Service life analysis of marine structures made of tropical hardwoods

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Summary
In the Netherlands with its many waterways, engineered structures are often made of tropical hardwoods for both freshwater and saltwater applications. The tropical hardwoods used are imported from around the world with azobé, basralocus and demerara greenheart being the most widely used. A research programme has been performed to study degradation mechanisms of these structures in terms of mechanical and biological loads, but also in terms of end-of-life wood quality for re-use. An important focus relates to the differences between durability, safety and their interrelation (service life). This is illustrated by a practical example of a fendering structure. The relation between safety and durability is illustrated by a reliability calculation of a single pile of a fending structure loaded with a collision force.

1 Introduction
Timber as a structural material for hydraulic works can be found all over the world. Basically they can be divided in structures made from durable (tropical) hardwoods or from treated softwoods. In the Netherlands, most of the time tropical hardwoods are used. Example structures are slackening structures, fenders, sheet pile walls, lock gates etc. The tropical hardwoods used are imported from around the world with azobé (Lophira alata), basralocus (Dicorynia guianensis) and demerara greenheart (Chlorocardium rodiei) being the most widely used. The interest in wood as a construction material for these waterworks is growing again, because it has been shown in practice that these structures have long service lives and because wood is a renewable material and CO\textsubscript{2} neutral. The Dutch Government has now implemented a policy for the stimulation of use of sustainably produced timber as well as reuse of timber. Therefore a research programme was started to study degradation mechanisms of these structures in terms of mechanical and biological loads, but also in terms of end-of-life wood quality for re-use. An example of a marine structure in a saltwater environment is shown in figure 1, taken at the Isle of Texel in the North sea.
2 Degradation mechanisms

2.1 Introduction

Timber degradation can be distinguished in four different forms: mechanical, physical, chemical and biological. Mechanical degradation occurs in the form of long term stresses that deform the structure and slowly reduce the strength. This is generally called a duration of load effect and is accounted for in design standards such as Eurocode 5. For long term strength, loads must be classified in a load duration class, which can be instantaneous, short term, medium term, long term or permanent. It has been shown in [1] that mechanical loads only cause damage when they are short term and very high.

Hydraulic structures can be assigned to service Class 3, but the loads can vary from instantaneous for fendering structures, to permanent for sheet pile walls. Permanent loads are too low to cause serious damage and do hardly influence the service life of the structure, except for pile foundations. Physical degradation occurs either in case of fire (temperature), wind, UV radiation or drying. Especially in older structures, drying cracks may be visible above the waterline. Depending on the size of these cracks, the structural safety may be at risk, but generally only when shear is one of the governing failure modes. Bending strength is hardly affected, mainly because in most marine structures the highest stresses in bending occur below the waterline. The depth of these cracks depends on factors such as initial moisture content, climate after installation, sawing pattern of the beam and whether the heart of the tree is present or not.

The by far most important parameter for service life modelling is biological degradation, in combination with mechanical loads. Due to biological attack, structures are affected and cross section may be changed as a result. Examples are piles and poles and hydraulic structures in general that may be attacked by fungi or insects at the waterline, ground-air level or at groundwater level.

Horizontal beams in marine structures that cannot dry to sufficiently low moisture content levels are also at risk. Saltwater structures may also be susceptible to shipworm or gribble attack. Typical degradation of wood attacked by shipworm and gribble is shown in figure 2.
2.4 Fungi growth and fungi recognition

Mid and Near Infrared Microscopy are relatively young techniques used to detect and analyse fungi decay in wood. They can give insight in how much decay is present and what is the extent of the decay in terms of molecular changes and consequently changes in mechanical resistance. In order to evaluate the service life of a structure affected by fungi decay, it is important to estimate, besides the strength loss, the rate of decay (or speed) of the process. Experimental data for the activity, expressed as weight loss in time, of different fungi species on different wood species are reported in studies focused on testing effectiveness of wood preservatives against wood decay according to standards such as EN 113. However, those methods have limitations when used for service life prediction of structures. The main limits are concerned with the restricted exposure time (generally up to 16 weeks) and the relatively small size respectively volume of the specimen (max 10x25x250 mm$^3$). The relation between volume of the wood specimen and the rate of degradation has not been reported in the literature so far. In this research it was proven that the rate of degradation is strongly influenced by the volume of the samples: decreasing up to one third when increasing specimen’s volume from 10$^4$ mm$^3$ to 40 times bigger for larch samples. In [2] it was shown that chemical changes of the cell wall caused by fungi can be related with strength changes, whereas more generally researchers have been studying the direct relationship between fungi and weight loss [3]. The present study deals with two aspects: Develop a new protocol for laboratory decay tests considering decay value by volume/time relations, together with CATAS Spa Testing Laboratory (Italy). The second aspect deals with the characterization of wood decay using the Attenuated Total Reflection (ATR) IR spectroscopy. NIR spectra of the samples were acquired after different exposure times and spectral differences were analysed by Multivariate analysis (MVA). Backgrounds of this new protocol can be found in [4]. The techniques are used here to study the durability of hardwoods, in terms of chemical changes, from existing marine structures for future service life and possible re-use in other structures.

3. Service life and damage modelling

3.1 Background of structural assessment and service life predictions

Flow charts for structural assessment have been developed by a number of researchers and institutes have been developed in order to be able to make a reliable assessment [5], [6]. Generally, these flow charts require analysis of the original structure, its uses, localization of defects/degradation and classification. On the basis of an analysis of the (historical) situation, the results of the inspection and the planned future use of the structure, an estimate is made on the residual lifetime and the necessity of repair or replacement. Since timber has a load and time dependent strength, the full short term resistance based on modern design principles may no longer be fully available, especially in the case of foundations, where the ratio between dead and live load is quite different from floors and roofs. In this respect, timber from floor and roof structures can be expected to have 100% strength capacity [7]. In some marine structures the dead load is negligible, while in others, dead weight can be important (lock gates). However, biological decay may affect the load carrying capacity. Decay may be either active or non-active, the effects on the resistance of the structure have to be examined. The expected future loads can be determined from the new building plans or from current design codes. Depending on the situation and legal requirements, deviations from loads specified in design codes could be accepted in certain cases. The information obtained from the expected loads and the state of the structure allows for calculations of the residual strength of the structure and in conjunction with that the expected 'remaining' service life.

After an assessment of the structure, the final step is to predict the load carrying capacity and the residual lifetime. A new approach for this is the assessment of the strength using a modified damage accumulation model. Damage accumulated models have been used in timber research describing the strength development of timber under long term loads. Several models can be found in literature [8], [9], [10] but the one from [11] will be used here as an example. Since these models only describe the strength development in time they have to be modified to include the influence of deterioration on the material properties, for instance
biological degradation decay of the cross section and this may have considerable effect on the strength capacity of members. By combining durability models with strength models, it becomes possible to model the 'residual lifetime' of structures. Different approaches are possible using probabilistic calculations [12], of kinetic based models [13], but here the exponential damage accumulation model of [11] is modified. The limit state function is generally written as:

\[ Z = R - S \]  \hfill (1)

with \( Z \) = the limit state, \( R \) = the resistance and \( S \) = the solicitation or load. In reality, both the resistance and the solicitation are varying in time and the limit state function can be written as:

\[ Z(t) = R(t) - S(t) \]  \hfill (2)

A structure is assumed not to have failed while \( Z(t) > 0 \). In figure 3 this is shown schematically.

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

The damage \( \alpha \) takes a value: \( 0 \leq \alpha \leq 1 \). By definition, failure occurs when \( \alpha = 1 \). This means that while \( 1 - \alpha > 0 \) the structure is still able to carry the load at that point in time and \( Z(t) = 1 - \alpha \). The parameters \( C_1 \) and \( C_2 \) in the damage model are determined on the basis of time to failure tests on timber [7], [11] or joints [1], [15]. The damage function can be used to estimate residual lifetimes of structures. The stress function \( \sigma(t) \) describes the load from time of erection until the end of the time span under consideration. The strength \( f_s(t) \) represents the

**Figure 3 Schematic representation of the distribution of lifetimes of structures**

The probability of failure increases, since the resistance of members generally decreases with age. In case of timber, the resistance \( R(t) \) depends on the load and the load history. Moisture content and temperature also have an influence, but these are neglected here. Equation (2) can thus be written as:

\[ Z(t) = R(s(\tau), t) - S(t) \]  \hfill (3)

For the resistance function \( R(s(\tau), t) \), the Gerhards damage function [11] is used here, which is easy and straightforward to use, but now the material strength is modified depending on the amount of decay and residual strength of decayed timber. Thus, a time dependent resistance \( f_s(t) \) is introduced in the model:

The diagram shows the distribution of lifetimes, the average lifetime, and the distribution of resistance and solicitation over time.
time dependent load carrying capacity of the material. This can be written in terms of bending capacity, shear capacity or normal strength capacity and has a relation with the degraded cross section in terms of moment of area or effective cross section [14]. Depending on the type of degradation, the following time dependent mechanisms can be recognized:

3.2 Assessment of degradation

A number of piles have been inspected for degradation, from both saltwater and sweetwater structures. A number of areas are distinguished along the pile axis for investigation: above water, at the waterline, below the waterline, at the water-ground interface and below ground. Normally, the worst degradation is expected at the waterline. However, all areas of the piles have been inspected as far as possible: above the waterline, at the waterline and below the waterline. Above waterline degradation is generally biological decay caused by mould growth, plants, etc. but also physical decay (cracks) and mechanical decay (collisions, ropes) are observed. In addition, damage is most likely to be worse on all horizontal parts of the structures. In saltwater structures it is also possible that biological activity starts to grow on the surface around the waterline. An example is shown in figure 4. Areas that were designed such that they could easily dry out, generally did not suffer from decay. On the waterline and splash zone most of the decay was observed. On average after 28 years, piles were degraded at the waterline from the outside inwards by about 25 mm. The piles were placed in a sweet water environment, but the measurements give indications for saltwater environments as well, provided there is no shipworm or gribble degradation. However, very often the waterline degradation is not uniform over the cross section, but one, two or three sides are degraded more or only a single corner. For safety however, it was chosen in the assessment procedure to take the maximum degradation as uniform. Below the waterline the decay was much smaller and only some millimetres were assumed to be biologically degraded. In the seabed far below the waterline, it is currently assumed that the oxygen level is so low that no biological attack occurs, but bacterial decay is under investigation. In figure 5 some typical damage-time relationships are shown that can be observed in practice. These relationships can be used in equation 5 and the result will be a prediction of the current state of the structure in relation to the original state. From here, an

Typical fungi growth rate  Typical impact damage  Typical linear degradation

Figure 4. Marine life at waterline on a hardwood pile

Figure 5. Time dependent degradation for fungi and impact load and a schematic representation of the statistical distribution of a typical linear degradation.
outlook can be made for the future on how the structure will behave in time and when the damage is such that repair or replacement needs to be considered. For pile foundations which are common around Europe such scenarios have been calculated depending on fungi growth as a function cross section and the residual strength of decayed timber [14].

3.3 Service life prediction

For the fendering structure three types of analysis have been performed. The current state of the structure, including decay at the waterline have been analysed for structural safety. On the basis of the measurement a 95% upper limit of the maximum degradation at the waterline could be determined, before the structural safety against bending was reduced. This coincides with a four sided decay pattern of just over 50 mm, for a pile with an original cross section of 300 x 300 mm$^2$. The structure was analysed using the Blum’s theory for equilibrium, the principle of which is shown in figure 6.

![Figure 6. Blum’s method for the calculation of fendering structures with a collision force.](image)

To calculate service life, the load carrying capacity at the waterline including the effect of degradation shall be equal to or greater than the load carrying capacity in the ground. In this case bending is taken as the governing failure mode. In Table 1, three scenarios are given for the service life. Scenario 1 is the current situation without any alterations. Scenario 2 is the current situation; however the 10 worst piles out of 64 are replaced when degraded heavily. Scenario 3 has regular maintenance in the form of cleaning and small repairs, but start from better structural detailing. The values for scenario 3 have been estimated from the current state of the analysed structures and the structural details with which they have been designed.

| Table 1. Service life predictions for three scenarios. |
|---------------------------------------------|-----------------------------------|-----------------------------------|
| Scenario 1: Current structure | Scenario 2 Replacement of worst piles | Scenario 3 Regular maintenance good detailing |
| Average decay rate (mm/side/year) | 0.9 | 0.8 | 0.5 |
| St.dev. of decay rate | 0.4 | 0.3 | 0.2 |
| Design value for decay rate | 1.6 | 1.3 | 0.8 |
| Expected service life (year) | 33 | 40 | 64 |
| End of life in year: | 2011 | 2018 | 2042 |
4 CONCLUSIONS

Timber structures service life can be estimated combining damage accumulation models with fungi growth models and drying crack growth models. Using such modified damage models, residual lifetimes can be predicted using different scenarios for rate of decay, the remaining strength of partly decayed timber or physical loads such as drying cracks. With such decay models, damage accumulation models can be solved for different load histories and mechanical resistances, indicating the service life of the structure, or in case of the analysis of existing structures, the remaining service life. The strength data of the timber, as well as the attack risks and velocity can be varied, so a reliable analysis of the structure can be made. In addition, the sensitivity of the structure for further (biological) attack can be studied. A coefficient of variation in the decay rate of fungi is not uncommon.

To adjust for fungi growth, a new test decay procedure has been developed in order to induce decay in two sets of samples differing in volume sizes. FT-NIR technique and multivariate analysis were applied to characterize wood decay. The spectral analysis showed that it is possible to discriminate sound and decayed samples by infrared spectroscopy. Within the decayed samples, it was possible to discriminate between “low” and “high” decay, giving useful information about the spread of the fungi inside specimen.

Furthermore, insight has been obtained in the importance of the volume of wood in relation to the decay rate. Apart from the laboratory analysis on decay rates, actual structures have been analysed for wood quality and decay.

Existing marine structures in sweet- and saltwater have been analysed for degradation patterns and decay. It was found that structures often are decayed in the splashzone, but also that the splashzone is a fruitful biological environment for marine life growth. However, this does not always have to lead to a lack in structural safety. Measurements have shown a rate of decay of about 25 mm over a period of close to 30 years.

It has been shown that on the basis of an analysis of a fendering structure, the current expected lifetime of 30 years can be doubled with the right maintenance and structural details and maintenance.

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