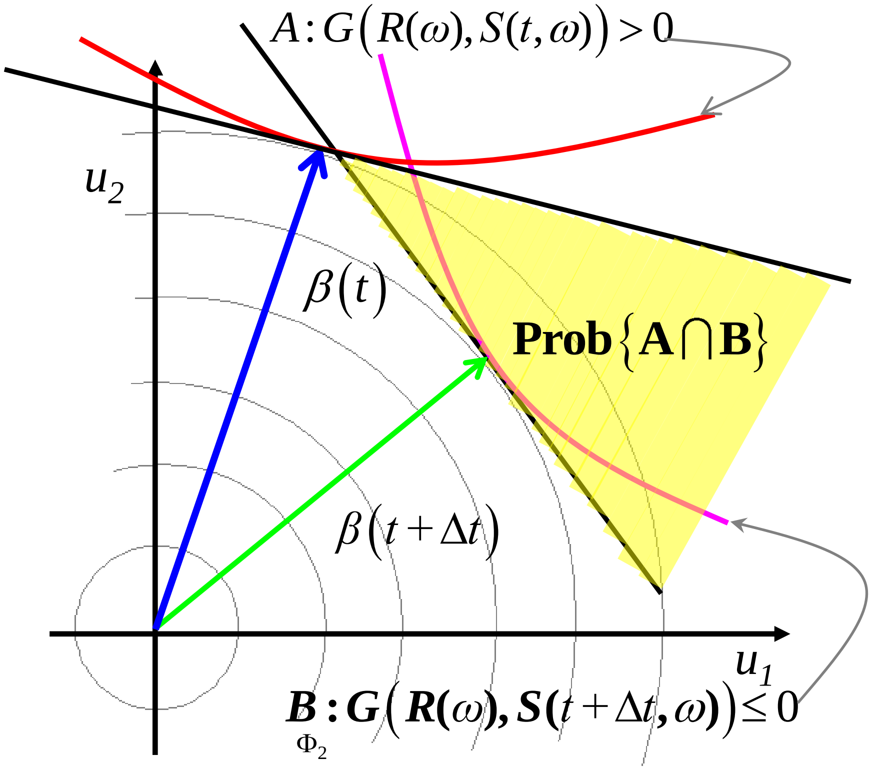
# Time-variant reliability Analysis

## The $\Phi_2$ method

- Approximating the outcrossing rate by FORM analysis

$$\upsilon(t) = \frac{\|\alpha(t+\Delta t)-\alpha(t)\|}{\Delta t}\,\varphi(\beta(t))\,\Psi\left(\frac{\beta(t+\Delta t)-\beta(t)}{\|\alpha(t+\Delta t)-\alpha(t)\|}\right)$$

$$\Psi(x) = \varphi(x) - x\Phi(-x)$$



- The cumulative probability of failure is approximated with :

$$P_{f,c}(0,T) \approx P_{f,i}(0) + \int_0^T v(t)\,dt$$

# Timber decay model

- Viitanen et al [Viitanen 2010] → model for the decay growth of brown rot in pine sapwood under variant climate conditions.
- The model is divided into two processes :
    1. **Activation** process
    2. **Mass loss** process.

## ➢ Activation process

- α is a relative measure of the deterioration of fungi deterioration activity.
- $\alpha$ is set initially to 0. Once it reaches the limit value $\alpha = 1$, the mass loss initiates

$$\alpha(t) = \sum_{i=0}^{t} \Delta\alpha(i) \quad \text{with} \quad \alpha(t) \in [0,1]$$

**where:**

$$\Delta\alpha(i) = \begin{cases} \dfrac{\Delta t}{t_{crit}(RH(i), T(i))} & \text{if } T(i) > 0^{\circ}\text{C} \text{ and } RH(i) > 95\% \\ -\dfrac{\Delta t}{17520} & \text{otherwise} \end{cases}$$

**and:**

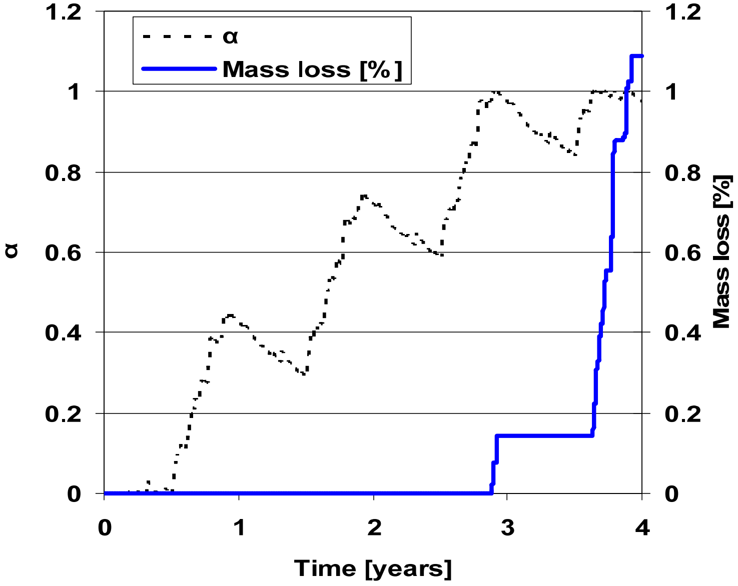
$$t_{crit}(i) = \left[ \frac{2.3T(i) + 0.035RH(i) - 0.024RH(i)T(i)}{-42.9 + 0.14T(i) + 0.45RH(i)} \right] 30 \times 24$$

# Timber decay model

$RH(i)$ and $T(i)$ represent the $i^{th}$ values of the relative humidity and temperature, $\Delta t$ represents a time step between two consecutive climate records (in hours), and $t_{crit}$ (in hours).

## ➢ Mass loss process

- Mass loss (in % of initial weight) occurs once the fungi activation process is reached, ($a(t)$ = 1) and it is estimated as:
- Mass loss only takes place when the temperature is above 0°C and the relative humidity is above 95%. Otherwise mass loss process is stopped.



$$ML(t) = \sum_{i=0}^{t} \left( \frac{ML(RH(i),T(i))}{dt} \times \Delta t \times 1_{\alpha}(i) \right)$$

Where:

$$1_{\alpha}(i) = \begin{cases} 0 & \text{if} \quad 0 \leq \alpha(i) < 1 \\ 1 & \qquad \alpha(i) = 1 \end{cases}$$

$$\frac{ML\big(RH(i),T(i)\big)}{dt} = 5.96.10^{-2} + 1.96.10^{-4}\,T(i) + 6.25.10^{-4}\,RH(i) \quad (\%\ \text{loss/hour})$$

# Probabilistic Climate change

- ❑ The climate change of Marseille and Saint-Nazaire in France, is developed on the basis of the French program CNRM-CM5 which is an Earth System model based on climate simulation that can generate climate scenarios for these two cities.
- ❑ The temperature and relative humidity models are based on the records of temperature and humidity during a few years with values taken at different moments during the day: at sunrise, at noon.

## ➢ Temperature model

The temperature on a certain time *t* is simulated with a deterministic part and a stochastic part:

$$T(t) = \underbrace{T_{mean} + T_{\sin}(t) + T_{day}(t)}_{\text{Deterministic part}} + \underbrace{T_{stoch}(t)}_{\text{Stochastic part}}$$

$T_{mean}$ represents the mean temperature of the time series and $T_{sin}(t)$, $T_{day}(t)$ and $T_{stoch}(t)$ are functions that represent the temperature variations of one year, of every day and the stochastic part of the model.

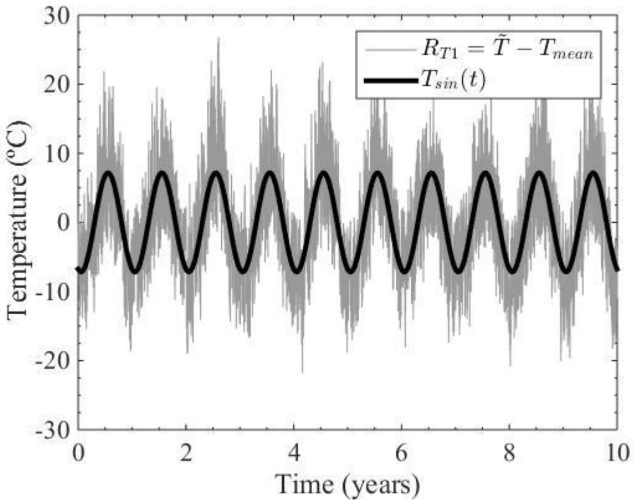
# Probabilistic Climate change

## ➢ Temperature model

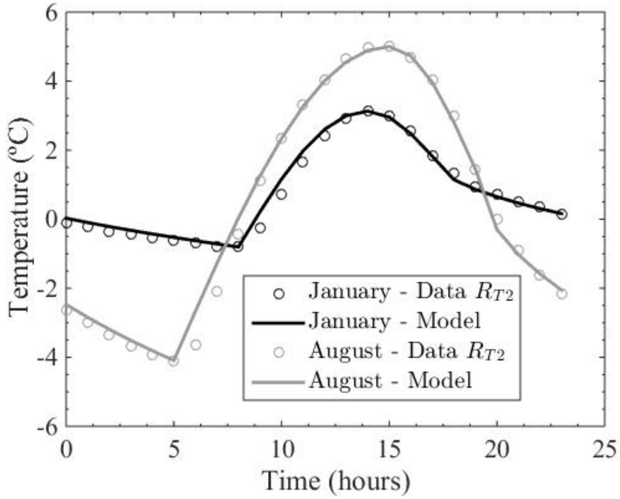
$T_{mean}$ is calculated as a mean between the temperatures of the series of time:

$$T_{mean} = \frac{1}{n_h}\sum_{i=1}^{n_h} T_i$$

- $T_i$ represents the temperature recorded at time $i$, $n_h$ is the total number recorded temperature.
- $T_{sin}(t)$ is simply sinusoidal variation of temperature
- $T_{day}(t)$ is the variation of the daily temperature



$$T_{day}(t) = \begin{cases} T_n + (T_x - T_n)\sin\left(\frac{t - t_n}{t_x - t_n}\frac{\pi}{2}\right) & si\ t_p \le t < t_x \\ T_0 + (T_x - T_0)\sin\left(\frac{\pi}{2} + \frac{t - t_x}{t_0 - t_x}\right) & si\ t_x \le t < t_0 \\ T_0 + (T_p - T_0)\sqrt{\frac{t - t_0}{t_p - t_0}} & si\ t_0 \le t < t_p \end{cases}$$



$T_n$ is the temperature corresponding to the moment of sunrise $t_n$, $T_0$ is the temperature corresponding to the moment of sunset $t_0$, $T_x$ is the maximum temperature of a day corresponding to the time $t_x$ .

# Probabilistic Climate change

## Relative humidity model

The same modelling as the temperature is used for the relative humidity simulated with a deterministic part and a stochastic part:

$$RH(t) = \underbrace{RH_{mean} + RH_{\sin}(t) + RH_{day}(t)}_{\text{Deterministic part}} + \underbrace{RH_{stoch}(t)}_{\text{Stochastic part}}$$

## Probabilistic part

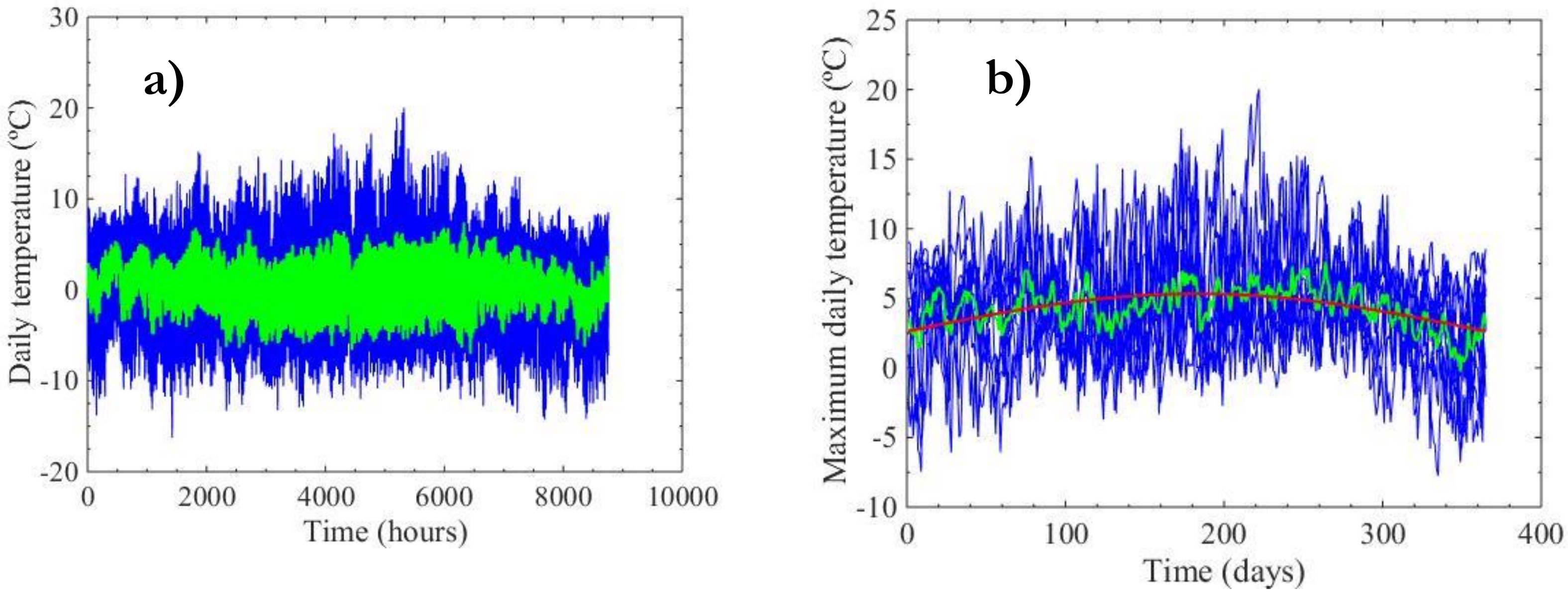
- The stochastic parts of the temperature and relative humidity models are defined by a stochastic process.
- A stochastic process is a set of random variables indexed with time.

The Kahunem-Loève expansion represents a stochastic process by a a finite set of orthogonal deterministic functions weighted by a set of random [Ghanem et al. 2003]

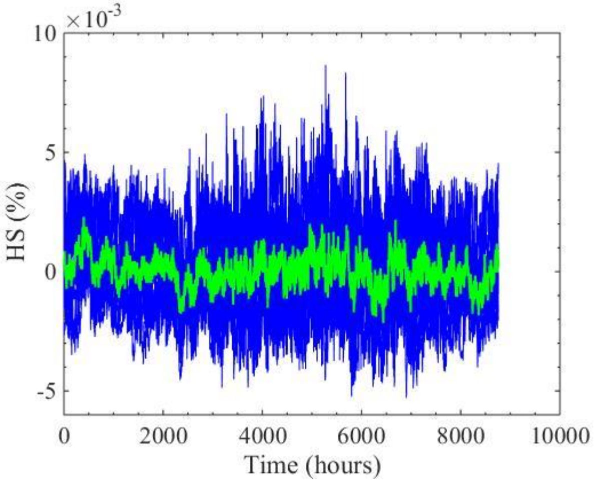
$$Z_{stocastic}(t,\xi) = \mu_z + \sigma_z \sum_{i=1}^{n} \sqrt{\lambda_i}\,\xi_i\, f_i(t)$$

$\mu_z$ and $\sigma_z$ are respectively meran value and the standard deviation of the stochastic process, $\xi_i$ is a set of a Gaussian random independent centered variables $\lambda_i$ and $f_i(t)$ are respectively the eigenvalues and the eigenfunctions of the covariance function, $n$ is the number of terms of the truncated discretization.

# Probabilistic Climate change



Simulated temperature values during one year **a)** the time is expressed in hours **b)** the time is expressed in days

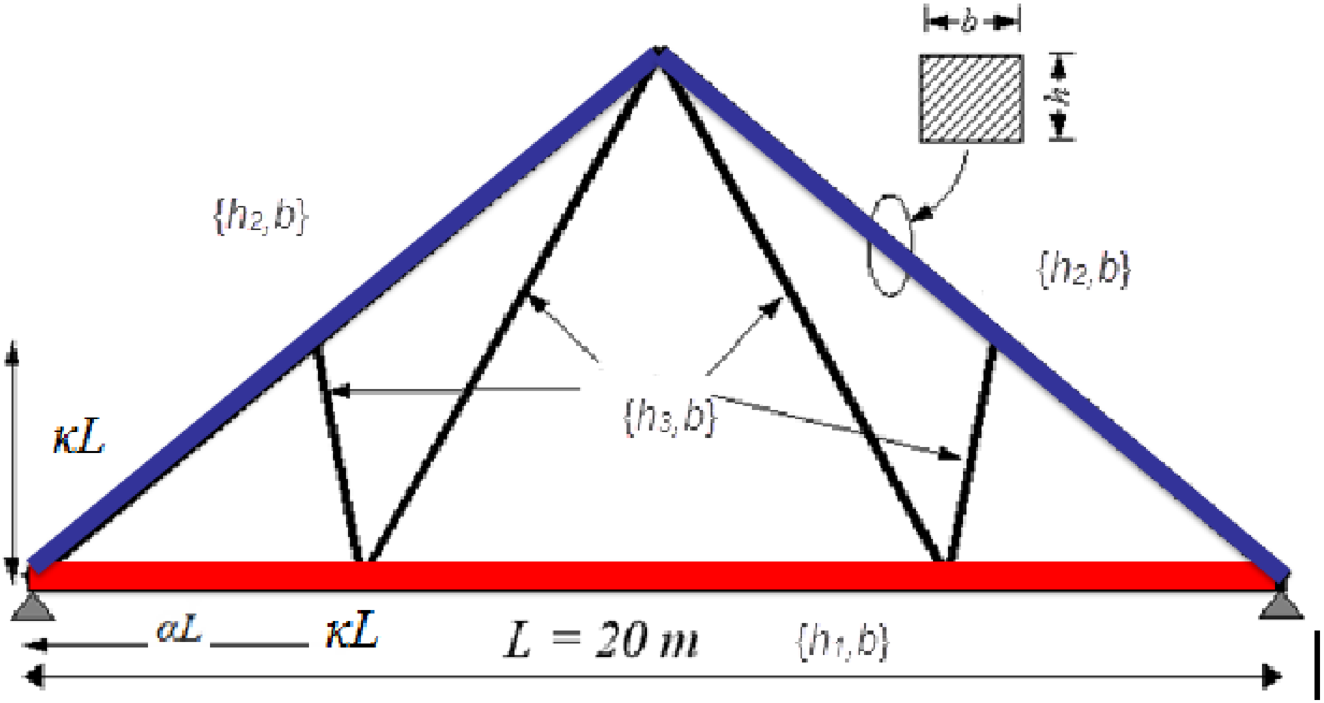


Simulated relative humidity values during one year

# Timber roof application

Objectives:

- Study the time-variant reliability of the timber roof subjected to decay regarding simulated climate change.



# Limit state function

- Ultimate Limit State (ULS):
  - tension and bending: where the tension is parallel to the grain;
  - compression: where members are checked for compressive strength as well as for buckling;
  - shear: for all the truss members for a timber roof truss subjected to decay.
  - The target reliability index for one year is fixed by the Eurocodes 1 to 4.7 [NF-EN 1990]

- Serviceability Limit State (SLS):
  - instantaneous deflection;
  - final deflection composed with the instantaneous and creep deflections.
  - The target reliability index for one year is fixed by the Eurocodes 1 to 2.9 [NF-EN 1990]

- The target reliability index at the allowable life time $T_L$, depending on the target reliability related to one year reference period by:

$$\beta_{T_L}^{c} = \Phi^{-1}\left(\Phi\left(\beta_1^{t}\right)^{T_L}\right)$$

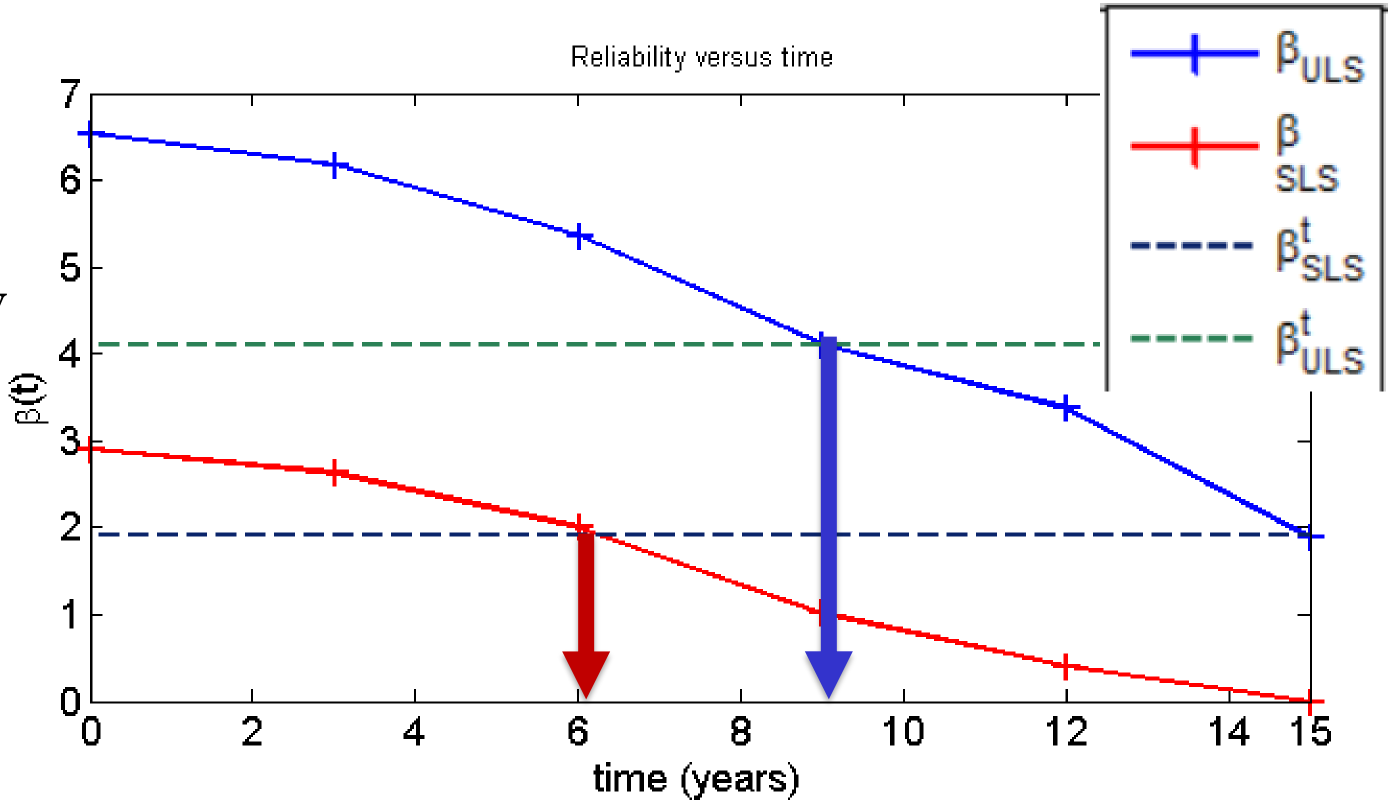
# Statistical parametets

*Table 1: Statistical parameters for materials and loads*

| **Parameter** | $x_k$ | $x_m$ | ***cov*** |
|---|---|---|---|
| $f_m$ (MPa) | 24 | 33.9 | 0.2 |
| $f_c$ (MPa) | 21 | 29.66 | 0.2 |
| $f_t$ (MPa) | 14 | 19.77 | 0.2 |
| $f_{c,90}$ (MPa) | 2,5 | 3.53 | 0.2 |
| $f_v$ (MPa) | 4 | 5.65 | 0.2 |
| E (GPa) | 10.78 | 11 | 0.2 |
| Permanent load (kN/m²) | 620 | 466.52 | 0.2 |
| Snow (kN/m²) | 1193 | 798.81 | 0.3 |
| Wind (kN/m²) | 1320 | 883.53 | 0.36 |

- Exposure to a very humid environment corresponding to city of **Nantes** in France during 30 years [1980-2010].
- Nantes: annual mean temperature of **12.7 ºC** and relative humidity of **81%.**

# Time-variant reliability results



ULS target reliability at one year 4.7

SLS target reliability at one year 2.9

# Conclusion

➢ Time-variant Reliability analysis of timber structures subjected to decay degradation, with taking into account climate variations allows us to estimate the probability of failure during the whole life time.

➢For unprotected timber roof, the partial safety factors are not calibrated with considering decay deterioration.

## Ongoing works

- Several climate change scenarii
- Calibration of the partial safety factors regarding timber decay degradation.
- Risk-based optimization with including failure and environmental costs.
- Semi-rigid model of timber joints.
- Maintenance (inspection and repair actions) optimization.

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Thank you for your kind attention!