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The influence of deterioration on the lifetime of timber structures

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Abstract

Decay and drying cracks affect the strength of historic timber structures. Because of the traditional timber dimensions used, drying cracks are often large, decreasing the effective cross section of members. Deterioration can also be caused by biological decay, depending on wood species, climatic conditions, structural detailing, etc. Decay can affect the load carrying capacity, having considerable economic and cultural consequences. However, when the decay is no longer active and the damage is limited, repair is not always necessary. When the reliability of the structure is above a certain minimum acceptance level, it is still able to fulfil its task and can be maintained in the original state as much as possible. A method to determine the safety of deteriorated structures is lifetime modelling using damage accumulation models. It allows for the assessment of structures, combining both the influence of mechanical loads (live, wind and snow loads) as well as reduced strength values caused by cracks or decay. Some of the parameters of the model have been determined on the basis of time to failure tests on timber and timber joints, already lasting 40 years. The influence of cracks and decay on the strength of timber members is presented and the consequences for the lifetime expectancy of structures are shown. The model accounts for the level of decay, which is generally determined via in-situ measurements, the rate of decay, as well as the residual strength of decayed timber. The latter two are generally determined in laboratory or field experiments. Different safety factors can be used in the model and future maintenance schemes can be developed. Practical examples are given dealing with cracked beams and with the residual lifetime of decayed piles.

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1 Introduction

Damage models describing the strength development of timber under long term loads have been developed by for instance Gerhards [1987], Foschi and Yao [1986], and Van der Put [1986]. The applicability of damage models to describe the long term behaviour of timber joints has been shown in Van de Kuilen, [1999a, 1999b]. However, these models only describe the strength development in time. In practice, buildings and structures are subjected to a variety of loads other than mechanical. For instance biological attack by insects and fungi can cause decay of the cross section and this may have considerable effect on the safety level.
By combining decay models with strength models, it becomes possible to work on 'lifetime' modelling of timber structures. This allows not only the design stage to be dealt with, also possible scenarios during the structures lifetime can be analysed and if necessary anticipated to. In addition to this, existing timber structures can be analysed for residual strength and residual lifetime. In this paper information on decay of timber is included in an exponential damage model. Numerical integration allows for different scenarios to be analysed. A practical example of a timber pile foundation is given.

2 Reliability and durability based design

The limit state function on which most design codes are currently based of a structure is generally written as:

$$Z = R - S \tag{1}$$

with:
Z = the limit state;
R = the resistance;
S = the load.

In reality, both the resistance and the load are varying in time and the limit state function can be written as:

$$Z(t) = R(t) - S(t) \tag{2}$$

The structure is assumed not to have failed while Z(t)>0. In figure 1 the lifetime distribution of structures is shown. In time the probability of failure increases. Timber shows a load, moisture and temperature dependent resistance. Loads may eventually lead to failure of the timber or the joints. Consequently, eqn (2) can be written as:

$$Z(t) = R(s(\tau), t) - S(t) \tag{3}$$

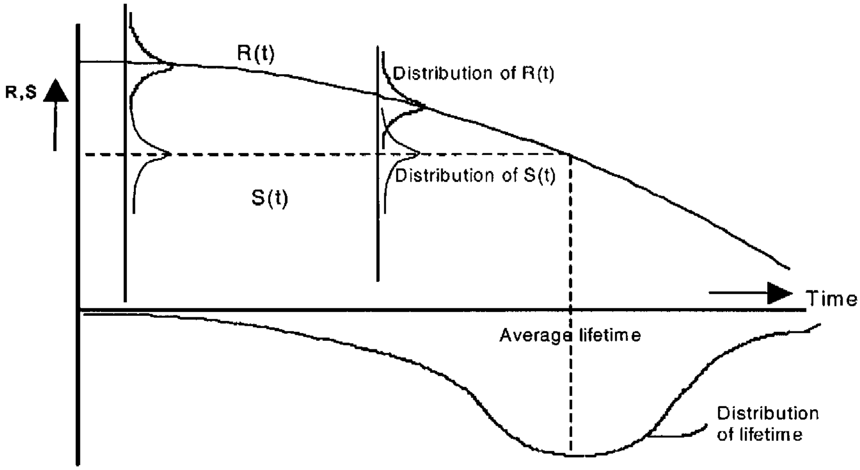

Figure 1 Lifetime distribution of structures

For the resistance function R(s(τ),t) damage functions can be used. The function chosen is an exponential damage equation. The damage takes a value: $0 \leq \alpha \leq 1$. Failure occurs when $\alpha = 1$. This means that $1 - \alpha$ is a measure for the residual strength and thus $Z = 1-\alpha$. The exponential damage function [Gerhards and Link, 1987] reads:

$$\frac{d\alpha}{dt} = \exp\left(-C_1 + C_2 \frac{\sigma(\tau)}{f_s(t)}\right) \tag{4}$$

Parameters C_1 and C_2 are to be determined from time to failure tests. The stress function $\sigma(\tau)$ represents the load history from the time of erection of the structure until the end of the time span under consideration. $f_s(t)$ equals the short term strength. Foschi and Yao [1986] developed a more complex damage function that may also be used. This model was shown to be a special case of a molecular bond breaking damage model by Van der Put [1986]. The difference between the Foschi and Yao model and eqn (4) is relatively small and only relevant for the final failure stage of structures [Van de Kuilen, 1999b].

Safety factors as used in design codes can be applied by replacing $\sigma(\tau)$ with the load values derived from permanent and variable loading:

$$\sigma(t) = \gamma_P P(t) + \gamma_Q Q(t) \tag{5}$$

The design strength $f_{s,d}(t)$ can be introduced by using the material factor:

$$f_{s,d}(t) = f_s(t) / \gamma_M \tag{6}$$

The partial factors have been determined for use in design codes and depend on [Vrouwenvelder and Schießl 1999]:

- the target reliability level β for the limit state;
- the statistical and time variability V of the action or the resistance parameter;
- the sensitivity of the structure to the action or the resistance parameter.

In a reliability analysis of existing structures the values for γ_P, γ_Q and γ_M can be varied and the influence on the lifetime can be investigated. The value of γ_P for instance is specified in Eurocode 1 [1994] as 1.35. If the existing structure is well documented and the permanent loads can be determined with great accuracy, a partial factor for permanent loads of 1.3 may be too high.
γ_M is specified in Eurocode 5 for solid timber as 1.3. This value is based on both material uncertainties as well as dimension uncertainties [ISO 2394:1998]. In an existing structure, the dimensions can often be determined with great accuracy and a different value of γ_M may be applied.
When existing timber structures are assessed decay patterns may be found which can be either active or inactive. Inactive decay is found when the biological activity of fungi or insects has occurred but the environmental conditions at the time of inspection are such that the decay is inactive. The situation is stable and the material strength is decreased but can be assumed constant in time. if measurements are taken that the future condition of the structure is such that the decay will not become active again, this constant but decreased material strength can be taken as f in eqn (6). Active biological activity reduces the strength of the timber at a certain rate and an estimation can be done of the residual lifetime by introducing a time dependent function $f(t)$ for the strength analysis. The parameters may also be modelled using their average value and determination of statistical variations, which allows for more probabilistic calculations.

3 Determination of the short term strength

3.1 General

In the assessment of existing structures the short term strength often has to be estimated. For this estimation, several procedures can be followed, but generally, among others, the following steps are taken:

- determination of the species;
- determination of visible characteristics (cracks, knots, growth ring widths, etc.);
- determination of the moisture content;
- determination of dimensions.

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Where possible static or dynamic stiffness measurements can be performed and sometimes (old) design codes can provide useful information. Visual grading rules can also provide valuable information on the determination of the short term strength and stiffness.

3.2 Decay rates

Decay rates in timber very much depend on the type of biological attack. Decay rates are often expressed in term of loss of mass per time. However loss of mass does not concern the engineer when assessing an existing structure. An engineer needs values for strength and stiffness of decayed timber and he needs information about the distribution of decay in a cross section. The disadvantage of mass loss measurements is that the relationship between mass loss and strength is weak, if existing at all. For softwoods, the bending strength can be predicted on the basis of known relationships between density and strength, but there is no experimental evidence that the same relationship can be used for decayed softwoods. In addition, such a relationship would have to be determined for each type of decay. For hardwoods it is even more complex since the correlation between density and strength in hardwoods is weak and if mass loss is concentrated in wood constituents that do not contribute to the strength it is a useless parameter. Concerning the type of decay it would be an advantage if decay rates could be expressed as rate of penetration in millimetres per time (mm/time). If this would be the case then reduced cross sections and moments of resistance/inertia can be introduced.

3.3 Strength of decayed timber

Most types of biological attack cause a reduction in timber strength. Depending on the type of biological attack, the surface of the timber can be affected or the interior parts. Literature surveys about the relationship between type of decay and the strength are limited. Liese and Stamer [1943] determined the influence of fungi on the compression strength of timber. Wilcox [1978] gave an extensive literature review on the effects of early decay on the strength, making a distinction between brown rot and white rot but did not specify the actual type of fungi. The amount of mass loss was related to several types of loading situations with bending, compression parallel to the grain and perpendicular to the grain being the most useful for the assessment of existing structures. With such data the strength of decayed timber can be determined and consequently used in eqn (4). In figure 2 the relationship between weight loss and strength loss is given based on the results of Wilcox [1978] for brown rot deterioration of softwoods.
As an example, when a weight loss of 10% is reported and measures have been taken so the active decay has been stopped, a remaining strength value of 50% can be used in eqn (4) for stresses parallel to the grain.

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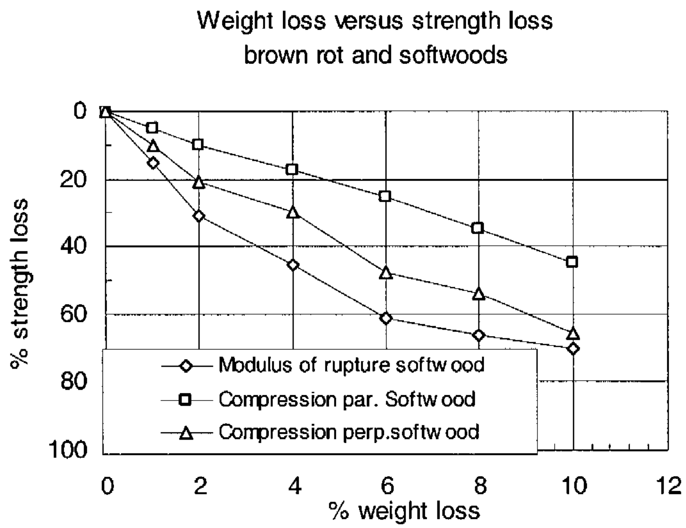

Figure 2. Relationship between weight loss and strength loss [Wilcox, 1978].

3.4 Strength modelling of decayed structural elements

The strength of decayed structural elements can be modelled by assuming a cross section that consists of a non-decayed part and a decayed part. As an example a compression member, for instance a timber pile in a foundation will be used. The characteristic value of the compression strength of timber is denoted $f_{c,0,k}$ and the cross section is denoted A_{tot}, consequently the characteristic value of the pile resistance $F_k = f_{c,0,k}A_{tot}$ when there is non decay present. However, as a result of unexpected decrease in ground water level the upper side of the pile was exposed to soil conditions leading to severe decay of the sapwood of the pile and after a number of years the cross section without decay was decreased to A_{rem} (the remaining cross section). Denoting $f_{c,0,dec}$ the strength of the decayed section and A_{dec} the cross section of the decayed section, the new pile resistance can be written as:

$$F_k = f_{c,0,k}A_{rem} + f_{c,0,dec}A_{dec} \tag{7}$$

Eqn (7) can be further modified when the ratio between the remaining non-decayed cross section and the total cross section can be defined as:

$$\delta = \frac{A_{rem}}{A_{tot}} \tag{8}$$

and similarly, the strength ratio between the decayed strength and the undecayed characteristic strength can be defined as:

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$$\beta = \frac{f_{c,0,dec}}{f_{c;0;k}} \tag{9}$$

Eqn (7) can now be written as:

$$F_k = f_{c,0,k} A_{tot} \left(\delta (1\text{-}\beta) + \beta\right) \tag{10}$$

This equation can be used to study the influence of the amount of decay and the type of decay on the residual lifetime of the foundation. Parameter δ can be determined from in-situ measurements, while parameter β can be determined from figure 2 or from tests on removed parts of the pile. Obviously, parameters δ and β can be time dependent, which can easily be introduced in the model. The parameters C_1 and C_2 in the damage model are determined on the basis of time to failure tests on timber [Foschi and Yao, 1986], [Gerhards and Link, 1987], [Hoffmeyer, 1990] or on timber joints [Van de Kuilen, 1999a].

Eqn (10) gets the same form when deduced for shear or bending capacity.

4. Lifetime predictions

A practical lifetime prediction will now be shown on the basis of a problem sometimes occurring in pile foundations. A typical modern pile foundation in the Netherlands is shown in figure 3 [Timber Engineering STEP 2, 1995]. Siviero and Murat [1993] have shown pile foundations as for instance found in Venice, which resemble the older Dutch pile foundations. All calculations have been made with a pile diameter of 160 mm. The characteristic load on the structure was 100 kN, excluding the safety factors as specified in eqn (5). Three levels of reduction in cross section are presented. It is assumed that the reduction has taken place in a relatively short period after 100 years of service. This might have happened for instance when the ground water level was reduced below the pile top after 100 years and biological attack has reduced the cross section. Cross section ratios δ of 0.8, 0.7and 0.6 are calculated, as shown as in figure 4. In addition, two values of β are assumed (β = 0.3 and 0.0). A β value of 0.0 always gives a safe approximation because it neglects any contribution to the load carrying capacity from decayed timber.

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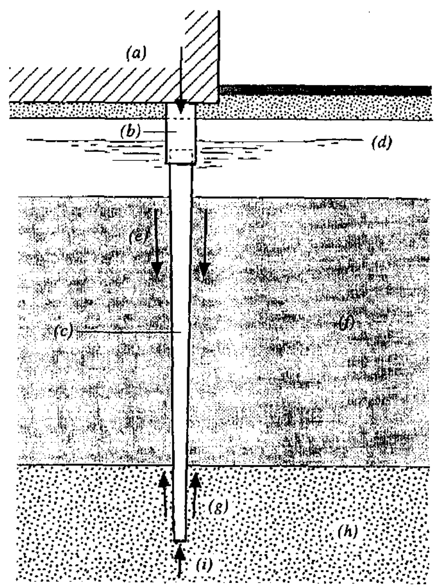

Figure 3. Schematical drawing of a pile foundation, (a) structure, (b) concrete extension pile, (c) timber pile (tapered), (d) ground water level, (e) negative skin friction, (f) weak clay, (g) positive skin friction, (h) load bearing soil layer, (i) pile toe resistance.

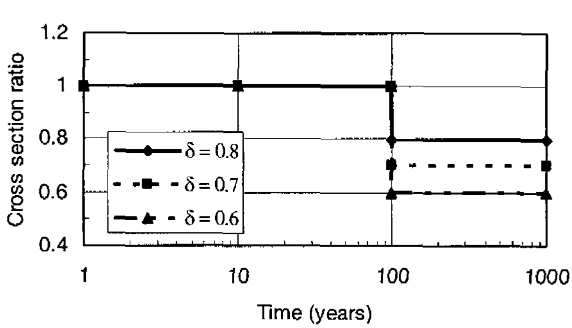

Figure 4. Time dependency of the non-decayed cross section of a pile.

The results of the residual lifetime calculations for are given in figures 5 and 6, for β values of 0.3 and 0.0 respectively. From figure 6 it can be concluded that when the decayed area has zero strength, the residual lifetime that is to be expected drops rapidly. Consequently, it can be of great importance of the type of decay is determined and the strength of decayed timber is well known.

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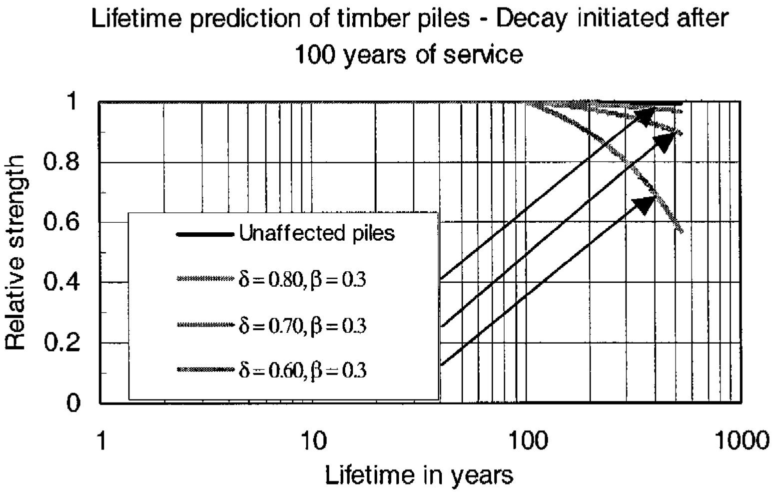

Figure 5. Lifetime prediction for piles for three levels of δ and β = 0.3.

Besides the analysis of the influence of decay, the model can also be used to study the influence of safety factors. Not only the load factors can be varied but also the material factor. Especially for existing structures that have to be assessed it may be necessary to have a closer look on those values.

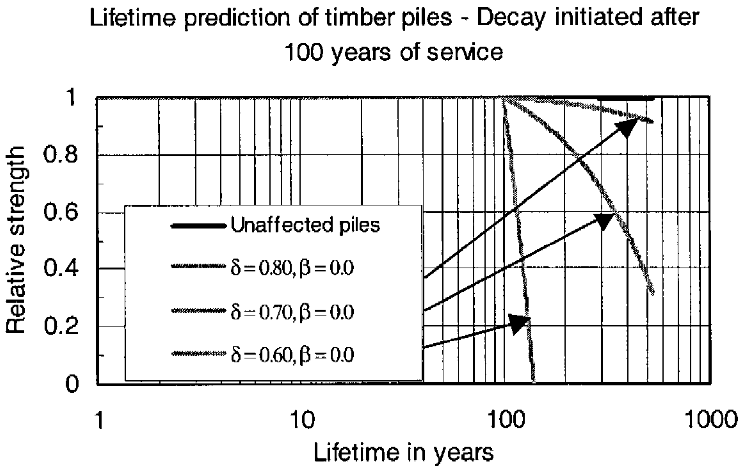

Figure 6. Lifetime prediction for piles for three levels of δ and β = 0.0.

5. Conclusions

A damage model from literature with parameters derived from time to failure analysis of timber and timber joints have been combined with strength reduction

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models as a result of decay. An example in which a strength reduction factor was given for compression parallel to the grain was given and the influence on the residual lifetime could be shown. However, the same principle can be used to check bending stresses and support conditions. The combination of a damage model with the decay influence on the strength and cross section results 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. The sensitivity of the structure for load factors and material factors can be analysed as well.

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