RESIDUAL SERVICE LIFE ESTIMATION USING DAMAGE ACCUMULATION MODELS

Jan-Willem van de Kuilen[1,2], **Wolfgang Gard**[1]

ABSTRACT: Service life modelling of timber structures is combined with damage accumulation models in order to capture the combined effect of long term loads (mechanical) and biological of physical wood degradation. The combined model allows for the estimation of residual service life and an analysis of safety factors that may need to be applied. Also, a sensitivity analysis can be performed for future risks. It is shown that the accumulation of damage is very sensitive to the applied models and that failure in timber structures occurs within a very short time frame. A number of practical cases are shown.

KEYWORDS: service life, damage accumulation, degradation, residual strength models, safety factors.

1 INTRODUCTION

A common problem in timber engineering is the assessment of existing structures. Such structures may have different levels of degradation, where degradation may have biological, physical, mechanical or chemical background. Both structures belonging to cultural heritage as well as structures, generally more recent, may have problems. In order to asses such structures, distinct steps in the analysis need to be taken, with a primary focus on as little intervention as possible. Depending on the state of the structure, interventions can be of different levels and of different complexity. Clearly, high level cultural heritage buildings generally have more means of high quality interventions than ordinary buildings. As a results, different levels of intervention can be identified. However, whatever the level of intervention, an assessment of the state of the structure needs to be performed, and most likely a prediction of remaining service life, with or without intervention is required.

2 ASSESSING STRUCTURES

2.1 BUILDING HISTORY

Basic starting point of the intervention is an assessment of the current state of the structure. This current state depends on the historic use of the structure and the assessment tools available. Generally the historical context of the building is known to some extent, and also the use of the building or structure is documented in some way. Consequently, a first estimate of the historical load levels inside the building can be made as well as of the indoor climate. In addition to the indoor climate, it has to be kept in mind that the use of wet or air-dried timber was normal practice. A common problem of drying cracks may consequently be seen as a reduced cross section that occurred relatively shortly after the erection of the building. Indoor climate generally changed over the ages from rather humid with low temperatures to more dry and warmer indoor climates, especially in the northern parts of Europe. With respect to the loads, these can also be estimated on the basis of the historical use of the building. Clearly, no estimate can be made of possible single occurences in history with extreme loads when these are not documented. However, excessive snow loads can generally be estimated from available documentations. On the basis of this, an estimate of the accumulated damage can be made for the most critical parts in the structure, and together with this, an estimate of the sensitivity to variations in loads over time.

2.2 DEGRADATION MECHANISMS

Degradation of structures normally starts from day 1 after the structure has been completed. Since wood is an organic polymer, biotic agents are of high importance. Biological degradation of the wood is caused by fungi, insects, marine borers and to a small extent bacteria. For service life prediction of a structure it is important to know under which conditions degradation phenomena occur and how it will propagate in the long run. All organisms are acting under certain living conditions. The speed of ingestion depends on the degree of living

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conditions. Living conditions of fungi for wood degradation are dependent on moisture content of the substrate, temperature, pH-value and free oxygen for their metabolism. Insects which belong to the dry-insect category, are less sensitive to moisture content but to temperature and the presents of nutrition such as polysaccharides. Marine borers live in water and destroy the wood by channeling the substrate [1]. Salt water is necessary to maintain reproduction and growth of marine borers.

Figure 1 *Results of marine borer attack*

Many attempts have been done to predict deterioration of wood by micro-organisms and insects. [2] developed a prediction model for Australia assuming a time-lag of decay followed by a steady decay rate. Such a time-lag was also found in [3] for foundation piles, but only for heartwood. The decay rate has been expressed by penetration depth of decay per time unit. Essential parameters have been identified such as wood species, geometry and orientation of the structural element and the climate parameters. Time of wetness of wood caused by liquid water has been ascertained as one of the indicators for decay rates. Of cause the model contains many factors which are related to the specific circumstances of the application. But also expert opinion has been involved to determine certain factors. Failure criteria were based on a fixed decay depth in the structural element. In [4] the model is based on mass loss at certain depths of the structural element. The coefficients for the model regarding mass loss, have been determined by laboratory tests with small specimens. Heat and moisture balance in decayed wood have been considered by including analytical models. However, failure criteria and the application range of the model have not been reported. [5] also identified, as other authors [1,2], temperature and the duration of wetness as most important for wood decay. He tried to combine results from laboratory fungi tests, field tests and surveys on structures in service to build up a dose-response function. The dose comprises both moisture content of wood and temperature function on daily bases. From this a decay rate has been derived and a critical dose has been defined.

All attempts have made a step forward to predict decay levels. From own literature study it seems that the coefficients for prediction models have been derived from different exposure circumstances, fungi species, wood species and timber dimensions. Because of this, the relationship between mass loss and exposure time varies considerably and is hard to use for modeling.

However the connection between decay level of structural elements and strengths properties is still challenging. [6] showed that chemical decomposition of cellulose in the wood cell wall , caused by fungi, occurs before mass loss can be recognized. However, in [6] it is also concluded from their special test setup that mass loss caused by brown rot decay correlates significantly with strength properties.

The propagation of fungi growth and decay pattern in structural size elements needs further investigation. Decay rates which have been derived from mass loss values are weak, because of the huge variation of test and application parameters. Empirical models need a huge number of different data records in order to cover most of the applications. Analytical models would be more complex but more flexible for the application. Furthermore, mass loss as traditional parameter can only be applied on small size specimens, whereas large structural elements would require insight in the spatial variation of degradation.

Besides the typical biological degradation, wood may also suffer from physical or chemical degradation. Drying is an important case, but others can be identified, for instance fire, UV-radiation and cavitation at the water line due to natural waves and waves caused by ships passing. A typical example is the degradation of beams by drying cracks, see Figure 2. A number of drying cracks can be identified, one of which is extremely long and has grown from the bottom side of the beam to the side. Here, a large reduction in section modulus can be expected.

Figure 2: *Cracked beam in a historical structure*

As it is known from history that beams, especially with large cross sections, were applied in wet condition, it may be expected that drying cracks will have developed rather shortly after the building was completed. As a consequence, the cross section available for bending or shear stresses will have decreased rapidly and for most of the lifetime the beam will have been supposed to higher stresses than anticipated. More recent problems with cracks are found in glulam structures, especially in outdoor applications, see for instance Figure 3, where a dark coloured glulam beam is exposed, showing a number of cracks near the neutral axis.

***Figure 3:** Cracked glulam beam in outdoor climate. Cracks occur where the maximum shear stresses are expected.*

2.3 DAMAGE ESTIMATE AND MODELLING

Since many years, damage accumulation models are under development with varying levels of complexity. Backgrounds of these models are sometimes simple fenomenological explanations [7], [8] or have a more physical background [9], [10]. Basic assumption is a damage parameter than increases over time until it reaches the failure state. The parameters of these damage models are mainly derived from time-to-failure studies at constant or varying load level where sometimes also variations in moisture content and/or temperature are considered. Most of the load cases studied deal with bending, but a few studies on joints have also been performed [11]. Considerations about the time to failure in the strength development over time has been shown in [21]. Whereas in [9] and [10] the models and their results of [7] and [8] could be explained, the analysis in [11] showed that too complex models should be avoided. The scatter in test results is such, that a relatively simple approach (p.e. [7]) can be accepted as being accurate enough for practice. In addition, using damage accumulation concepts for structural analysis, it was shown in [11] and [12] that only a single high load during the lifetime is governing for failure (killer pulse concept). The studies of [9] and [10] have shown that physical basics of bond breaking and reformation can give a profound basis for the parameters that influence time to failure. Bond breaking and reformation can be expressed using rate equations for chemical kinetics:

$$\frac{d\rho}{dt} = C_f\rho_f - C_b\rho_b \qquad (1)$$

where:

$$C_{f,b} = \frac{kT}{h}\exp(-\frac{E_{f,b}}{kT}) \qquad (2)$$

and $\rho_{f,b}$ the concentration of bonds for the forward or backward reaction respectively.

The reaction rate equation can be further developed. As an external stress is applied, the shape of the energy surface is changed. For instance, when a tensile stress is applied on a cellulose chain, this stress will be transferred through shear stresses (on the molecular bonds) to a partly overlapping parallel cellulose chain. On a higher scale, a similar effect will occur on microfibrillar level. An on a still higher scale, this may occur at cell wall level, where shear between the S1, S2, S3 and P layers will take place. However, on all levels it will be molecular bond breaking and reformation that will be responsible for time dependent creep deformations and time-rupture events. The applied stress will change the potential energy surface with a certain amount of energy, W. Equation (1) and (2) will then become:

$$C_f = \kappa\frac{kT}{h}\exp(-\frac{E_f + W_f}{kT}) \qquad (3)$$

$$C_b = \kappa\frac{kT}{h}\exp(-\frac{E_b - W_b}{kT}) \qquad (4)$$

with $W = W_f + W_b$

Whereas [9] developes the equation for a single energy barrier, thus describing a single molecular deformation process, [10] developes the total energy surface into a number of parallel acting processes, describing the time dependent changes in the material on a generic level, comprising more than one molecular deformation process. Then, the potential energy surface can be approximated using a Fourier-series approximation. The creep and damage process is conesquently regarded as a parallel acting system of symmetrical consecutive barriers [10].

As the non-stressed material is in equilibrium and the number of temperature induced forward reactions is equal to the number of backward reactions, $E_f = E_b$.

In [14], [9] and [10] the equation has been further developed. In [10], the rate equation for bond breaking is given as:

$$\frac{d\rho}{dt} = 2\kappa\frac{kT}{h}\rho_1\exp\left(\frac{-E'}{kT}\right)\sinh\left(\frac{W}{kT}\right) \qquad (5)$$

or, in reduced form:

$$\frac{d\varepsilon}{dt} = \frac{1}{t_i}\sinh(\sigma_1\varphi_1) \qquad (6)$$

with:

$t_i = \dfrac{1}{2\kappa\frac{kT}{h}\rho_1\exp\left(\frac{-E'}{kT}\right)}$, the relaxation time of the i-th expansion term of the energy surface. Equation 6 can be applied to a number of processes in material, a.o.

creep, relaxation and long term strength analysis [14], [9] and [10].

Equation (5) gives the also the basis for damage accumulation modelling and long term strength equations. It explains damage accumulation models from [7] and [8]. [7] gives the exponential damage accumulation equation which gives the time to failure when integrated for $\alpha = 1$ and $t=T_f$

$$\frac{d\alpha}{dt} = \exp\left(-a + b\frac{\sigma(t)}{f(t)}\right) \tag{7}$$

in which σ(t) is the stress over time and $f(t)$ the strength. Integrating for constant loading (σ(t) = c, creep load and $f(t)$ = the short term strength = f_s) gives:

$$\int_0^\alpha d\alpha = \int_0^t \exp\left(-a + b\frac{\sigma}{f_s}\right)dt \Rightarrow$$

$$\alpha = t \cdot \exp\left(-a + b\frac{\sigma}{f_s}\right) \tag{8}$$

With $\alpha = 1$ and $t=T_f$, this can be written as:

$T_f = \exp\left(-a + b\dfrac{\sigma}{f_s}\right)$ or, written as a traditional ´time to failure´ line:

$$\frac{\sigma}{f_s} = \frac{a}{b} + \frac{1}{b}\ln T_f\,. \tag{9}$$

This equation is of course only valid for a determinate value of the strength and a constant load. In practice, this does not normally occur, but as a start, a fixed value for the short term strength f_s may be assumed. One important item in the traditional damage accumulation models is the ratio between applied load and short term strength. The latter is the most easy to estimate. In existing structures, the wood species can be determined and often also the wood quality can be estimated. Often the beams cannot be accessed from all sides and assumptions have to be made, but as for many species the relationship between quality, grade and strength are known, strength values can be estimated more accurately than just taking the strength class value or the minimum grade value. When assessing glulam, some estimates of the lamella grades can be made as well, provided the small sides of the lamellas are accessible. More difficult is the load history but also here, estimates can be made on the basis of historic use of the building (live loads), or readings with regard to snow levels etc. As a consequence, the ratio between load and strength can be estimated. It becomes more difficult when the structure is degraded or, in other words, when damage accumulation has taken place because of other reasons than mechanical loads.

2.4 DEGRADATION AND RESIDUAL STRENGTH ESTIMATE

Such an effect can be taken into account in the damage accumulation model by modifying the stress/strength ratio using degradation parameters that describe the time dependent stress/strength ratio. This changes equation (7) into:

$$\frac{d\alpha}{dt} = \exp\left(-a + b\frac{\sigma(t)}{f(t,T,\omega,\lambda,\mu.....)}\right) \tag{10}$$

The equation can be solved for different strength degradation developments, by stepwise time-integration. The wood strength in the denominator has now been made dependent on the time, moisture content, temperature and two degradation parameters λ and μ. λ describes the ratio of the cross section that is degraded as compared to the non-degraded section, μ describes the strength of degraded material, relative to non-degraded material. The parameters *a* and *b* may also be affected, but as currently no infomation is available whatsoever, these are kept constant. Generally, one would expect a steeper time-to-failure line in the case of long term testing of already degraded wood, similarly to the steeper time-to-failure lines for particleboards and several types of fibre boards. However, as the ratio $b/f(t, T,\omega...)$ has now been made time dependent and degraded material dependent, this steeper ratio is considered to be included in the model.

2.5 LOAD CARRYING CAPACITY

For residual service life estimations with (partly)degraded cross sections, equation (7) needs to be modified slightly, where not the stress and the strength are given, but the load and the load carrying capacity, i.e. in N or Nmm.

For elements under normal stresses, the total load carrying capacity is written as:

$$F_u = f_{c,0}A_{rem} + f_{c,0,dec}A_{dec} \tag{11}$$

with $A_{rem}+A_{dec}=A_{tot}$

Defining now:

$\lambda = \dfrac{A_{rem}}{A_{tot}}$ and $\mu = \dfrac{f_{c,0,dec}}{f_{c,0}}$ equation (6) can be rewritten as:

$$F_u = f_{c,0}\lambda A_{tot} + f_{c,0,dec}(A_{tot} - \lambda A_{tot}) \tag{12}$$

or:

$$F_u = f_{c,0}\lambda A_{tot} + \mu f_{c,0}(A_{tot} - \lambda A_{tot}) \tag{13}$$

or:

$$F_u = f_{c,0}\lambda A_{tot} + \mu f_{c,0}A_{tot}(1-\lambda) \tag{14}$$

or:

$$F_u = f_{c,0}A_{tot}(\lambda(1-\mu)+\mu) \tag{15}$$

The residual load carrying capacity is now a function of the original load carrying capacity, the ratio of the decayed cross section and the original cross section and the ratio of the strength of the decayed wood and the non-decayed wood.

In a time dependent problem, such as the decay of round poles for overhead lines, the remaining cross section can be written as:

$$\lambda(t) = \frac{A_{rem}(t)}{A_{tot}} = \frac{\pi(d_0 - 2r)^2}{A_{tot}} \tag{16}$$

with r in mm/unit time. (p.e. 1 mm/year)

Another problem in roundwood applications, may be the occurrence of brown rot decay in the juvenile wood as shown in Figure 4.

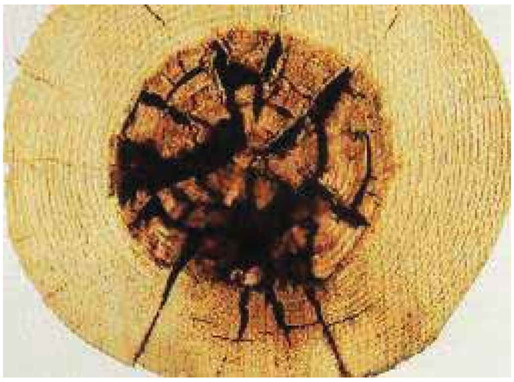

__Figure 4__ Brown rot decay of juvenile wood

In this case, the cross section is written as:

$$\lambda = \frac{A_{rem}}{A_{tot}} = \frac{\pi(d_0 - d_i)^2}{A_{tot}} \tag{17}$$

with d_i the diameter of the decayed juvenile wood.

Similarly for the decayed wood, the strength may be written as:

$$\mu = \frac{f_{c,0,dec}(t)}{f_{c,0}} \tag{18}$$

The effect of this time dependent load carrying capacity is that when a structural member degraded, this degradation leads to higher stresses in the non-decayed zone, as there is stress redistribution in the cross section. If the ratio of equation (18) is set equal to zero, a safe approximation is achieved. In such a case, only the remaining cross section is able to take up the stresses. As these stresses automatically increase, the damage accumulation in the cross section is increased and a shorter residual lifetime will be the result.

For shear and bending, similar models can be derived. The shear capacity of a rectangular cross section is:

$$V_u = \frac{2}{3} f_v bh \tag{19}$$

If it is now assumed that large drying cracks develope within a period initiating at time $t_{cr,i}$ and finished at time $t_{cr,f}$, then the width b_0 will be reduced to b_{cr}. Crack depths up to 50% of the original width may easily occur, but after a while, due to the release of stresses, the system is rather stable and crack growth has come to a halt. Consequently, the shear load carrying capacity over time will decrease with 0.025b per beam side per year, giving:

$$0 \le t < t_{cr,i} \rightarrow V_u = \frac{2}{3} f_v b_0 h$$

$$t_{cr,i} < t \le t_{cr,f} \rightarrow V_u(t) = \frac{2}{3} f_v \left(b_0 - \frac{(b_0 - b_{cr,f})}{(t_{cr,f} - t_{cr,i})}(t - t_{cr,i})\right)h$$

$$t > t_{cr,f} \rightarrow V_u = \frac{2}{3} f_v b_{cr,f} h \tag{20}$$

For bending, the equations become slightly more complex, as the ratio of bending stress over bending strength is needed. For a rectangular cross section, several ´attack´ patterns can be identified, each having a particular impact on the section modulus. Consequently, equation (4) can be written as:

$$\frac{\mathrm{d}\alpha}{\mathrm{dt}} = \exp\left(-\mathrm{a} + \mathrm{b} \frac{M(\mathrm{t}, \omega, \mathrm{T}) / W_0}{M_{\mathrm{s}}(\mathrm{t}, \omega, T) / W_t(b_r, h_r, \omega, T)} \right) \tag{21}$$

On the rectangular cross section, one can envisage attack models on all sides at the same time, but also insect attack that creates an almost hollow core.

For the load, a number of models can be used as well.. For the loads, a number of approaches are available, see for instance the JCSS Model Code [13], Eurocode 1 [15] and ISO 2394 [16] give guidance. For the problem under study here, long term loading and time to failure, a Ferry-Borges-Castagneta (FBC) model [13] is more than sufficient.A fully random load system requires a time consuming integrating and does not seem necessary for the majority of the cases. For instance, if snow load on a roof is to be analysed, one may model a single year in two or three block loads having 6 or 4 months duration each.

3 EXAMPLE CALCULATIONS

3.1 INTRODUCTION

A number of scenarios will be shown, ranging from the foundation pile in figure 8, to the cracked beam in figure 3. In addition, an analysis will be shown of an out-or-service mooring post that have been in service for 25 years in a saltwater environment and has been analysed for its natural durability and remaining load carrying capacity.

3.2 PILE FOUNDATIONS

Pile foundations where decay is present do not necessarily have lost their load carrying capacity to such extend that replacement becomes unavoidable. If the sapwood of timber piles is deteriorated, the remaining heartwood section might still have sufficient load carrying capacity. Consequently, the ratio between decayed area and non-decayed area is an important parameter that can be used when the remaining lifetime of the structure has to be determined. In addition, depending on the type of decay, the strength of decayed timber does not necessarily have to be taken zero. In

Figure 5 the results of parallel to the grain tests are shown, taken from small round specimen drilled from piles [17]. The age of the piles varied between 70 and 640 years. The scatter is very large [18], but still some conclusions can be drawn. The strength decreases with age, but the cause of the strength decrease is not known with certainty, but many factors play a role [19]. Both load and decay will cause a reduction in strength and since the load level during the service life was not known, mechanical damage will have accumulated to a certain extend. The straight lines have been determined on the average values of the test data of the heartwood and sapwood data respectively. The test results on full piles from Delft University have been added. These piles had an age of 100 years (6 specimens) and one of 167 years old. The strength ratio of these data has been calculated on the basis of the average strength value in wet condition of new piles which has been determined at 20.5 Mpa [20]. The results fit in quite well and indicate that the residual strength of piles is mainly governed by the amount of heartwood in the cross section. It must be kept in mind that is not known to which load level the piles have been loaded. The construction of foundations was based more on experience than on engineering practise and therefore stress levels are difficult to determine when structures of one hundred years of age or more are studied.

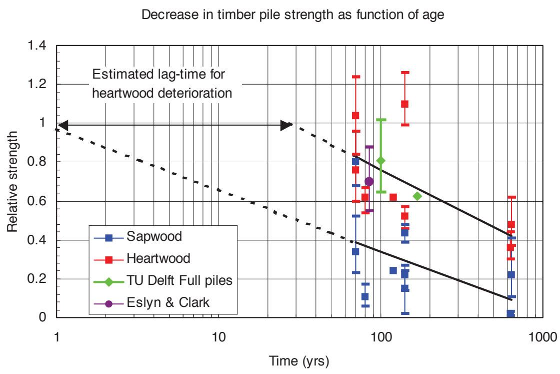

Figure 5 *Residual strength of degraded wood from foundations*

The example calculation contains a modern pile foundation, as shown in figure 6.

The timber pile foundation is analysed and it has been discovered that after 50 years of service life, the groundwater level has been lowered to such a level that the upper part of the pile became exposed to unsaturated soil conditions. As of then, different decay patterns can be distinguished and have been analysed with the service life and damage model. The residual service life scenarios are plotted for two scenarios. The first secnario contains: No degradation (red line) and 3 combinations of λ and μ, where μ=0.2, i.e. the degraded timber material is considered to have 20% of its original strength. The second scenario is a safe approximation as it is considered that the degraded material has not residual strength whatsoever.

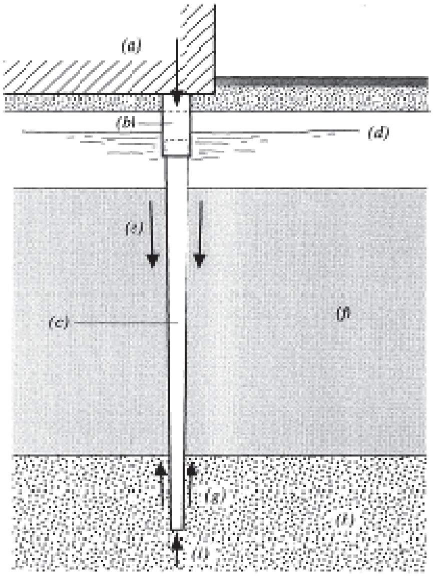

Figure 6*. (a) structure, (b) concrete extension pile, (c) timber pile (tapered), (d) ground water level, (e) negative skin friction, (f) weak clay, (g) positive skin friction, (h) load bearing soil layer, (i) pile toe resistance.*

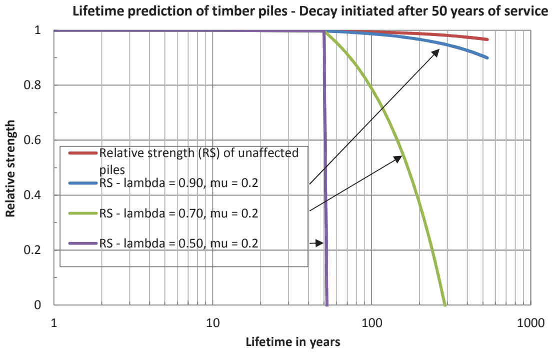

Figure 7: *Residual load carrying capacity of a timber pile for λ = 0.9, 0.7 and 0.5 and μ=0.2*

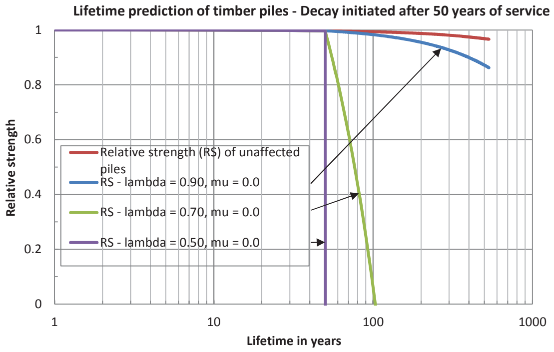

Figure 8: *Residual load carrying capacity of a timber pile for λ = 0.9, 0.7 and 0.5 and μ=0.0*

From Figure 7 and 8 it becomes clear that damage models are very sensitive for the input variables. In this case μ has been lowered from 0.2 in Figure 7 to 0.0 in Figure 8, and a clear shift to shorter residual failure times can be observed. This sensitivity has both positive and negative aspects. The negative aspect is that with increasing uncertainty in the input, the residual service life analysis becomes more difficult and one tends to conclude that the structure can no longer be used. The positive aspect is that if the model gives hardly any change in output, it can be expected that the model output is robust and gives confidence. It must be kept in mind however, that the models are plotted with a logarithmic time scale. A small shift gives a large time span where active measures can be persued. As an indication, in Figure 7 and 8 the combination $\lambda = 0.7$ and $\mu=0.2$ or 0.0 (green line), shift the 100% damage point between 300 and 100 years respectively. Is such an outcome is obtained, there is time for analysing different measures for foundation repair.

3.3 CRACKED GLUED LAMINATED BEAM

The glued laminated beam of Figure 3 is part of a sports hall structure in the alpine region in Europe. The structure can be assigned to service class 3 according to Eurocode 5, i.e. a non protected outdoor environment. As a result, sun, wind and rain induced loads have resulted in cracks and delaminations, mainly along glue lines. From Figure 3 it can be seen that most of the cracks are at the location where the highest shear stresses in the cross section are expected to occur. The residual lifetime (or the actual level of safety against collaps) is to be estimated to decide whether structural repairs measures are needed.
The following calculations are performed.

Basic data:

Glulam	GL24h
width at t= 0	200 mm
width at t=13 years	120 mm
crack development:	3 yrs < t < 13 yrs
depth	800 mm
shear strength:	5 N/mm^2
Load carrying capacity in shear:	480 kN (t=0)
Load scenario 1:	30% constant load
Load scenario 2:	15% constant + 20% snow load, 1 month per year.

In load scenario 1, a basic static long term load is applied. After 3 years the first delamination cracks starts to grow and after 13 years the crack is fully developed. The damage evolution and the residual strength are plotted in Figure 9, together with the development of the relative beam width and the increasing stress level. In Figure 10, the same structure is analysed, but with a 1 month snow load each year starting from year 1. Even though there is only a five percent difference in maximum load, the load accumulation makes itself noticeable, even though this higher load is only acting 1 month per year.

Finally, a third scenario is calculated with the following assumptions:
Assumption 1: after 40 years crack initiation starts. This may be due for instance to a change in use of the structure. Cracks develop between 40 and 60 years.
Assumption 2: the remaining width is 160 mm.
Assumption 3: the load levels are assumed at 15% constant load and one month per year 40% snow load.

Now, from Figure 11 it can be deduced that damage accumulation has already reached close to 10% of the load carrying capacity, before crack initiation starts. Clearly, an extreme snow load of 40% of the short term load carrying capacity is high and can be expected only once every 10 or 50 years, depending on the definition, but it shows the importance of good load estimates and in particulare their time scales. After the crack growth initation, the already damaged cross section (even though this is not visible to the naked eye), continues to lose capacity at even higher rates, leading to collapse of the structure in a very short period.

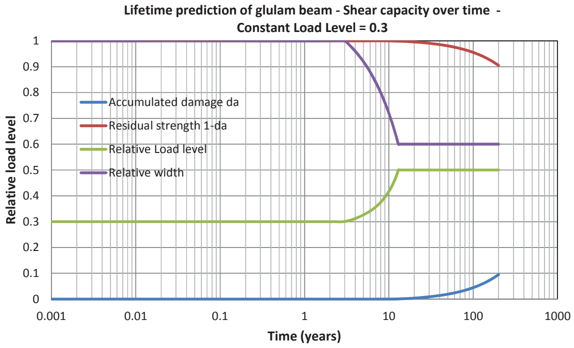

Figure 9. *Damage evolution for load scenario 1*

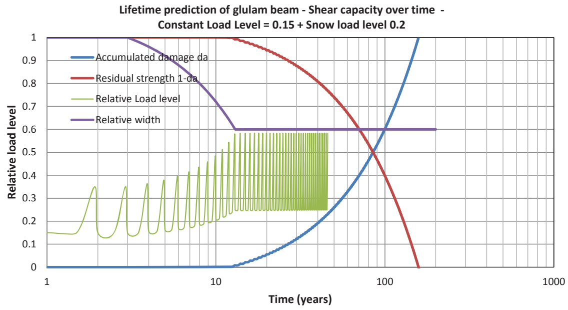

Figure 10*. Damage evolution for load scenario 2 (for clarity, the relative load level is shown only until 45 years.)*

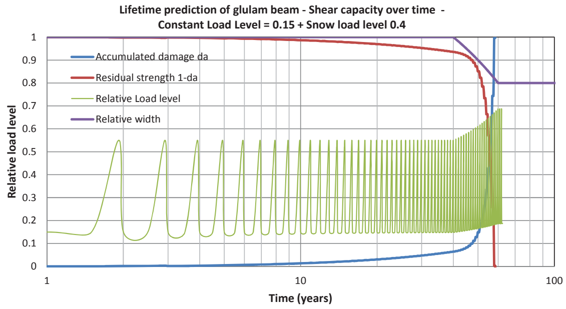

Figure 11*. Damage evolution for heavy snow load and late crack initiation (for clarity, the relative load level is shown only until 60 years.)*

4 CONCLUSIONS

Damage models for a number of load cases and degradation mechanisms have been derived. The damage model uses parameters from standard time to failure tests that have been performed on timber and timber joints. The load carrying capacity that changes over time as a result of biological and physical changes has been modelled. The calculated damage is an indication for the residual lifetime that may be expected. The combination of a damage model with deterioration influence on the strength properties has resulted in a model which can easily be used to study the sensitivity of structures for different load sets and material parameters. When structures are found with decay, either active or inactive, the model can also be used to analyse the effectiveness of different measures that can be taken and the influence of the future use of the structure. In the examples, the calculations have been made using fixed values for strength, but probabilistic calculations could be made when strength distributions are entered in the model. For the loads, an FBC-assumption has been made which can also easily be varied. From the analysis results it becomes clear that modelling of extreme load pulses (or ‘killer pulses’ or ‘peak loads’) seems to be an applicable approach and that failure of structures is indeed initiated in a very short period of time.

Regarding the influence of decay on the strength it seems necessary that more knowledge on the residual strength of decayed wood is gathered. Possibly even more important, the rate at which the decay reduces the cross section of timber elements should be further studied, or how decay spreads across the cross sections.

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