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Influence of the climatic changes on wood structures behaviour

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Abstract

The mechanical and physical properties of wood structural elements and of wood structures are strongly affected by the combination of humidity, temperature variation and biological attack.

The aim of this study is to develop a design model able to estimate timber elements decay function of the exploitation climatic conditions (temperature and humidity).

The deterioration program may be applied on any type of wood element and is indicating the necessity of increasing the cross section dimensions if and when the specific humidity and temperature become of significant influence.

The results of this study are of great importance as the behavior of a non-treated timber element can be surveyed when directly influenced by changes in climatic conditions (relative humidity and temperature).

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1. Introduction

The variations of humidity and temperature have a great influence on the behavior of construction materials and mostly on the wood itself, on which we are interested in this study.

To improve the behavior of wood influenced by these variations, we will try to better analyze the results. We will analyze the records of temperature and humidity during a few years with values taken at different moments during the day: at sunrise, at noon, when the temperature has the highest value and at sunset; then, we will divide the results in one deterministic part and other stochastic.

For some years, researchers have been making studies on the developments of performances for the fungal decay and their impact on wood and also on the augmentation of mold. The studies have been based on multiple strategies and on different variables of wood such as: mass loss, loss of resistance, influence of moisture, life expectancy of wood, appearance.

In order to see how climate change can affect the regions of Marseille and Saint-Nazaire from France, we will use a French program CNRM-CM5 which is an Earth System model based on climate simulation that can generate climate scenarios for the two villages.

It is necessary to have complete models of deterioration to have a big picture of the influence of climate on wooden elements. The climate factors: temperature and humidity have to be integrated in these models of deterioration to see exactly the way in which the climate influences the properties of the material.

This model, that is function of time, temperature and humidity, has to be integrated in the decay models in order to evaluate climate effects that will change over a period of time. However, because of the difficult integration between the two models, it is necessary to make a simplified approach that will be analyzed in this study. It will depend on the influence of climate change during seasons and the random change in temperature during one season.[3]

For the estimation of temperature values, we have to measure the maximum and minimum temperature to see the trends of the diurnal temperatures. This is made even if when measuring time, one has a high accuracy for estimating values of degree days. [4]

The calculation is made with the Matlab software, with some verification in the Excel software.

2. The model created for the temperature

For the temperature series, it is necessary to make a model that will be rely on known representations taken from data calculated by the French model of national circulation CNRM-CM5, explained above. The temperature variations are considered on each hour and the components of this series are deterministic and stochastic.

The temperature on a certain time t (calculated in hours) is analyzed as following:

$$T(t) = \underbrace{T_{mean} + T_{sin}(t) + T_{day}(t)}_{\text{La partie deterministe}} + \underbrace{T_{stoch}(t)}_{\text{La partie stochastique}} \quad (1)$$

where:

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 an year, of every day and the stochastic part of the model.

2.1 The analysis of the deterministic part

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

$$T_{mean} = \frac{1}{n_h} \sum_{i=1}^{n_h} \tilde{T}_i \quad (2)$$

n_h represents the total number of hours for the time series and \tilde{T}_i represents the temperature recorded at a certain moment i ;

$T_{sin}(t)$ is simply analyzed as a sinusoidal variation (fig.1.a):

where:

s_1 and s_2 are parameters resulted from the equation $R_{T_1}(t) = \tilde{T}(t) - T_{mean}$

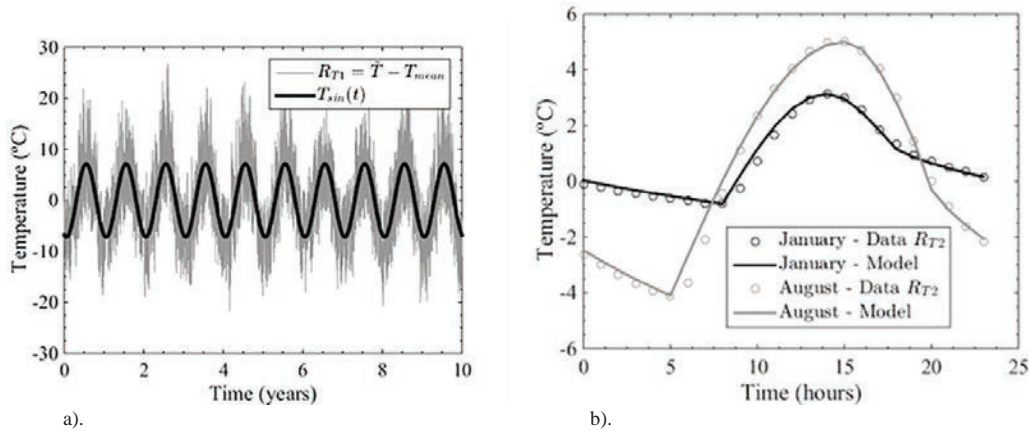


Fig. 1. a). The model for the centered temperature together with the sinusoidal part;
 b). The representation of the model for the daily temperature and a comparison between the estimated value of the temperature and the model

Fig. 1a shows the final representation of the model created for the temperature considered in the study. The T_{mean} temperature and the $T_{sin}(t)$ temperature are introduced in the model with the original values taken from the survey.

A pattern is created for the model and the data can be easily introduced in the study in order to simplify the calculation. The period time for the graphic is 10 years with daily records, and the temperature in (°C) in [-30; +30]°C.

In fig. 1b we can see the comparison between record of temperature on one day in January and one day in August with the model created. The curves are almost the same with the circled lines which states that the model closely follows the real data and that makes the study more accurate.

The variation of the daily temperature is calculated as following (fig.1b):

$$T_{day}(t) = \begin{cases} T_n + (T_x - T_n) \sin\left(\frac{t - t_n}{t_x - t_n} \frac{\pi}{2}\right) & \text{si } t_p \leq t < t_x \\ T_0 + (T_x - T_0) \sin\left(\frac{\pi}{2} + \frac{t - t_x}{t_0 - t_x}\right) & \text{si } t_x \leq t < t_0 \\ T_0 + (T_p - T_0) \sqrt{\frac{t - t_0}{t_p - t_0}} & \text{si } t_0 \leq t < t_p \end{cases} \quad (3)$$

where:

T_n is the moment of sunrise (hr), T_0 is the moment of sunset (hr), T_x is the time of the maximum temperature of a day, T_p is the moment of sunrise from the next day, T_n is the temperature of the sunrise (°C), and T_n is the temperature of the sunrise for the next day (°C). For the simplicity of the calculation, we will consider only one day for every month. This corresponds to the mean hourly temperature during a month. T_n and T_0 are estimated from the residuals of $R_{T_2}(t) = \tilde{T}(t) - T_{mean} - T_{sin}(t)$ in which it is used a mean of temperature for the time of the sunrise and the time of the sunset.

In fig. 2 the graphics represent the variation of the daily temperature during a period of one year. In fig. 2a, the time interval is expressed in hours, while in fig. 2b, the daily temperature is expressed in days during one year.

Fig. 2a presents the progression of daily temperature during a day and the relationship between these values and the values from the model that eventually show that it follows the same pattern.

In fig 2b, the graphic presents the evolution of the maximum daily temperature during 365 days and the model curve that simplifies the recorded values.

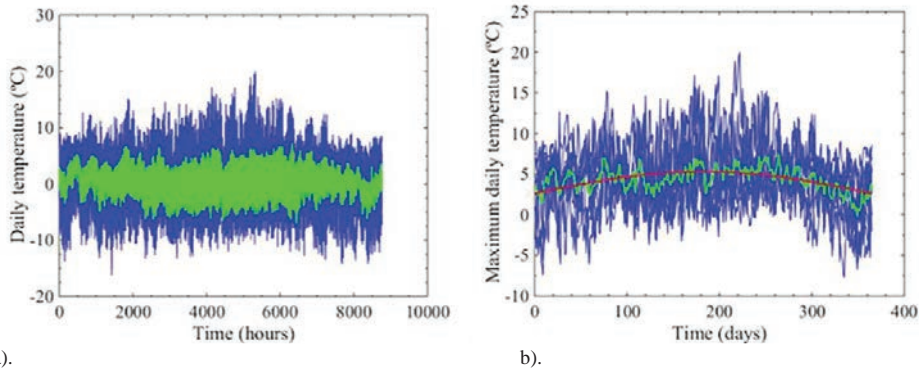


Fig. 2. Details of the characteristics of the temperature: a. the temperature values during one year (the time is expressed in hours); b. the maximum value of the temperature during one year (the time is expressed in days)

2.2 The analysis of the stochastic part of the equation

It is given a probabilistic space (Ω, F, P) , a stochastic field with time Z that is a collection of random indexed variables from a combination between s , a "space" and t "time". The notation $Z(x, \theta)$ is used for a stochastic field with a certain dimension where θ represents the random variable and x the space coordinate.

This study follows the expansion Kahunem-Loève for the representation of the stochastic domain for an amount of interest $Z(x, \theta)$ (resistance, porosity, water content, etc.). The Kahunem-Loève expansion represents a stochastic field as a combination of orthogonal functions in a specified interval $[a, -a]$:

$$Z(x, \theta) = \mu_z + \sigma_z \sum_{i=1}^{n_{kl}} \sqrt{\lambda_i} \xi_i(\theta) f_i(x) \quad (4)$$

where:

μ_z represents the mean of the Z field, σ_z is the standard deviation of the statistic and homogenous field Z , n_{kl} is the number of terms in a limited series, $\xi_i(\theta)$ represents a combination of Gaussian random independent centered variables λ_i and $f_i(x)$ are values and custom functions that depend on the type of the autocorrelation function $\rho(\Delta_x)$. The determination of the eigen values λ_i and the custom functions $f_i(x)$ can be determined for some of the autocorrelation functions.

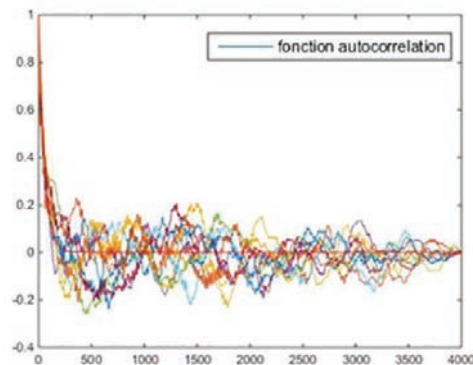


Fig.3. The representation of the autocorrelation function

In fig. 3 we can see the set of autocorrelation coefficients given by the series of quantities arranged as a function of separation in time that measure the correlation between observations at different times because future values depend on current and post values. The organized curvature of the autocorrelation function shows that the entry values of the temperature at a certain time can be exploited for predictions.

3. The model created for the specific humidity

The specific humidity, noted as HS , is defined as the ratio of the water mass from the humid air.

In order to make a model of the specific humidity it is necessary to follow the same steps as in the creation of the temperature model, based on a deterministic part and a stochastic one. The data are taken from a series used in the study.

So, the specific humidity in a time t , in hours, is modeled in the expression below:

$$HS(T) = \underbrace{HS_{mean} + HS_{\sin(t)} + HS_{day(t)}}_{Partie\ déterministe} + \underbrace{HS_{stoch(t)}}_{Partie\ stochastique} \tag{5}$$

where:

HS_{mean} represents the mean of the HS for all the series of a specific period of time established before and the functions $HS_{\sin(t)}$, $HS_{day(t)}$ and $HS_{stoch(t)}$ represent the variations of the HS during years, days and the stochastic part of the model.

3.1 The analysis of the deterministic part $HS_{\sin(t)}$

HS_{mean} represents the mean of the specific humidity of all the series values.

$$HS_{mean} = \frac{1}{n_h} \sum_{i=1}^{n_h} \widetilde{HS}_i \tag{6}$$

where:

n_h is the total number of hours from the series of HS and \widetilde{HS}_i is the value of HS registered at a certain time i .

$HS_{\sin(t)}$ is a model for a function represented as a sinusoidal variation, in the same way as the case of the temperature (fig. 4).

$$HS_{\sin(t)} = d_1 * \sin(2 * \pi * \frac{t}{365 * 24} + d_2) \tag{7}$$

where d_1, d_2 represent the parameters from $HS_{centered} = HS(t) - HS_{mean}$

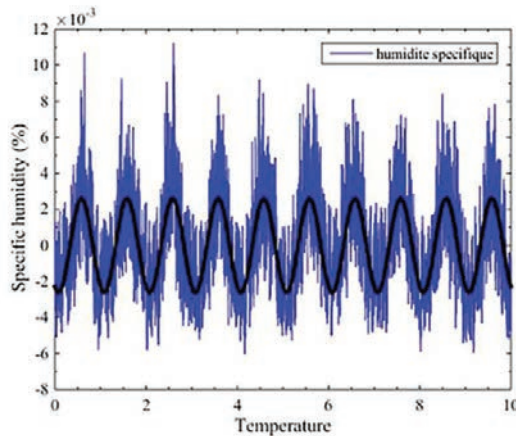


Fig. 4. The model created for the specific humidity

Fig.4 shows the final representation of the model created for the specific humidity considered in his study. A pattern is created for the model and the data can easily be introduced in the study in order to simplify the calculation. The period time for the graphic is 10 years, with daily records and the specific humidity is calculated in %.

For the creation of the model of the daily representation of the HS it is used the same model as the one for the temperature, explained above, together with the six parameters that influence the function: T_n is the temperature at sunrise ($^{\circ}\text{C}$), T_0 is the temperature at sunset ($^{\circ}\text{C}$), T_x is the maximum temperature of the considered day ($^{\circ}\text{C}$), HS_n is the HS at sunrise (%), HS_0 is the HS at sunset (%), HS_x is the HS of the considered day (%) (fig. 5).

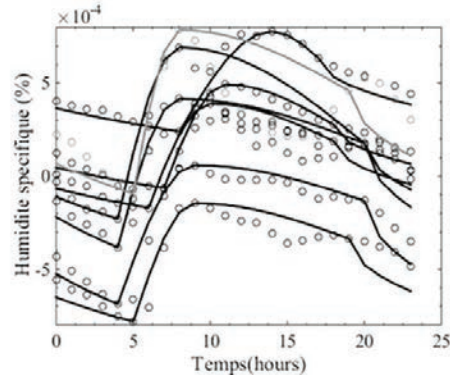


Fig. 5. The representation of the model for the daily specific humidity and a comparison between the estimated value of the specific humidity and the model

In fig.5 the curves are almost the same with the circled lines which stated that the model closely follows the real data and that makes the study more accurate.

In the fig. 6 there is a graphic that shows the variation of the SH during a period of one year with the time expressed in hours. The comparison with the model shows that the two series follow the same pattern.

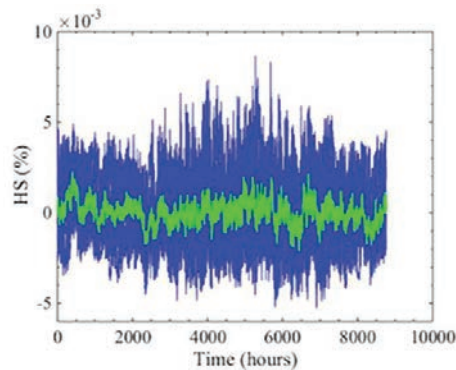


Fig. 6. The representation of the specific humidity expressed in % during one year

3.2. The analysis of the stochastic part of the equation

The stochastic part of the HS follows the same model as the one for the temperature after the Karhunen-Loève expansion. Using the autocorrelation function the values and the custom functions can be found (see the analysis of the stochastic part of the temperature in chapter 2.2)

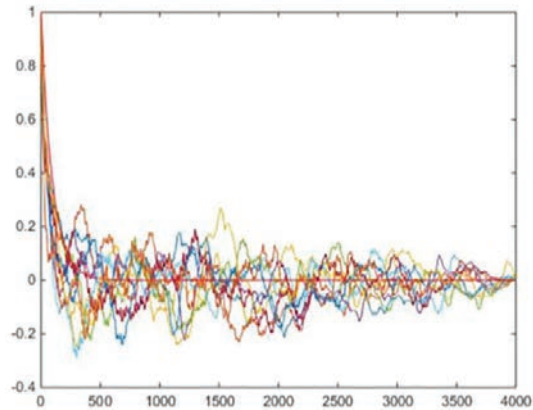


Fig. 7. The representation of the autocorrelation function for the specific humidity

In fig.7 we can see the set of autocorrelation coefficients given by the series of quantities arranged as a function of separation in time that measures the correlation between observations at different times because future values depend on current and past values. The organized curvature of the autocorrelation function shows that the entry values of the humidity at a certain time can be exploited for predictions.

4. The model for the composition of wood

Researchers have started to analyze more and more the effects of moisture on wooden constructions. For this reason, they have made studies and degradation models with different scenarios based on humidity and temperature variations on different types of wood. The main objectives are in finding a precise estimation of life of the wood material, moreover, the life of a structure.

Isaksson and al. (2012) have proposed a model for the degradation based on measurements made on Scots pine and Douglas Fir. The examples were exposed to natural and multiple conditions of climate in 24 test sites from Europe, between 2000 - 2008.

The main objective of the model developed by Isaksson and al. (2012) is the degradation in terms of dose-response factors. The dose is expressed as a function of daily moisture content of wood and of wood temperature where the level of degradation is defined as in EN 252 1990. Eurocode 5 offers 5 levels of degradation conditions starting from no-degradation to severe degradation. These levels are used when the evaluating conditions of the material are based on serviceability limit states. However, this doesn't give quantitative information on the loss of the wood sections that are used for an estimative mass loss. This is the reason that this model will not be used in this study. [19]

4.1. The degradation adapted model

Following the studies of Viitanen (1996), Viitanen and al (2010) we see that they have developed a model for the augmentation of brown rot in the sapwood of pine while exposed to climate conditions. This type of model is divided into two processes: (i) the activation process and (ii) the mass loss process. [11]

4.1.1. The activation process

In this part of the study a parameter α is used which measures the deterioration activity of the wood because of the fungi attack on wood. The initial value of this parameter is 0 and when it arrives to 1 it means that the mass loss is starting to affect the piece, in time.

$$\alpha(t) = \sum_{i=0}^t \Delta\alpha(i) \text{ with } \alpha(t) \in [0,1] \quad (8)$$

where:

$$\Delta\alpha_{(i)} = \begin{cases} \frac{\Delta t}{t_{crit}(RH(i), T(i))} & \text{si } T(i) > 0^{\circ}\text{C} \\ & \text{et } RH(i) > 95\% \\ -\frac{\Delta t}{17520} & \text{in other cases} \end{cases} \quad (9)$$

$RH(i)$ and $T(i)$ represent the values of the humidity (in %) and of the temperature ($^{\circ}\text{C}$) in a certain point i , Δt represents a time step between two consecutive climate records (in hours), and t_{crit} (in hours) has the following expression:

$$t_{crit}(i) = \left[\frac{2.3T(i) + 0.035RH(i) - 0.024RH(i)T(i)}{-42.9 + 0.14T(i) + 0.45RH(i)} \right] * 30 * 24 \quad (10)$$

The equation shows that $\Delta\alpha_{(i)}$ is increasing when $T > 0^{\circ}\text{C}$ and $RH > 95\%$. The decreasing is realized linearly from 1 to 0 in two years (17520 hours) under dry and cold conditions.

4.1.2. The mass loss process

The mass loss process starts when $\alpha_{(t)} = 1$, this means that the fungi start to affect the piece of wood; it is represented by the % of the initial mass and has the next expression:

$$ML(t) = \sum_{i=0}^t \left(\frac{ML(RH(i), T(i))}{dt} * \Delta t * l_{\alpha}(i) \right) \quad (11)$$

where:

$$l_{\alpha}(i) = \begin{cases} 0 & \text{si } 0 \leq \alpha(i) < 1 \\ 1 & \text{si } \alpha(i) = 1 \end{cases} \quad (12)$$

and

$$\frac{ML(RH(i), T(i))}{dt} = -5.96 * 10^{-2} + 1.96 * 10^{-4}T(i) + 6.25 * 10^{-4}RH(i) \quad (13)$$

[% loss/hours]

The conclusion is that the mass loss always happens when the temperature is above 0°C and the relative humidity is above 95%. If not, the mass loss process stops.[11]

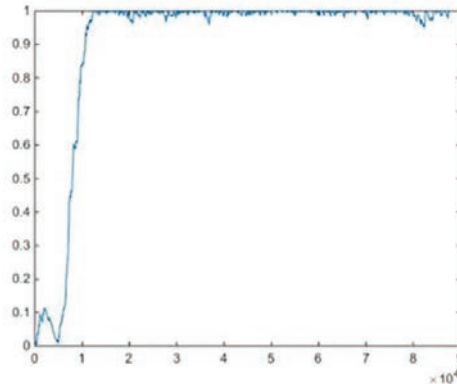


Fig.8. The division of the autocorrelation function. The representation of the degradation model of wood during 10 years

Fig. 8 shows the evolution of the moment until de mass loss begins. It characterizes the parameter α which starts from the 0 value (no deterioration of the wooden piece) and it slowly develops until it arrives to the value 1 (the start of the degradation of the wooden piece). Until the value remain at 1 the wood is deteriorating continuously in time.

4.2. The simulation of wood degradation

In order to show the mass loss of a wood piece and also the application of this study, a simulation of 30 random climates has been conducted on a period of 15 years.

These climates have been further applied on the model of wood degradation on series that represent the influence of combined actions of temperature and humidity directly on wood. For extended periods of time the risk of wood degradation will be amplified.

The wood used in this study is natural and without any protection applied on it.

A comparison between the deterministic model and the wood degradation, together with the model of the 30 random climates in needed and it is noticed that the series follow the same trajectory.

According to fig. 9 in the first two years more or less, the mass loss is almost 0 because the condition $\alpha = 1$ is not accomplished (α -parameter of the empirical model of wood decay, presented above).

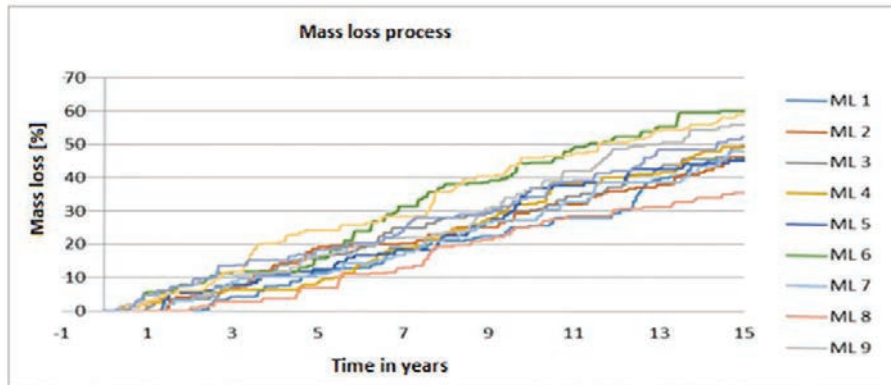


Fig.9. The representation of the autocorrelation function for the model created for 15 years on 9 types of climate.

The study provides a deterministic model that is further used for showing the mass loss and the exact moment when the wooden piece starts to give away and cannot be used anymore. And also the graphic shows that the material gradually starts to deteriorate when the mass loss commences to increase.

The main principle is to find the exact moment when the effort used on the section (calculated before according to Eurocode 5) do not fill anymore the verification condition.

5. Conclusions

The mechanical and physical properties of a wood element and mostly of wooden structure can and will be affected by a combination between moisture content, temperature, biological activities etc.

The purpose of this study is to create a model of calculation that can predict wood degradation for elements exposed to climate conditions, function of temperature and humidity.

The life duration of a material depends on the relative humidity in different combinations with temperature and exposure time. Together, these factors can deteriorate the material by developing mold surfaces.

The predictions on wood deterioration have been taken into consideration from the studies of Viitanen et al (2010) that propose a deterministic model for wood deterioration considering humidity content and influence of temperature.

After using the Matlab software for the model, 30 random climates have been created, following a period of 15 years in order to see the deterioration of the piece of wood in this period of time. Also, the model creates an evolution of the material's behavior with an exact moment when the deterioration begins.

This program of deterioration can be applied on any type of wood and it can provide us the necessity of increasing the wood section in certain regions where specific humidity and temperature have a great influence.

The conclusions of this study are important because they show the evolution of the behavior of a wooden piece that has not been treated and is directly influenced by the climate conditions: temperature and relative humidity.

However, models have to be verified with real data and with practical experiments on different types of wood,

submitted to different climate conditions in order to establish a pattern of wood degradation. Also, a more detailed numerical example is needed to see the evolution of a structural system from an engineering point of view.

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