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Mirra, Michele; Gard, Wolfgang; Pagella, Giorgio; Ravenshorst, Geert; van de Kuilen, Jan Willem

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ANALYSIS AND PREDICTION OF SAPWOOD AND HEARTWOOD PROPORTIONS IN WOODEN FOUNDATION PILES IN RELATION TO BACTERIAL DECAY

Michele Mirra¹, Wolfgang Gard¹, Giorgio Pagella¹, Geert Ravenshorst¹, Jan-Willem van de Kuilen²

ABSTRACT: In the historic city centre of Amsterdam (NL), the most widespread foundation system consists of wooden piles. Since these foundations are fully below the water table, they are mostly subjected to bacterial decay. This biodegradation phenomenon proceeds slowly over time, and usually involves the less durable sapwood, with heartwood remaining sound. Hence, obtaining an estimate of sapwood and heartwood proportions in wooden piles can provide information on how deep in the cross section bacterial decay is expected to proceed. This is relevant, for instance, when developing service life models, since the remaining sound cross section of a pile can be estimated. Thus, the present work involves a comprehensive investigation on sapwood and heartwood proportions in spruce, pine and fir wooden foundation piles from different construction periods, ranging from 1727 to 2019. The amount of sapwood and heartwood was determined with computed tomography (CT) scans on 49 wet discs retrieved from the piles. Such measured sapwood width was then compared with that predicted with an empirical model from literature, based on the number of annual rings and growth rate, obtaining a successful validation. Micro-drilling measurements were also conducted on the discs to identify decayed portions, which appeared to always affect (part of) the sapwood only. Finally, this outcome was further validated against a broader dataset of micro-drilling measurements taken on over 200 pile segments, for which the sapwood widths were predicted with the aforementioned empirical model, and were found to be overall greater than the corresponding decayed portions, even in wooden piles having been in service for 300 years.

KEYWORDS: Wooden Foundation Piles, Sapwood, Heartwood, Decay, Micro-Drilling

1 – INTRODUCTION

The utilization of wooden piles as foundation system of historic or existing buildings has been widespread throughout Europe. In this context, the city of Amsterdam (NL) constitutes one of the reference examples for such foundation structures: millions of wooden piles still support existing and historic buildings or bridges, and given the essential function of these foundations and their spatial extension, estimating the remaining service life of the piles is crucial for arranging timely maintenance interventions.

Therefore, an extensive experimental campaign has been started in cooperation with the municipality of Amsterdam [1–6], aimed at characterising the current state of wooden foundation piles, as well as providing solid input for service life prediction models. Since the piles are fully submerged under water, they are mostly subjected to decay by bacteria, which are able to degrade

wood in anoxic conditions. Bacterial decay proceeds more slowly over time than fungal attack, and this allows the piles to perform their function for centuries before showing a substantial reduction of the load-carrying capacity [2, 6–8].

Wooden foundation piles in The Netherlands mostly comprise softwood species such as spruce (*Picea abies*), pine (*Pinus sylvestris*) and fir (*Abies*) [2, 6, 8], susceptible to bacterial degradation in saturated soils. Bacterial attack always proceeds radially inward within the cross section of a pile, at first affecting the less durable sapwood, while the inner part of the cross section of the pile, including the heartwood, tends to exhibit a lower degree of decay or remains sound [6–17]. Determining the proportion of sapwood and heartwood in the piles can thus be relevant for estimating the remaining sound cross section in service life models, and constitutes the focus of the present work. While for pine piles the sapwood can be identified by its different colour with respect to

¹ Michele Mirra (m.mirra@tudelft.nl), Wolfgang Gard (w.f.gard@tudelft.nl), Geert Ravenshorst (g.j.p.ravenshorst@tudelft.nl), Giorgio Pagella (g.pagella@tudelft.nl), Bio-Based Structures and Materials, Delft University of Technology, Delft, The Netherlands

² Jan-Willem van de Kuilen, Bio-Based Structures and Materials, Delft University of Technology, Delft, The Netherlands, & Wood Technology, Technical University of Munich, Munich, Germany, vandekuilen@hfm.tum.de

heartwood, for spruce and fir this visual distinction is not possible [18, 19]. However, in wet or green conditions, computed tomography (CT) scans allow to accurately detect sapwood and heartwood in these species, as proved by relevant previous studies [20–23]. Furthermore, the number of annual rings [20, 24–26] and the radial growth rate [26] of spruce and pine logs appeared to be well correlated with their sapwood width, with empirical models for determining the proportion of sapwood and heartwood in spruce having been proposed and validated in the literature, based on these parameters [26]. These formulations can be particularly useful to estimate sapwood width, since CT scans are not a viable option for in-situ inspections on the wooden piles.

Therefore, the main focus of this work is the analysis of sapwood and heartwood proportions in 49 discs retrieved from spruce, pine and fir foundation piles having different construction periods, ranging from 1727 to 2019 (Section 2). First, CT scans were performed to accurately determine the sapwood width within each disc. Second, an empirical model from literature [26] was employed to predict the sapwood width from the annual rings and growth rate determined on the discs. This sapwood width was then compared to that measured from CT scans, obtaining a successful validation. Third, micro-drilling measurements, which have become the reference method for in-situ assessment of wooden piles in Amsterdam [4], were conducted on the discs, and the decayed portions, if present, were determined from these signals. The measured sapwood widths were then compared to the extent of the outer layer degraded by bacteria. Finally, these outcomes were further validated against a larger dataset of over 200 pile segments [6] provided by the municipality of Amsterdam, obtaining a comprehensive picture of the extension of bacterial decay affecting the piles' cross section in comparison to the sapwood width estimated with the adopted empirical model.

2 – MATERIALS AND METHODS

2.1 MATERIALS

In this study, 49 30-mm-thick discs were retrieved from wooden foundation piles of bridges, which had been extracted from selected locations in the historic city centre of Amsterdam [2, 6]. The sapwood and heartwood proportions were determined for these discs, out of which 17 belonged to pine piles, 30 to spruce piles, and 2 to fir piles. The main properties of the retrieved discs are reported in Table 1.

The outcomes obtained from the examined discs, were then used in a broader dataset of over 200 spruce and fir pile segments, to estimate the sapwood width and compare it to the extent of degraded outer layer due to bacterial decay. The main properties of these pile segments, examined in detail in a dedicated study [6], are reported in Table 2.

Table 1. Main properties of the 49 discs analysed in this study.

Wood species	Diameter range [mm]	Number of discs per construction year				
		1727	1886	1922	1932	2019
Pine	150-240	-	-	-	2	15
Spruce	120-260	12	6	5	2	5
Fir	140-240	-	2	-	-	-

Table 2. Main properties of the 201 pile segments extracted from the historic city centre of Amsterdam, analysed in [6] and used in this study to compare the extension of bacterial decay and the sapwood width within the pile cross section.

Wood species	Diameter range [mm]	Number of discs per construction year		
		1727	1886	1922
Spruce	98-276	90	41	50
Fir	123-260	-	20	-

2.2 METHODS

This study consisted of four phases: (i) determination of sapwood and heartwood proportion in the 49 examined discs (Table 1); (ii) prediction of the sapwood width within the cross section of the discs by means of an empirical model from [26], with validation against the measured values; (iii) comparison between the sapwood width of the discs and the extension of their degraded areas, when present; (iv) prediction of sapwood width and comparison with the extension of the decayed layer for the larger dataset of 201 pile segments (Table 2).

In phase (i), two methods for measuring the sapwood and heartwood proportions in the analysed discs were employed in this study: visual assessment (only for pine discs), and CT scans (for all discs). In dry conditions, visual assessment of the sapwood and heartwood extension within a cross section is possible for pine piles, because it can be detected by the difference in colour [18] due to the presence of extractives [19]. On the contrary, in the case of spruce and fir piles, the boundary cannot be distinguished, as the colour is uniform [18] throughout the cross section. Yet, CT scans conducted on logs in green conditions proved to provide a reliable picture of the proportion between sapwood and heartwood [20–23]. This is because of two properties of sapwood: a higher density compared to heartwood, and a larger moisture content in green segments, resulting in a recognizable difference in CT scans' grey values between the two. This is related to the different water-absorption coefficient along the grain of sapwood compared to heartwood [27–29]: in the longitudinal direction, i.e. the one of interest for the discs examined in this study, spruce sapwood can have a water absorption coefficient up to five times larger than that of heartwood [27].

Therefore, all 49 discs were subjected to CT scans, including the pine discs, in order to have an additional validation of the sapwood width visually determined for them. To replicate the situation of logs in green conditions, where it is possible to clearly observe the heartwood/sapwood differentiation [20], the discs were

placed in plastic containers and submerged under water 8 hours before scanning. This procedure is underpinned by previous investigations on (submerged) wet spruce pile segments [30], where it was noticed that the moisture content gradient along their cross section was very close to that of logs in green conditions [30]. Next, immediately prior to scanning, the containers were emptied and the discs were covered with plastic foil to retain humidity. Finally, CT scans were performed on the discs adopting the same CT device and resolution of [20, 21], so that a clear differentiation between sapwood and heartwood could be detected.

After measuring the sapwood widths of the discs, in phase (ii) an existing empirical model from literature [26] was employed, allowing to estimate the sapwood width W_s on the basis of their number a of annual rings and average radial growth rate I_r [mm/year]. The number of annual rings was determined by counting them for each disc, while the radial growth rate was computed by considering the number a' of growth rings over the outer 75% of the pile radius, in accordance with NEN-EN 1309-3:2018 [31], thus $I_r = 0.75d/(2a')$, with the diameter d expressed in [mm]. This standardised procedure allows to exclude the contribution of juvenile wood, where the rings are usually more spaced and not representative for the overall growth of a tree. Finally, the determined number of annual rings and growth rate of each disc were used to predict the sapwood width adopting the empirical equation from [26]:

$$W_s [\text{cm}] = (3.48 \cdot I_r^{1.07}) / [1 + 6.82 \cdot \exp(-0.064 \cdot a)] \quad (1)$$

where:

W_s is the estimated sapwood width;
 I_r is the radial growth rate;
 a is the number of annual growth rings.

The estimated sapwood width was then compared to the measured value from CT scans for each disc, to assess the accuracy of the model for the present study.

In phase (iii), the sapwood width was compared to the extension of the decayed layer in the discs. To determine the degraded portions, two micro-drilling measurements per disc were executed along the cross section, for a total of 98 measurements, following a well-established protocol reported in detail in [2, 4, 6]. For these measurements, an IML-RESI PD 400 tool was used, with a drill speed of 2500 r/min and a feed speed of 150 cm/min [2, 4, 6]. Next, the extension of the decay in [mm] along the drilling depth was determined from the drilling amplitude, by means of an algorithmic procedure described in [4, 6]. An average outer decayed layer was calculated from the single degraded areas resulting from the two micro-drilling signals related to each disc, and compared with the corresponding sapwood width.

All outcomes from the previous phases were used for the final part of this work, phase (iv). For the 201 pile

segments analysed in [6] and whose properties have been summarised in Table 2, the number of annual rings and the growth rate were determined. The sapwood width was then estimated by means of the empirical model expressed by (1) and validated in phase (ii). Similarly to phase (iii), two micro-drilling measurements per segment were performed, for a total of 402 measurements, and the decayed portions were determined from these signals according to [4, 6]. Finally, the estimated sapwood widths and degraded layers were compared, in order to assess whether bacterial degradation had only affected (part of) the sapwood or had proceeded further into the heartwood.

3 – RESULTS AND DISCUSSION

The CT scans performed on the discs within phase (i) of this study, allowed to successfully highlight the sapwood and heartwood proportions in the discs. As shown in Fig. 1a-d, referring to pine discs, the scans accurately resemble the sapwood width visually observable for this wood species, confirming the reliability of this method demonstrated by previous literature studies [20–23].

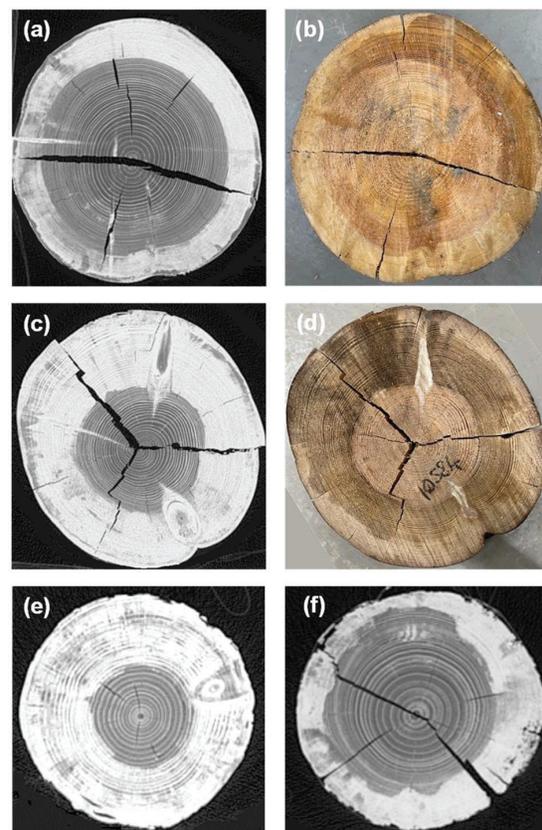


Figure 1. Comparison between a CT scan (a) of a pine disc and the actual sample (b) where the extension of heartwood is greater than that of sapwood; comparison between a CT scan (c) of a pine disc and the actual sample (d) where the extension of sapwood is greater than that of heartwood; representative CT scans of spruce (e) and fir (f) discs. In green conditions, the larger moisture content of sapwood makes it brighter, while the heartwood appears as darker.

Similarly, a clear representation of sapwood and heartwood was obtained for spruce (Fig. 1e) and fir discs (Fig. 1f), for which the sapwood width was determined from CT scans only, since no visual assessment could be conducted due to the uniform colour between sapwood and heartwood for these wood species.

Within phase (ii), the sapwood width measured from CT scans was compared to that estimated with the empirical model [26] expressed by (1), following the methodology described in Section 2.2. As shown in Fig. 2, the model allowed to calculate the sapwood width with a standard error of the estimate (S.E.E.) of 9.2 mm, and was thus successfully validated against the measured values.

Next, in phase (iii) the extension of bacterial decay within the cross section of the discs was determined from micro-drilling signals (Fig. 3a) and compared to the sapwood width measured from the CT scans (Fig. 3b). The degraded layers were in most cases limited to the outer 10 mm of the discs, with greater decay extensions, up to 32 mm, only observed in the most ancient discs, retrieved from piles installed in 1727.

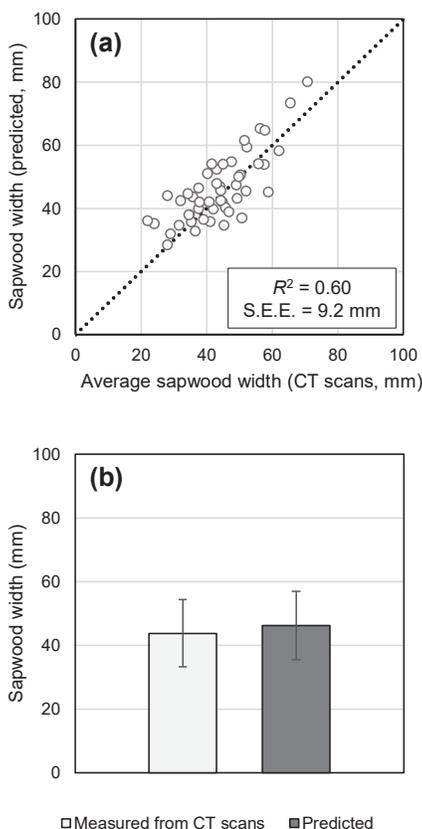


Figure 2. Comparison between the sapwood width measured from CT scans and predicted with the empirical model from [26], considering all data points (a) and their average and standard deviation (b); good correlation is observable, expressed by the coefficient of determination R^2 of 0.60 and a relatively low standard error of the estimate (S.E.E.).

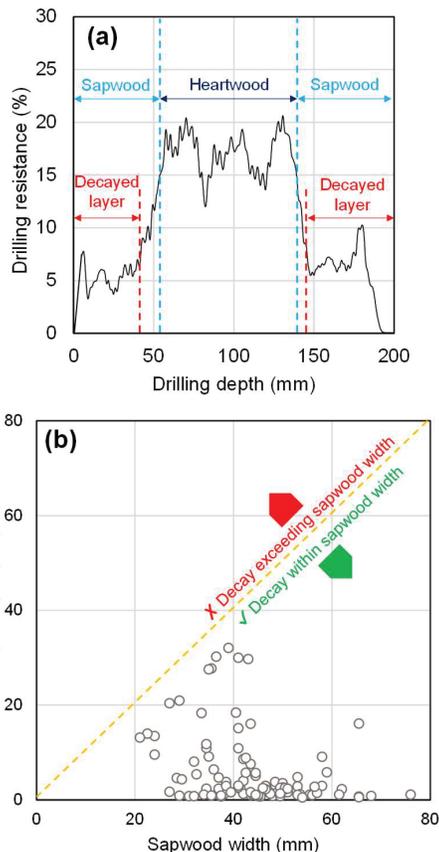


Figure 3. Decayed outer portions of a pile disc from 1727, determined from the corresponding micro-drilling signal, in comparison to the measured proportion of sapwood and heartwood (a); comparison between the detected degraded layers and the measured sapwood widths (b) for all 49 discs (30 spruce, 17 pine, 2 fir).

In all cases, the bacterial degradation was limited to the sapwood width (Fig. 3b), whose estimate through empirical models such as (1) [26], could provide the maximum potential decay extension, and thus the minimum remaining sound pile cross section, even when the degradation rate is unknown. In order to further verify this possibility, phase (iv) involved a larger, more comprehensive dataset of previously analysed pile segments [6]. Based on the successful validation of the empirical model from (1) [26], obtained for the 49 examined discs, the same equation was used for the 201 pile segments, for which both the number of annual rings and the growth rate had been previously determined, according to Section 2.2. This allowed to calculate the sapwood width of each segment with a standard error of the estimate of ± 9.2 mm, as determined from the analysis of the discs already shown in Fig. 2a. This uncertainty in the sapwood prediction is taken into account in the graph of Fig. 4, where the region corresponding to the standard error of the estimate is highlighted. Also in this case, the decayed layers of the pile segments determined from the two micro-drilling measurements conducted on each segment, were plotted against the corresponding sapwood widths, obtaining the graph shown in Fig. 4.

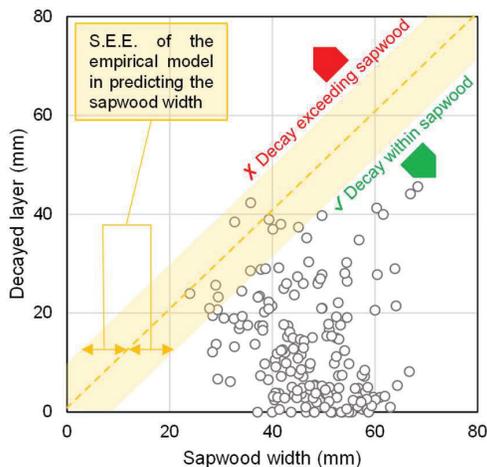


Figure 4. Comparison between the decayed layers detected from micro-drilling measurements and the sapwood widths predicted with the empirical model from (1) [26], including its standard error of the estimate (S.E.E.), for all 201 pile segments (181 spruce and 20 fir) tested in [6].

These outcomes confirm the findings from the previous analysis on the discs, since also in the pile segments the bacterial decay was found to affect only part of the sapwood in most cases, and the largest values of the outer decayed layer were associated with the most ancient piles from 1727. Only for two segments (1% of the dataset), the degraded portion was approximately 5 mm larger than the predicted sapwood width, but still within the range of the standard error of the estimate (Fig. 4). Even when considering all the datapoints falling in this same range, such decay extent was reached for a total of 11 segments, corresponding to 5% of the dataset. Therefore, also in this case, the prediction of the sapwood width could provide the maximum extension of bacterial decay within the cross section of the analysed pile segments.

4 – CONCLUSIONS AND OUTLOOK

This work has explored strategies to measure and predict the sapwood and heartwood proportion of spruce, pine, and fir foundation piles from different construction years (1727 to 2019), within the historic city centre of Amsterdam (NL), in order to investigate how this proportion can influence bacterial decay in the piles.

As a confirmation of previous research studies, an effective methodology for accurately determining the sapwood width consists of CT scans performed on discs or pile segments in green conditions. Since this methodology cannot be easily applied on site, alternative empirical models for the sapwood width prediction, based on annual rings and growth rate, have been employed and validated for a dataset of 49 discs, subjected to CT scans as well for an accurate determination of their sapwood and heartwood proportion. Additionally, micro-drilling measurements were performed on the discs to assess the presence of

outer decayed portions, due to bacterial degradation, in their cross section. The combination of all these investigation techniques allowed to validate the empirical model against the CT scans, and proved that the decayed portions resulting from the micro-drilling signals were always confined within the sapwood.

Therefore, estimating the sapwood width in softwood piles could provide the maximum potential decay extension, and thus the minimum remaining sound pile cross section, even when the degradation rate is unknown. This outcome was further validated in a larger dataset of over 200 pile segments from different construction years: also in this case, when comparing the sapwood width predicted through the empirical model with the extent of decay determined from micro-drilling measurements, it was found that the biodeterioration had not affected the heartwood even for the most ancient piles from 1727. Hence, this work has further underpinned the outcomes from previous literature studies, showing that the effects of bacterial decay in wooden foundation piles, is limited to the sapwood portion of the cross section, and this also applies to the context of the city of Amsterdam.

In light of these findings, a good prediction of the remaining sound cross section in the piles can thus be obtained by estimating the sapwood width and subtracting it from the whole cross section. In addition, the validated empirical model from literature allows to determine the sapwood width on the basis of the annual rings and the growth rate of the piles. This result is promising, since further studies could investigate possibilities for estimating or retrieving these parameters directly from the signals obtained from in-situ micro-drilling measurements. Therefore, future research is envisaged in relation to the direct prediction of sapwood and heartwood proportion in softwood foundation piles, starting directly from micro-drilling signals, which would constitute a relevant input for estimating the remaining sound cross section in service life models.

5 – ACKNOWLEDGEMENTS

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