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INTEGRATED APPROACH TO PREDICT DETERIORATION OF MECHANICAL PROPERTIES OF DECAYING WOOD

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ABSTRACT: The aim of this paper is to present a methodology to predict bending or compression resistance of structural wooden elements during the onset and growth of the material decay. Two methods are proposed to calculate remaining bending and compression resistance under the attack of brown rot and white rot are presented: (1) reduction of material strength or (2) reduction of the cross-section of the wooden element. The methods are based on the bending and compression tests of material exposed to extreme moisture and are demonstrated as a part of the structural integrity online calculation tool introduced in this paper. They are applicable to planed wood where the decay is expected to progress from the surface inwards. It should be noted that the prediction of structural resistance is in the present state limited to specific loading conditions and decay mechanisms and it is not recommended to replace structural design according to the building codes. However, the estimation of the remaining structural integrity of the material may be very important for the planning of maintenance actions in the structures, such as bridges, where the immediate replacement is not possible or for better safety measures in removing, renovating or demolishing decaying wooden construction.

KEYWORDS: Structural Integrity, Wood decay, Dose-response model, Mass loss, Bending, Compression

1 INTRODUCTION

Exposure of timber products to the external climate, condensate or accumulated water in interiors may lead to biotic degradation of the material. One of the common problems related to the prolonged periods of high moisture is rotting that can lead to material loss and degradation of its mechanical properties [1].
Wood rot, also known as decay, affects the durability and integrity of wood products. It is caused by fungi that grow and feed on the cellulose, hemicellulose, and lignin, breaking down these materials and causing the wood to soften, weaken, and eventually collapse. This paper focuses on the effect of two most common types of rot, brown and white, on the mechanical properties of wood. Brown rot is the most common type of rot and causes the wood to become brittle and crumbly. White rot, on the other hand, affects the lignin in the wood, causing the wood to become stringy and fibrous. The less common forms of decay such as soft rot are not discussed herewith, but the methodology presented in this paper can be easily extended to account for their effect as well.
In order to prevent the decay, it is important to control the moisture levels in the environment surrounding the wood. This can be done by properly sealing and finishing the wood elements to prevent moisture from penetrating, providing adequate ventilation to prevent moisture build-up, and keeping the wood away from sources of moisture like leaky pipes or standing water. If wood rot has already occurred, it is often necessary to remove and replace the affected wood to restore its structural integrity.
The severity of degradation caused by the rot is typically described as decay rating and can be tested on site [2]. The loss of wood mass and mechanical properties due to the decay can be verified experimentally [3].
It was observed that both, the decay rating and mass loss, correlate with the cumulative duration of the high-moisture state above the fibre saturation point at suitable temperature rate (see Figure 1).

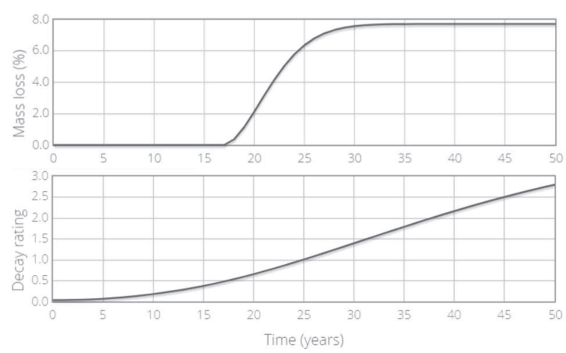

Figure 1: *Example of mass loss (top) and decay rating (bottom) prediction due to brown rot in 80x160 mm softwood member exposed to a constant dose of 10 points per year [4].*

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In order to predict those effects several so-called dose models were introduced earlier [4] by some of the partners of ClickDesign project (Delivering fingertip knowledge to enable service life performance specification of wood) coordinated by the Building Research Establishment in UK. Dose stands for the normalized time of exposure of the material to temperature and moisture levels favourable for the development and growth of wood decay. The aim of the work under the ClickDesign project was to extend the knowledge of the dose-related material loss and to provide practical indicators about the structural integrity of decaying material under the external loads. The tool developed in the ClickDesign project will be then used in Horizon Europe research project 5G-Timber [5] to provide estimation of the quality of the wood waste generated during the service life of modular wooden building.

2 PREDICTIVE MODELS

The most computationally demanding part of the estimation of moisture-induced effects is the numerical prediction of the moisture and temperature dose from the external conditions. This is typically done by hygro-thermal simulation of moisture diffusion, heat conduction and their respective surface emissions implemented in finite element or finite difference models with boundary conditions corresponding to the external climate. For the practical reasons, we assume that the total yearly dose is pre-calculated for untreated wood and the effect of wood treatment, impregnation and surface coating that affects the moisture dose is added explicitly. The following predictive models are based on the existing theories, extended and modified for the practical use in the structural verification of sawn timber

2.1 Mass loss

The loss of material mass ML in % can be modelled by the dose-response function in Equation (1), where the accumulated dose D is obtained either by logistic dose model (LM) or simplified logistic dose model (SLM) [4] and the initial dose before the onset of decay D_0 is assumed to be 150 days. It should be noted that the time before decay cannot be estimated very precisely and in the case of verification of material already contaminated by fungi, we recommend the term $D - D_0$ to be the cumulative dose during the real observed decay period. The final (reduced) mass m_{red} of the wooden element can be then calculated from Equation (2) where its original mass is m.

$$ML = A_{ML}\left(1 - exp(-k_{ML}(D - D_0)^{n_{ML}})\right) \quad (1)$$

$$m_{red} = m(1 - ML) \quad (2)$$

The regression parameters A_{ML}, k_{ML} and n_{ML} in Table 1 and Table 2 were obtained on 15 x 25 x 50 mm specimens of sapwood from *Pinus sylvestris* L.(Scots pine, softwood) and *Fagus sylvatica* (Beech, hardwood) inoculated by *Coniophora puteana* (brown rot) and *Trametes versicolor* (white rot) [6].

Table 1: *Parameters of the mass loss prediction based on logistic dose model LM [6].*

Decay type	A_{ML}	k_{ML}	n_{ML}
Brown rot			
- softwood	52.15172	0.00092	1.72185
- hardwood	41.03166	0.00102	1.69278
White rot			
- softwood	21.557946	0.000732	1.66255
- hardwood	21.188634	0.001542	1.947474

Table 2: *Parameters of the mass loss prediction based on simplified logistic model SLM [6].*

Decay type	A_{ML}	k_{ML}	n_{ML}
Brown rot			
- softwood	42.12828	0.00109	1.86345
- hardwood	32.78056	0.00104	1.88263
White rot			
- softwood	12.776551	0.000591	2.011779
- hardwood	20.833677	0.001235	2.166626

In this paper, the wood decay is assumed to be surface phenomenon (progressing from the surface inwards), and therefore the mass loss ML will be different for wood components with different cross-section from the test samples. In order to generalize mass loss calculation, the value of ML has to be corrected by the shape factor k_{sh} depending on the real width b and height h of the cross-section (see Equation (3)).

$$k_{sh} = 7.9\frac{b + h}{bh} \quad (3)$$

2.2 Decay rating

Decay rating DR is modelled in this paper by the dose-response function in Equation (4). The parameters a_{DR} and b_{DR} are calibrated on the softwood samples of from *Pinus sylvestris* L. (Scots pine), *Pseudotsuga menziesii* Franco (Douglas fir), *Larix decidua* Mill. (European larch) and *Picea abies* Karst. (Norway spruce) and presented in Table 3 [7]. The hardwood rating is not used in the present decay rating model.

$$DR = 4 \cdot exp\left(-exp(a_{DR} - b_{DR}D)\right) \quad (4)$$

Table 3: *Parameters of the softwood decay rating model [7].*

Decay type	a_{DR}	b_{DR}
Brown rot (shade)	2.026	0.0037
Brown rot (no shade)	1.564	0.0054
White and soft rot	1.7716	0.0032

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2.3 Structural integrity

Apart from the loss of wood mass, decay causes changes in the material behaviour, especially reduction of its strength. The knowledge of wooden element cross-section and characteristic strength of the material is typically needed to estimate the element's resistance to external loads. For the practical reasons, only one of those parameters can be modified, while the engineers may continue using the nominal value of the second one (nominal cross-section with reduced equivalent strength or vice versa).
Therefore, two methods to calculate bending and compression resistance were developed: reduction of material strength and reduction of element's cross-section. They are based on the bending and compression tests [9] and are demonstrated as a part of the structural integrity online calculation tool [10] introduced in this paper.

2.3.1 Reduction of the material strength

The calculation of reduced material strength is directly based on the approximation model of tested bending or compression resistance at different levels of mass loss [9]. It represents equivalent strength of the homogeneous material with the nominal cross-section (see Figure 2).

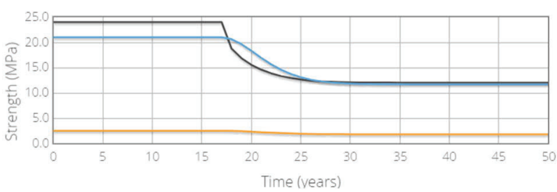

Figure 2: *Example of predicted material characteristic strength degradation in bending (black line), compression parallel to the grain (blue line) and perpendicular to the grain (yellow line) of 80x160 mm member from C24 grade wood.*

The loss of material strength FL can be calculated from the mass loss ML using sigmoid function in Equation (5) with parameters A_{FL}, k_{FL} and n_{FL} fitted to the experimental data for bending [8] and compression [9] in Table 4, Table 5 and Table 6 and the shape factor k_{sh} is obtained from Equation (3). The reduced material strength f_{red} can be then obtained from Equation (6), where f is the characteristic strength of the specified timber grade.

$$FL = A_{FL}\left(1 - exp(-k_{FL}(k_{sh}ML)^{n_{FL}})\right) \tag{5}$$

$$f_{red} = f(1 - FL) \tag{6}$$

In our models, we use experimentally calibrated parameters for bending and compressive strengths, and therefore the applicability of the method is currently limited to structural components subjected to the respective loads.

Table 4: *Parameters of the bending strength reduction model [8]*

Decay type	A_{FL}	k_{FL}	n_{FL}
Brown rot			
- softwood	0.8833	9.6601	0.6155
- hardwood	0.7256	1048.283	2.0538
White rot			
- softwood	2.7368	1.9995	0.7448
- hardwood	54.7094	49.0366	3.2411

Table 5: *Parameters of the compressive strength parallel to gran reduction model in softwood [9].*

Decay type	A_{FL}	k_{FL}	n_{FL}
Brown rot	0.901353	13.069994	1.155478
White rot	1.085979	7.631163	1.248356

Table 6: *Parameters of the compressive strength perpendicular to gran reduction model in softwood [9].*

Decay type	A_{FL}	k_{FL}	n_{FL}
Brown rot	0.989291	5.823211	1.103143
White rot	1.049224	3.977650	0.775042

2.3.2 Reduction of the cross-section

Alternatively, it is possible to describe the effect of degrading resistance as an artificial reduction of structural member's cross-section from the surface towards its centre. The reduced cross-section represents equivalent section of the wooden member and shall be used together with the original material strength (see Figure 3). The reduction depth d is equal from all sides and will be different in different loading situations.

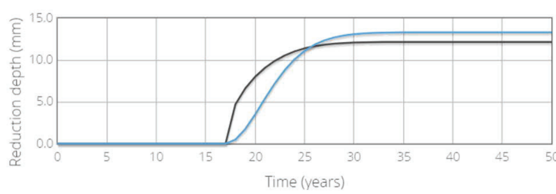

Figure 3: *Example of predicted depth of nominal cross-section reduction in bending (black line) and compression parallel to the grain (blue line) of 80x160 mm member from C24 grade wood.*

It is assumed that the equivalent rectangular cross-sectional area of the compressed member is proportional to the reduction of material strength as in Equation (7).

$$A_{red} = A(1 - FL) \tag{7}$$

We can then express the depth d in compression from Equation (6) as function of cross-section b width and height h and strength loss FL. The solution for root of quadratic Equation (8) is expressed in Equation (9).

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$$(b-2d)(h-2d) = bh(1-FL) \tag{8}$$

$$d = \frac{bh - \sqrt{(bh)^2 - 4bh \cdot FL}}{4} \tag{9}$$

Similarly, the bending load requires proportional reduction of the section modulus in Equation (10).

$$W_{red} = W(1-FL) \tag{10}$$

For bending along the horizontal axis of rectangular cross-section, the root of cubic Equation (11) has analytical solution in Equation (12) with coefficients k_1 to k_6 present in Equations (13) to (18).

$$\frac{(b-2d)(h-2d)^2}{6} = \frac{bh^2}{6}(1-FL) \tag{11}$$

$$d = k_1 - \frac{k_2}{3k_1} - \frac{k_3}{3} \tag{12}$$

$$k_1 = -\left(\frac{k_4 + \sqrt{k_4^2 - 4\,k_2/27}}{2}\right)^{1/3} \tag{13}$$

$$k_2 = k_5 - \frac{k_3^2}{3} \tag{14}$$

$$k_3 = \frac{(4b+8h)/bh^2}{k_6} \tag{15}$$

$$k_4 = \frac{FL}{k_6} + \frac{2k_3^3 - 9k_3k_5}{27} \tag{16}$$

$$k_5 = \frac{(-4b-2h)/bh}{k_6} \tag{17}$$

$$k_6 = -\frac{8}{bh^2} \tag{18}$$

2.4 The effect of surface treatment

If the moisture and temperature dose is pre-calculated for untreated wood, it can be later modified (reduced) concerning a specific material protection. This is not as computationally demanding as numerical pre-calculation of dose for every specific surface treatment. Moreover, it enables a wide range of possible treatments, coatings or structural protective measures with temporal variation of their performance. For instance, the effect of paint that starts degrading after 15 years and is renewed after 25 years is demonstrated in Figure 4. Similar scenarios can be studied in real-time using the ClickDesign structural integrity calculator [10].

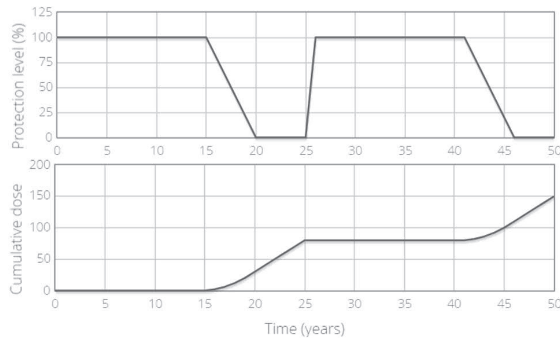

Figure 4: *Example of simulated performance of surface paint (top) and a corresponding delayed dose response (bottom).*

Such behaviour can be modelled using the following three parameters affecting the cumulative dose D entering Equations (1) and (4): treatment maximum protection k_p is the percentage of dose of untreated wood that is avoided by the surface treatment during the first year after its application; treatment durability t_0 expresses the duration (in years) of the maximum level of protection; and finally, the third factor, treatment degradation rate k_d, stands for the percentage loss of the maximum protection k_p per year. Then the total yearly dose of treated wood D_t can be obtained from the pre-calculated yearly dose of untreated wood D_u following Equation (19) where t is the time (in years) from the last renewal of the surface treatment. The value of D_t is limited to interval $\langle 0, D_u \rangle$.

$$D_t = D_u\left(1 - \left(k_p - k_d(t-t_0)\right)\right) \tag{19}$$

Figure 4 (top) shows the protection level $k_p - k_d(t-t_0)$ for parameters $k_p = 1$, $k_d = 0.25$ and $t_0 = 15$ years. The cumulative dose D in Figure 4 (bottom) is then a sum of the total yearly doses D_t calculated over a given period (e.g. design life of a building).

3 STRUCTURAL INTEGRITY TOOL

The predictive models described in the previous Section are included in the Python script and integrated in VTT's Modelling Factory simulation environment "modellingfactory.org". This platform enables efficient online publication of various calculation tools developed in different programming languages or spreadsheet editors and it provides powerful user interface builder with links to the calculation inputs and outputs. The source code of the scripts and user interface are typically published with the Modelling Factory tools.

3.1 Architecture of the tool

The Python script calculates a series of values of cumulative dose D by summing up the yearly dose D_t modified by the optionally defined effect of surface treatment (see Section 2.4) from 0 years until the design life of the wooden element a_{max}. Then the calculation follows the flowchart in Figure 5 generating time series data of different model variables.

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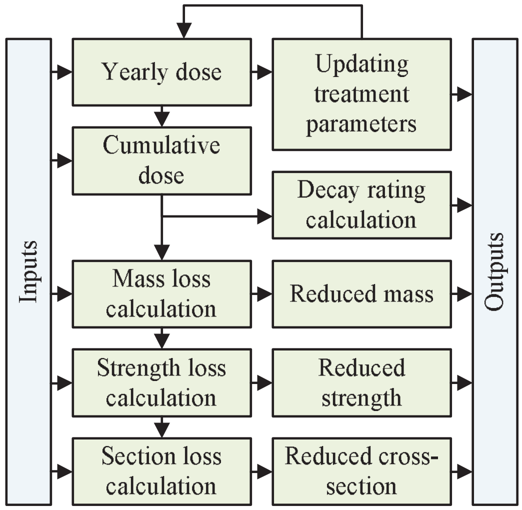

Figure 5: *Architecture of the structural integrity tool with elements of user interface (blue) and Python script (green).*

Mass loss ML and decay rating DR are calculated according to methodology described in Sections 2.1 and 2.2 respectively. Then the value of mass loss is used to estimate the loss of material strength FL in bending or in compression. The prediction of reduced characteristic strength or cross-section is then based on the FL value and follows the methods described in Sections 2.3.1 and 2.3.2.

3.2 User interface

In the case of ClickDesign structural integrity calculator [10], the user interface is divided into two parts: input forms on the left side (Figures 6-8) and output graphs on the right side (Figures 1-4). Since there is no numerical simulation of moisture transport (yearly dose D_u is entered directly in the form), the graphs on the right side are regenerated in real time. The graph data can be also downloaded in a spreadsheet form. For the convenience of the user, brief explanation of the required inputs is provided after clicking on the top-right button next to each input form. The irrelevant parts of the form are automatically hidden.
The dimensions of the wooden element in mm (width b, height h and length l) are entered in the first form (see Figure 6) together with the hardwood or softwood strength class according to EN 338 [11], design life a_{max} (e.g. based on the Eurocodes [12]) and method of structural integrity calculation according to sections 2.3.1 and 2.3.2 of this paper. The length of the member l is used only for the estimation of the full material volume in LCA calculation, which is not discussed in this paper. The design life a_{max} sets the limits of the calculated yearly results. The script then automatically selects the nominal characteristic strength f according to the selected material class. Structural engineers are typically familiar with those design parameters.

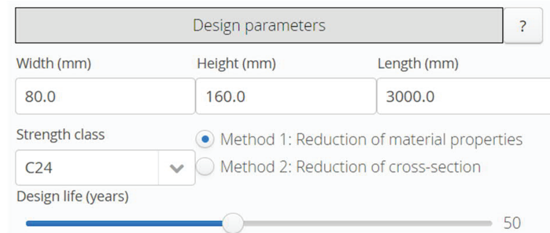

Figure 6: *Basic design values such as dimensions, strength class and design life, and selection of the reduction method.*

The second form (Figure 7) asks the user for additional parameters required for the predictive models. Our goal was to simplify this part and reduce the number of inputs as much as possible. The main requirement is the pre-calculated yearly dose D_u and the method, how it was obtained (logistic model or simplified logistic model [4]). The parameters of decay can be changed by the user, but the default selection (brown rot, no shade) represent the most conservative assumption.

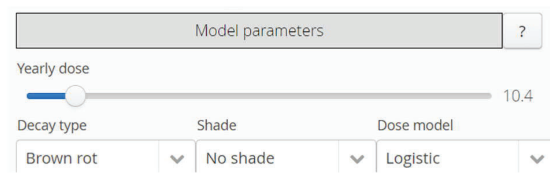

Figure 7: *Additional parameters required for the decay models.*

If the user wishes to simulate the effect of surface treatment, optional form is displayed with the parameters affecting the yearly dose calculation. Those values are not standardized and at the moment there is no experimental procedure how to determine them directly. Therefore, this part is non-compulsory and is hidden from the user by default. The link between commonly used properties of wood treatment (such as surface emissivity) and the model parameters can be the topic for further research and development of the tool.

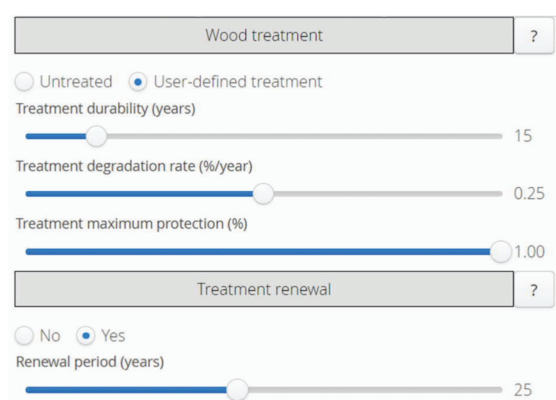

Figure 8: *Optional inputs for the surface treatment simulation.*

It should be noted that it is still possible to utilize the knowledge of the surface emissivity or water vapour resistance by providing pre-calculated yearly dose of the model with appropriate surface properties corresponding to the selected treatment in the "Model parameters" form. However, then the model will lose its real-time regeneration capabilities and possibility to simulate surface renewal in the pre-defined periods.

4 SUMMARY AND CONCLUSIONS

The estimation of the remaining structural integrity of the material is important for planning of maintenance actions in the structures, such as bridges, where the immediate replacement is not possible or for better safety measures in removing, renovating or demolishing decaying wooden construction. It is also useful for estimation of the quality of the end-of-life material in order to optimize wood waste recovery, reuse and recycling.
The presented tool and models integrated in the tool can be a powerful instrument to estimate remaining structural capacity of the wooden elements affected by rot. However, they are at the moment limited to specific loading conditions and rot types and are applicable only to planed wood where the decay is expected to progress from the surface inwards.
The next step in the model development are:

- to integrate material circularity and lifecycle indicators for the assessment of the embodied carbon and generated waste quality of the simulated solution;
- to connect numerical (finite element or finite difference) calculation of the moisture in wood such as already existing Modelling Factory tool called Hygro [13] together with the appropriate dose model;
- to extend the scope of the tool with the knowledge of more wood and fungi species and additional mechanical properties of wood;
- to provide full guidance how the values can be used together with the new Eurocode 5 and the future Eurocode provisions for the assessment of the existing structures [14].

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