An integral approach for the assessment of timber pile foundations

van de Kuilen, Jan Willem; Beketova-Hummel, Olga; Pagella, Giorgio; Ravenshorst, Geert; Gard, Wolfgang

Publication date
2021

Document Version
Accepted author manuscript

Citation (APA)
van de Kuilen, J. W., Beketova-Hummel, O., Pagella, G., Ravenshorst, G., & Gard, W. (2021). *An integral approach for the assessment of timber pile foundations*. Paper presented at World Conference on Timber Engineering 2021, WCTE 2021, Santiago, Chile.

WCTE 2021
WORLD CONFERENCE ON TIMBER ENGINEERING
SANTIAGO, CHILE | 9 - 12 AUGUST

AN INTEGRAL APPROACH FOR THE ASSESSMENT OF TIMBER PILE FOUNDATIONS

Jan Willem van de Kuilen[1,2], Olga Beketova-Hummel[3], Giorgio Pagella[4], Geert Ravenshorst[5], Wolfgang Gard[6]

ABSTRACT: Timber pile foundations are widespread in many areas around Europe and North-America. Especially in areas with weak soils, timber pile foundations have been a very good and economic solution. However, aging of the foundations can become a problem, as physical, biological and/or chemical degradation may occur over time. Now, that foundations can be up to 500 years in cities like Venice, Amsterdam, Hamburg, Boston and many others, questions arise about the reliability and which assessment methods can be used in order to estimate the current load carrying capacity and their residual service life. Residual service life is depending both on the time-to-failure behaviour of wood, as well as, the dead and live loads on the piles below buildings, quay walls and bridges. The approach taken integrates degradation models with a reaction kinetics based damage model. For wood that remains consistently below the waterline, the combination of bacterial degradation and long term loading is considered the most important, but degradation by fungi also may occur depending on soil and groundwater conditions. The integral assessment model will function as a tool for repair and maintenance strategies for asset managers and structural engineers.

KEYWORDS: Timber piles, Bacterial degradation, Assessment tool, Residual strength, Asset management

1 INTRODUCTION

Many historic buildings around Europe are founded on timber piles. Service life analysis of timber pile foundations is getting more important over time. Not only are the foundations getting older and older, also the economic activities are getting more and more important. In cities like Amsterdam or Venice [1],[2], economic activities in the centre of the city govern many decisions made by the city councils, whether related to normal activities for citizens or for tourism. Closing down infrastructure (bridges, quays) or buildings because of failing foundations can cause considerable economical losses. In addition, when modifications on existing buildings are planned, a structural assessment of the existing foundation is often necessary. Consequently, there are various design and maintenance aspects that have to be taken care of, in order to assess the quality of the entire foundation. This deals with assessment of the current state of the foundation from both a mechanical as well as a durability point of view. As the pile foundations were primarily designed based on historical experience, the stress state can only be estimated on the basis on an analysis of the current structure. After hundreds of years in service, the load carrying capacity of piles may be affected by the duration of load effect, but also by biological degradation. In order to understand these processes and creating a sound basis for the assessment of wooden pile foundations, a large project has been initiated by the community of Amsterdam, with a the goal of capturing many of the aspects that determine the current state of wooden foundations as well as their remaining service life estimate. This includes analysis of loading conditions, age of the structure, assessing the mechanical properties of wood, inspection techniques and remaining service life model development.

2 TIME DEPENDENT ASPECTS OF TIMBER PILES IN SOIL

2.1 DURATION OF LOAD EFFECTS

Duration of load effects include creep, relaxation and time to failure (TTF). Especially in loading situations on timber piles in soil, loads will be acting for hundreds of years. It means that the long-term strength of wood might become the limiting factor. Studies into the time to failure of wood are several and have resulted in code values that indicate that the long term strength of wood is around 50-

[1,2] Jan Willem van de Kuilen, Wood Technology, Technical University of Munich, Germany & Biobased Structures and Materials, Delft University of Technology, the Netherlands , vandekuilen@tum.de
[3]Olga Beketova/Hummel, Biobased Structures and Materials, Delft University of Technology, the Netherlands, o. Beketova-Hummel@tudelft.nl
[4]Giorgio Pagella, Biobased Structures and Materials, Delft University of Technology, the Netherlands, g.pagella@tudelft.nl
[5]Geert Ravenshorst, Biobased Structures and Materials, Delft University of Technology, the Netherlands. g.j.p.ravenshorst@tudelft.nl
[6] Wolfgang Gard, Biobased Structures and Materials, Delft University of Technology, the Netherlands, w.f.gard@tudelft.nl.

60% of the short term strength and that the coinciding lifetime of the structures at this load level may span about 100 to 1000 years. As time to failure processes are logarithmic by nature, large scatter in outcome will result. Generally, but especially for ´young´ structures, load levels are much lower during most of the lifetime, and consequently there are no safety issues. In Eurocode 5 and similar design codes, this is covered through the application of a factor for duration of load (p.e. k_{mod} in Eurocode 5). In foundations however, the age of the piles can be up to 500 years or more. Consequently, these piles are in service for much longer than modern design codes generally cover. The piles are primarily loaded in compression by dead weight, although in quay walls also a combination of compression and bending may occur.
Measurements on recovered piles in the Netherlands have indicated pile tip diameters generally range between 110 to 160 mm and length between 11 and 16 meters for the older foundations. With a mean wet compression strength of new timber piles of around 16 N/mm^2, the short term maximum load carrying capacity between 150 and 320 kN, which is being halved when applying the k_{mod} factor for long term loads in a saturated environment (Service Class 3). Experience also shows that the relative load level can be around the 50% load level, indicating that the long term strength of the wood may have been reached after being in service for one or more centuries.
Assuming that the long term load strength of wood in compression is equal to that in bending, and the time-to-failure line of Wood [11] is applicable, the time to failure can be estimated:

$$\frac{\sigma}{f_s} = 0.904 - 0.063 log t_f \qquad (1)$$

With σ = stress, f_s = the means strength and t_f = the time to failure in hours. For $\sigma/_{f_s} = 0.5$, a time to failure of 295 years is obtained, so a reduced load carrying capacity may be expected when inspecting very old piles having a service life in the hundreds of years. A number of these linear time to failure equations are available, some more favourable than others. The general trend is that at load levels between 40-60% of the average short term strength, wood failure may occur within the time frame of foundations. In the case of near pure compression loading, like in piles under bridges, this will normally not lead to catastrophic failure, but more to excessive vertical deformations. In quay walls however, often also horizontal load components may be present, and consequently failures can be more catastrophic.
More advanced models for the time to failure do exist as long term strength data are not always following the pattern of a straight line on a logarithmic time scale. Non-linear time to failure models for wood have been developed by Nielsen [12], Foschi and Yao [4],[13] and Van der Put [5],[14], who gave a physical foundation for the parameters of [4],[13]. The non-linear models often seem to fit the test data slightly better. The disadvantage of these models is that quantification of the model parameters is generally more challenging as reported in Van de Kuilen [15] for timber joints and Clerc et al [16] for the fatigue lifetime of glued wood components. The parameters are not only more difficult to determine, the model values are also quite sensible to the data. As data at load levels below 50% are very limited, the threshold level is very hard to estimate. On the other hand, the non-linear approaches seem to perform better in the load level range between 0.7 and 0.9.

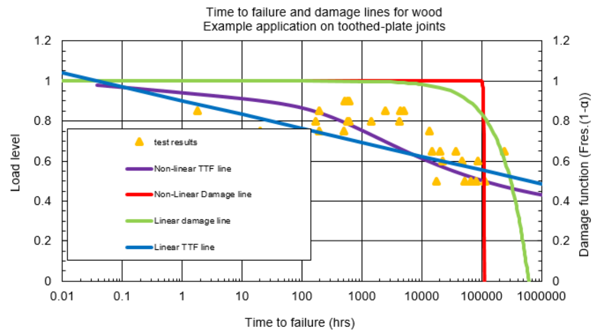


Figure 1: *Indicative Time-To-Failure and Damage development (actual strength at time t) for a linear and non-linear damage accumulation approach. Example based on [15]*

2.2 BIOLOGICAL DEGRADATION

As far is known to the authors, about 90 years ago the first indications came up that wood in pile foundations under water could be deteriorating by bacteria. A first fundamental study was performed by Varossieau [3] from the Centre of Materials Research in the Netherlands, which later became part of TNO, the Netherlands Organization of Applied Scientific Research. Various stages of bacterial decay were identified in old wood that had been in service in ground and below the groundwater table. One of the conclusions of this work was that bacterial decay starts relatively within first couple of years. The bacterial decay can be identified from the black areas in Fig. 2, where the cell wall is degrading.

Figure 2: *Microscopic image of incipient bacterial decay in wood from an old foundation in Rotterdam [3]*

The remaining load carrying capacity of wood within such a cross section may look like the 3D profile as shown in figure 3, slightly modified from [6,7].

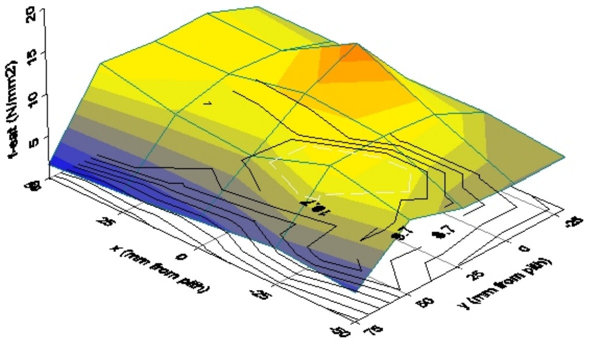


***Figure 3** Profile of remaining compression strength based on small square specimens extracted from a 167 year old pile: the exterior area is heavily decayed with low strength [6].*

It is derived from a timber pile recovered from a 167 year old foundation and is created on the basis of compression strength tests on squared specimen taken out of the circular pile. In this case severe decay is present on the outside layers with high amount of sapwood, with considerable reduction in material strength. The decay is expected to slowly working its way to the inside, but the rate of decay will be reduced when the decay front has reached the heartwood, which is more durable. The assumption of a constant decay rate over the circumference of a pile can be considered for bacterial decay and seems a justifiable assumption for an engineering model. But even there, the decay is generally not uniformly distributed over the circumference.

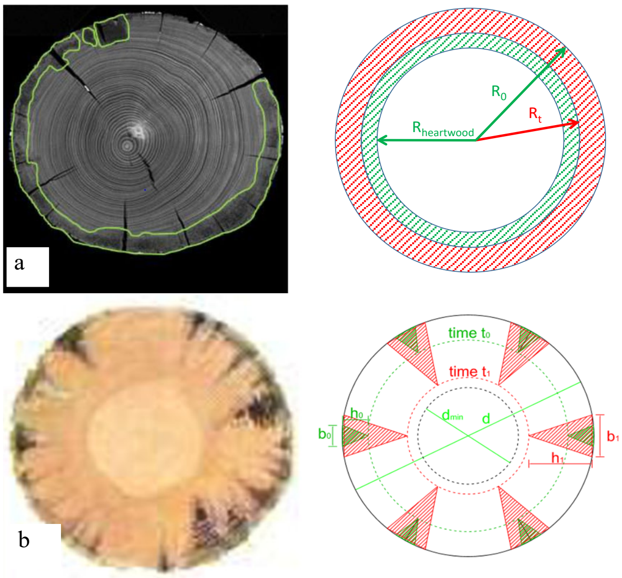


***Figure 4:** Cross section with decay profiles. a) Radial decay, b) Triangular decay, Left: Kleindienst et al, [8],Right: Gentner, N. [10].*

For fungal decay, also other patterns can be identified, such as the one given in Ibach [8] and Kleindienst [9], which shows a pie shaped pattern, see Figure 3b. The expectation is that fungal decay grows radially into the wood, and then gradually spreads out in the tangential direction. Schematically, both types of decay can be represented in an idealized manner as shown in Figure 4. More recently, CT-scanning was used to get a better insight in how decay may be distributed over the cross section. In figure 4a, a non-uniform pattern of decay along the circumference is shown, similar to that of figure 3. This makes it possible to better understand how the rate and shape of the decay is reducing the structural safety and the remaining service life of a foundation. The rate of decay depends on many different factors, but wood species and type of decay are among the most prominent.

The following graph from [6] indicates the effect of strength degradation as a function of age and sap- or heartwood respectively.

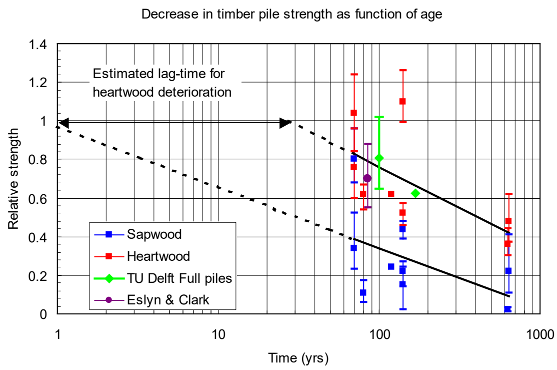


Figure 5:** Relative strength of sap- and heartwood as a function of age [6]**.

Extrapolation of the line for sapwood confirms the finding of [3], that degradation of softwood starts relatively early after completion. For heartwood, additional data was presented in Zelada et al. [20], confirming its location in the graph, and a delay time for heartwood degradation of about 30 years can be expected. The estimated lag-time for heartwood deterioration, is comparable to the lag-time for decay intitaion as presented in Wang et al. [22]. It must be mentioned that this is only a very rough assumption. The scatter is large and, as the thickness of the sapwood layer is different for different wood species, also the delay time will show a large scatter. On the other hand, there are also strong indications that progress of bacterial decay in for instance pine as very much reduced, as soon as the decay front has reached the heartwood. That indicates that there is kind of a natural maximum reduction of the cross section possible and the remaining cross section would continue to function for much longer, depending on the mechanical load level.

3 ASSESSMENT TECHNOLOGIES

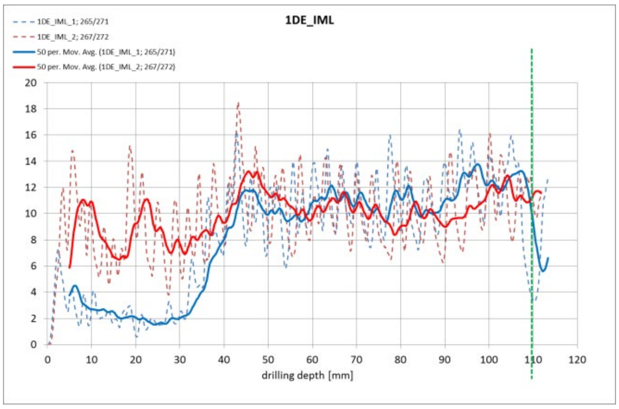
When performing an assessment of timber structures, or timber from existing structures, a number of devices and technologies are available [6]. Depending on the technology, in-situ measurements can be done, or material can be brought to a laboratory for more in-depth analysis, either small scale or full size. Taken samples can be analysed in the laboratory for the mechanical properties and type and state of degradation. An important aspect is the determination of the wood species. Despite the fact that wooden piles in Amsterdam are always below the water table, bacterial decay is more present in pine than in spruce, which is probably related to the more open structure of pine, especially the sapwood, allowing for bacteria to be transported through the cross section more easily.

Difficulties arise in case of pile foundations with long piles that are only accessible under water and at the top. The pile toe itself is too deep in the soil for inspection. This creates an uncertainty, as any noticeable degradation at the top is not necessarily present at the toe. In case of fungal decay, this generally works out in a positive manner, as deep in the soil the wood is fully saturated and consequently only bacterial decay can occur. At the top there is a higher risk of fungal decay, depending on the local situation and the variation in (ground) water level in particular. For bacterial decay and its severity it remains unclear if there is a correlation between toe and tip of the pile as the tip of the pile generally has a larger portion of sapwood and juvenile wood, and consequently is more vulnerable. The most basic on-site analysis techniques currently used are impact hammers such as Pilodyn and microdrilling devices.

One of a few non-destructive and in-situ methods that is available for wood inspection is micro-drilling, such as IML-RESI PD. An IML-Resi for underwater use, is currently in a trial stage. In [17] an extensive analysis of microdrilling resistance and some of the pros and cons of the technology have been presented. The drill is equipped with a needle, which is injected through the cross section of the wooden trunk in question. As the needle passes through the material, the amount of energy needed to drive the needle through the medium is recorded/captured as drilling resistance. In case of IML-RESI PD, the needle is 3mm diameter at a tip and 1.5 mm diameter at its shaft. Resulting data is plotted as resistances vs distance, and shows a wave plot in which amplitude displacements coincide with changes in density and moisture content [19].

***Figure 6**: Microdrill in use on an excavated pile.*

Both of the above mentioned methods result in data that can be converted into density profiles along the piles' cross sections. These plots show annual rings profiles, with maximum amplitudes marking latewood ings and minimum amplitudes pointing towards earlywood. Sometimes, there are also xtreme maximums and minimums. Those with higher values can be associated with the knots and other high-density anatomical variations, and lower value extremes pointing towards piths and cracks. In addition, since density is inverse to the moisture content, drill amplitude minimums also marks spot within the cross section with wood decay.



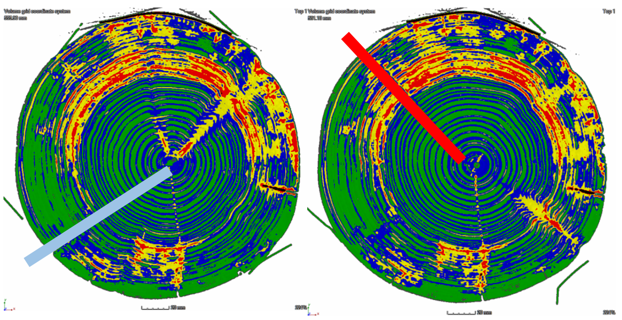


***Figure 7:** Top: drilling resistance profile created from micro drill test data. Bottom: CT-cross sectional image with location of micro-drill profile from the top graph.*

Figure 7 gives a fundamental difficulty in measuring on-site with penetrating devices like a microdrill. As these devices give only a local result, it may happen that an area with no decay is hit (Red), or an area with high decay (Blue). In practice, only a limited number of measurements can be done, so there is no guarantee to obtain a tomographic image of the state of the wood through the entire cross section. Complicating aspects are areas within the pile with low natural density or strength. Low natural density can have similar drill resistance values as high density wood with a light level of decay. As a consequence, the assumed compression strength capacity as related to the drilling resistance shows quite a high scatter, see indicatively in figure 8, modified from Schreurs [21]. Red, yellow and green areas are indicative. A considerable overlap between Resistance values and Compression strength values can be identified, making classification of piles for strength a difficult exercise.

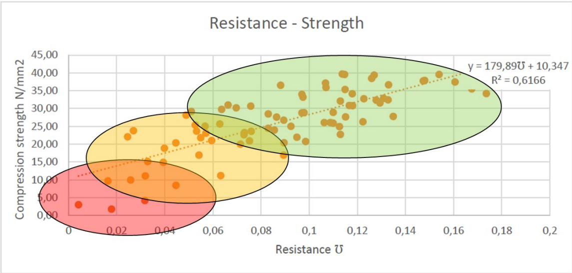


Figure 8: *Relation between drill resistance parameter and compression strength of square specimens taken from excavated piles, modified from [21].*

If the inspection also has to take place under water, the result of an inspection needs to be interpreted with great care. An advantage of some of the microdrilling devices is that the needle is long and can be penetrated through the full diameter of the pile, whereas some of the other wood penetrating equipment (or wood core-drilling) is much more limited with respect to the depth that can be reached. Additionally, pile spacing is often such that only the first row of piles of a foundation are accessible.

Another in-depth method of wood quality analysis is done with Computer Tomography (CT) scanning. This non-destructive method has been used for wood testing since the 80s [18]. It since has been used to determine density, wood quality and moisture content. Extracted old piles have been analyzed using a commercial CT-Scanner to determine wood quality as well as wood decay in the cross section, see Figure 9.

Figure 9: *CT scanning test of retrieved timber pile*

CT scans can provide highly detailed 3D images with features such as knots, cracks, heartwood and sapwood identifiable. A complicating issue is the moisture content during scanning. An example is given in Figure 10.
It can be seen that denser sapwood with high moisture content has a similar density level as the high density knots. Cleaning for moisture content allows for clear identification of the wood quality, including whorls that are generally governing the compression strength. Such a weak spot can be governing when verifying the load carrying capacity of a pile.

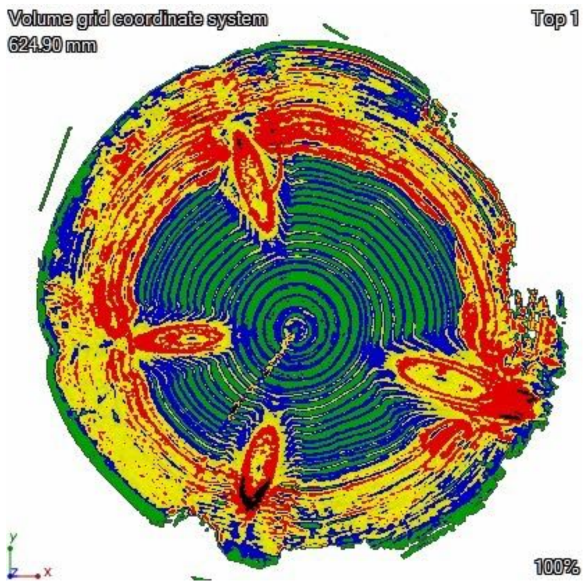


Figure 10*: High density knots and sapwood with high moisture content (yellow/red) and juvenile and heartwood in the center (green/blue).*

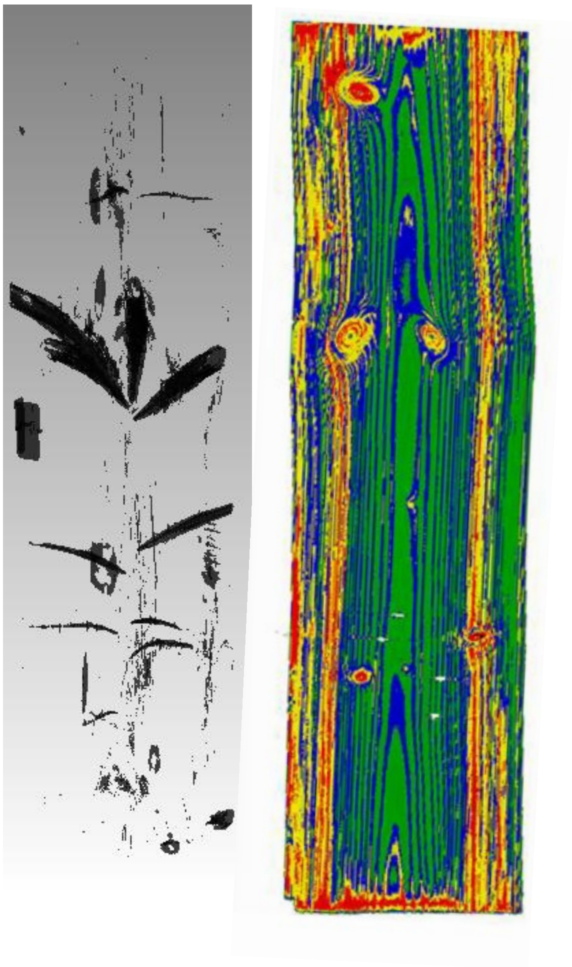


Figure 11: *CT scan, longitudinal cross section with whorls and knots clearly identifiable.*

For understanding the distribution of decayed wood within a pile section, the best option is to dry the piles, as especially then, the low density of decayed wood becomes clearly distinguishable from the sound wood. In Fig.4 a CT image of a dried specimen is shown, where the outer (sapwood) zone is decayed over almost the full circumference. From the greyscale, this is clearly identifiable.

4 FULL SCALE PILE TESTING

In order to understand the influence of long term loading in compression in combination with the effects of biological decay, existing piles are being retrieved from foundations of old bridges and quay walls in Amsterdam (some almost 300 years). Very little data is available with respect to the strength of old piles that have been in service for hundreds of years. A comparison with new piles may give indications on how much mechanical damage has been induced over the history. The objectives of the tests are firstly to determine the mechanical properties and the scatter, so this data can be used in a damage accumulation model. Secondly, investigations for in-situ measurements techniques that can be applied to piles in service to predict mechanical properties. Apart from RPD measurements, one possible in-situ measurement could be the determination of the dynamic modulus of elasticity, but so far such types of measurements are not yet applicable in situ in a foundation.

Mechanical testing on full scale pile sections is performed to determine (residual) compression strength and the static modulus of elasticity. For that, extracted piles are divided in three pieces (head, middle part and tail), debarked and prepared for the compression test. Depending on the diameter, the piles are cut in three different lengths (900 mm, 1350 mm, 1800 mm) according to the standards EN 408 and EN 14251 which prescribe an axial length of six times the smaller diameter of the cross section for a cylindrical pile. Before testing, the piles are submerged to reach the wet condition for the compression test, which means a moisture content higher than 70%. Figure 12 and 13 show the compression test set-up with pile sections up to 1800 mm length. LVDT sensors are place between the plate heads and on the piles itself to determine the static modulus of elasticity. In order to obtain both global and local strength and stiffness information, LVDT measurement devices are placed over the length of the section, over the section with the largest knots or the section that is expected to fail in compression first. When testing full scale sections with decay, this will be more difficult to address, as sections with decay may still have a load carrying capacity of similar order as section with high knottiness values. Figure 14 shows a actual failure pattern with crushing wood in and around areas with many knots. Because of eccentricities of knots in the cross section, failure may concentrate on one side of the pile only. Apart from compression wrinkles, longitudinal cracks also develop at later stages,

***Figure 12**: Large scale compression test set-up.*

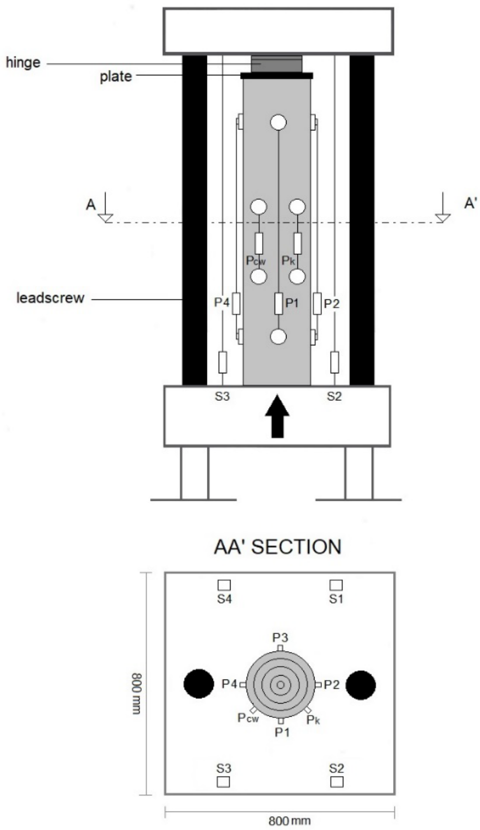


***Figure 13:** Instrumentation to obtain data from full scale pile sections.*

Figure 14: *Failure in compression around knots*

5 INTEGRAL DAMAGE MODEL

The results of the described measurement and analysis methods, will form the basis for a service life model that should be capable of predicting the remaining service life of pile foundations under bridges and quay walls. As the decay will slowly grow, an increase in stress ratio in non-decayed areas will result, leading to increased damage development per unit of time. Continuous degradation by decay as well as the time-load history for the foundation is captured in the model, but lack of reliable data requires more and specific laboratory testing. The load model that will be integrated is the Ferry-Borges-Castagneta model that is referenced in EC 0/1. For pile foundations, the prime load component is dead weight of the superstructure, plus the variable load of traffic in case of bridges. The general damage model reads as follows:

$$\frac{d\alpha}{dt} = F(\sigma(t), \alpha) \tag{2}$$

and linear or non-linear damage functions can be used. A straightforward application of a linear approach, but extended with the effects of biological degradation as shown in [6]. However, for various reasons as indicated previously, a more advanced damage model is required and a non-linear damage development approach from [4], [5],[12],[13-16] seems more appropriate, see also Figure 1.

The acting load on the cross section will be distributed over the cross section in equivalence to the ratio of modulus of elasticity of decayed and non-decayed wood respectively. So, the max. load carrying capacity F_u of the limiting cross section along the tapered shaft in a pile can be written as [6], [7]:

$$F_u = f_{c,0}A_{rem}(t) + f_{c,0,dec}A_{deg}(t) \tag{3}$$

in which the load carrying capacity is assumed to be the sum of the load carrying capacity of the healthy cross section as well as that of the decayed cross section.

Defining:

$$\delta = \frac{A_{rem}(t)}{A_{tot}} = \frac{A_{tot} - A_{deg}(t)}{A_{tot}} \tag{4}$$

and

$$\beta = \frac{f_{c,0,dec}(t)}{f_{c,0}} \tag{5}$$

this can be written as:

$$F_u(t) = f_{c,0}A_{tot}\delta + \beta f_{c,0}A_{deg}(t) = f_{c,0}A_{tot}\big(\delta(t)\big(1 - \beta(t)\big) + \beta(t)\big) \tag{6}$$

Assuming that the decayed part has zero strength (β=0) is a safe lower bound approach. If $\delta \rightarrow 0$, the load carrying capacity approaches 0, and the damage growths ever more rapidly. This results in a shift of time-to-failure and increased damage development lines as indicated in Figure 1. The approach taken can be further explained on hand of Figure 2. There, a typical examples of a decayed piles that show severe decay on the outside (primarily sapwood), but hardly or no decay on the inside (primarily heartwood). Because of the weak outside layer, the remained inner parts will have higher stiffness, and consequently attract a higher portion of the load. These higher loads, will result in higher stresses on the still healthy cross section, thus increasing the stress ratio ${}^{\sigma}/{}_{f_s}$, resulting in more damage per Δt. This process continues until the damage parameter α has reached 1 and the structure has failed. A complicating factor will be that the inner part of the heartwood, is juvenile wood, which also has lower stiffness compared to adult wood, and consequently the stress level is not constant over the healthy part of the cross section either.

Input parameters for the model will allow for a probabilistic approach, in line with [22], but model uncertainties will provide a major challenge. Both mechanical properties as well as biological decay will show large scatter. Basic model input will start from applied stress σ, threshold strength value $f_{c,0,thr}$ and short term compression strength $f_{c,0}$. The values for σ, and f are made time dependent (time varying load), as well as dependent on the changing geometrical ratio of sound and decayed wood. If a threshold level for wood strength exists, it is believed to be around 0.5 for the long term strength in compression. Information on this is expected to be determined from testing of sound piles that have been under load for 200 – 300 years. For those piles, recent increases in traffic loads on the superstructure will have had less influence, although these pile have generally smaller diameters than more recent foundations. Consequently they may have suffered from higher stress levels of longer periods.

6 CONCLUSIONS AND OUTLOOK

The complexity of the system is such that a straight forward strength verification is not realistic. On the one hand, it is clear that the lifetime of the structures are way beyond the permanent load duration class, which is normally taken as 50 years. Secondly, even though the short term strength of healthy recovered wood will indicate no strength loss, there is no guarantee that the 'new' long term strength is the same as for new wood, since preloading may have affected the remaining strength capacity with respect to time.

An approach is presented describing the long term effects in degrading timber piles, and what tyoes of techniques can be applied in order to obtain useful data for making an assessment. The model can be used deterministic but can also be used for a reliability based design assessment, including predictions for the remaining service life. It also allows for analysis as to when interventions (technical or otherwise) might be needed. For now, pile-soil interaction has not been addressed here, and is an issue for separate studies.

Further complicating factors relate to the retrieval in practice of reliable data. Retrieving data about the wood quality and the state of the wood under foundations remains difficult. In addition to that, retrieved data has to be interpreted and a good as possible estimate of the wood properties near the pile tip must be made, as there the governing cross section with regard to structural design and governing stresses needs to be made. Consequently, a probabilistic model allowing to take into account the statistical variations in sound material strength and stiffness, mechanical properties of degraded wood, the rate of decay as well as correlations between decay over the length of the pile may provide better insight, but at least allow for advanced sensitivity studies.

REFERENCES

[1] Van de Kuilen, J.W.G., Timber Engineering STEP 2, Lecture E18 Timber Piles, Eds. Blass et al. 1995.

[2] Biscontin G. et al., Il sistema delle fondazioni lignee a Venezia, CORILA, Venezia, 2009

[3] Varossieau, W.W., Opgegraven en aangetast hout vanuit biologisch oogpunt bezien. CIMO Delft, 1949 (in Dutch).

[4] Foschi RO, Yao RC (1986). Another look at three duration of load models. CIB/W18, Paper 19-9-1, 1986, Florence, Italy

[5] Van der Put, TACM., A model of deformation and damage processes based on the reaction kinetics of bond exchange. CIB-W18, Paper 19-9-3, 1986 Florence, Italy, 1986

[6] Van de Kuilen JWG (2007) Service life modelling of timber structures. Mat. & Struct. DOI 10.1617/s11527-006-9158-0

[7] Van de Kuilen JWG, Strengthening of wood and resistance to earth contact. Safeguarding Historic Waterfront Bryggen in Bergen as a case, pp. 269-284. Stiftelsen Bryggen, 2004, ISBN 83-918558-1-3.

[8] Ibach R.E. Biological Properties. In Handbook of Wood Chemistry and Wood Composites. CRC Press, 2005

[9] Kleindienst Q. Etude de la dégradation biologique des pieux de fondation en bois. Livrable du projet pieux bois. April 2014, 78 p.

[10] Gentner, N. Estimate of the remaining lifetime of existing timber piles: issues and models. Master Thesis TU Munich / INSA Lyon, 2014

[11] Wood, L.W. Behaviour of wood under continued loading, Eng. News-record 139(24):108-111, 1947.

[12] Nielsen, L.F. "A Lifetime Analysis of Cracked Linear-Viscoelastic Materials - With Special Reference to Wood", IUFRO conference, Borås, Sweden, 1982, pp.151 - 178

[13] Foschi R.O Folz, B.R., Yao, F.Z. Reliability-Based Design of Wood Structures, SRS, Report No. 34, UBC, Vancouver, Canada.

[14] Van der Put, T.A.C.M. Deformation and damage processes in wood, PhD Thesis TU Delft, 1989.

[15] Van de Kuilen, J.W.G. Duration of load effects in timber joints, Dissertation, TU Delft, 1999.

[16] Clerc, G., Lüthi, T., Niemz, P. Van de Kuilen, J.W.G., Reaction kinetics investigation in relation to the influence of humidity on fatigue behavior of wood lap joints, Holzforschung, doi.org/10.1515/hf-2019-0136

[17] Gard W. F., Van de Kuilen, J.W.G. Micro-drilling resistance measurements of dense hardwoods for hydraulic structures. WCTE - World Conference on Timber Engineering, Seoul, South-Korea, 2018.

[18] Lindgren, O. Medical CT-scanners for non-destructive wood density and moisture content measurements. Diss. Luleå tekniska universitet, 1992.

[19] Gao, S., Wang, X., Brashaw, B.K., Ross, R.J. Wang, L., Rapid assessment of wood density of standing tree with nondestructive methods—A review. Proceedings of 2012 International Conference on Biobased Material Science and Engineering. IEEE, 2012.

[20] Zelada-Tumialan, G. Konicki, W. Westover, P. Vatovec, M., Structural Forensics – Untreated Submerged Timber pile Foundations – Part 2: estimating Remaining Service Life –

[21] Schreurs, E., Deterioration of timber pile foundations in Rotterdam. M.Sc. Thesis, TU Delft, 2017.

[22] Wang, C., Leicester, R.H., Nguyen M., Probabilistic procedure for design of untreated timber poles in-ground under attack of decay fungi, Reliability Engineering and System Safety 93 (2008) 476–481