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MICRO-DRILLING RESISTANCE MEASUREMENTS OF DENSE HARDWOODS FOR HYDRAULIC STRUCTURES

W.F. Gard[1], J-W. van de Kuilen [1,2]

ABSTRACT: Hydraulic timber structures such as mooring poles, fenders, quay walls, lock gates and jetties are widely used in inner and marine harbours all over the world. In general, these structures give satisfactory performance with regard to the technical requirements. Because of the harsh exposure conditions such as brackish and contaminated water, drying-out and mechanical impact, the deterioration processes have to be monitored with regard to the service life performance. Visual inspection is limited to defects at the surface. Internal ´defects´ such as cracks, juvenile and intermediate wood as well as biological decay influence the mechanical performance and are difficult to detect. Until now, micro-drilling technique has been successfully applied to softwoods and some medium-dense hardwoods. In this paper it has been investigated what kind of defects through the cross section of hardwood beams can be detected with the corresponding accuracy and reliability. It could be concluded that drilling resistant measurements on eucalypt and azobé allows detecting of defects such as decay and cracks, but also high and low density zones due to slow growth rates and juvenile wood areas. For this it is necessary that the micro-drilling is calibrated especially with regard to the drilling depth, the wood cross section and the wood species.

KEYWORDS: micro-drilling, defects, high dense hardwood, marine structures, CT-scanning

1 INTRODUCTION

Hydraulic structures protect the shore, riverbanks, quay walls and keep shipping and harbours operational. Because of the importance of these assets, it is important to get detailed information of their performance on long term in order to optimise maintenance and if needed replacements. Due to economic and environmental reasons and limited availability of the material, better models are needed to predict the performance of the structure during service.

Marine structures are exposed to harsh conditions such as sea or brackish water, marine organisms, contaminated water and mechanical loads. In these kind of structure all materials deteriorate over the years because of the extraordinary loads. Different phenomena such as corrosion, hydrolysis, (micro)biological decay and mechanical impact all play an important role.

Tropical hardwoods have been used for marine structures because of their high mechanical properties and natural resistance against fungi and marine organisms such as marine borers (shipworm, pholads) and crustacean borers (gribbles). Important wood species for marine structures are greenheart, basralocus, azobé and recently for jetties and fenders also eucalypt.

In order to assess the structures with regard to integrity and remaining service life, the state of soundness of the timber through the entire timber cross sections and timber joints should be known [1, 2, 3]. We can choose. Internal ´defects´ in timber structural elements such as cracks, juvenile and intermediate wood as well as biological decay are influencing the mechanical performance. Therefore these ‘defects’ should be detected by semi- or non-destructive inspection techniques.

Commonly, for the assessment of hydraulic timber structures visual criteria of degradation features have been used. Micro-drilling is a semi destructive testing technique which is able to ‘look’ into the core of the timber elements. Since the early 1980s micro-drilling techniques have been used to investigate density gradients in standing trees, transmission poles and elements of timber structures [4, 5].

Micro-drilling has been successfully applied mainly on softwoods. A contemporary review of micro-drilling research [6] shows that only a few hardwood species such as oak, beech and chestnut have been investigated regarding density gradient modelling in timber elements.

In this research a first attempt has been made to use micro-drilling techniques to investigate high dense (tropical-) hardwoods of marine structures regarding defects and growth characteristics such as juvenile wood.

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Juvenile wood is located in the centre of a tree (pith) and counts about 15 growth rings. The mechanical properties are significantly lower than of mature wood and it has a lower density [7]. When the outer part of the wooden pole is deteriorated the 'inner' part becomes more important for the strength. In this case, the ratio of juvenile wood of the timber cross section increases and has to be determined.

2 MATERIAL AND METHOD

Timber in marine structures is mostly exposed to harsh conditions in the tidal-, splash zones and around the head cap (Figure 1). Due to anisotropic shrinkage and swelling the wood cracks at the surface and deeper inside of the timber element. Furthermore the cross section of the timber element could be reduced caused by impact actions of chips, but also by fungi decay and marine organisms (Figure 2).

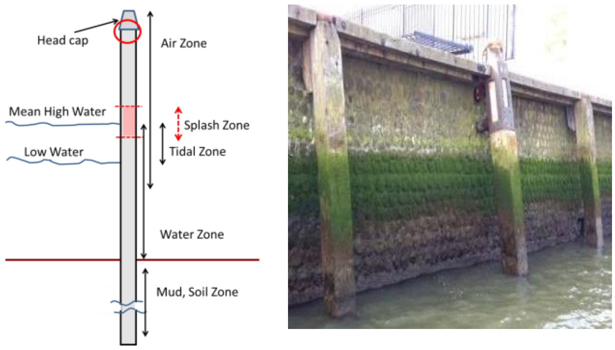


Figure 1: *Mooring pole with critical zones and fender at a quay wall*

2.1 MATERIAL

The investigated timber comes from the plash zone of mooring poles (Figure 2).

Figure 2: *Deteriorated zone (plash zone) of a mooring pole: left: fungi decay (between red lines), right: shipworm decay*

In this research azobé *(Lophira alata* Banks ex Gaertn.*)* (average density 1100kgm^{-3}) and eucalypt (*Eucalyptus cloeziana* F.Muell.*)* (average density 780kgm^{-3}) have been investigated. Sections of sound (reference) and deteriorated wood of the eucalypt and azobé were selected (Figure 3).

Figure 3: *Wood sections: left: eucalypt, right: azobé*

The cross section of the azobé beam was 300mm x 300mm and the diameter of the eucalypt pole 165 mm.

2.2 METHOD

2.2.1 Micro-drilling

The micro-drilling was applied with the IML-RESI PD (Figure 4). The drilling frequency through the cross section should give information about internal defects (cracks, decay) and juvenile wood. The micro drill is slender (ø 1.5mm), 400mm in length and has a drilling head with a diameter of 3mm (Figure 4). The drilling resistance is given by an amplitude of electrical power. Feed and drilling speed are separately controlled by two engines. The drill needle has a tip diameter of 3mm and a shaft diameter of 1.5mm (Figure 6). The thinner shaft diameter ensures the transportation of the cut chips from the inside to the surface.

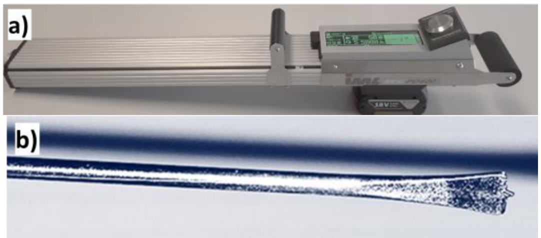


Figure 4: *IML-RESI PD drill equipment (a),drill needle (b)*

2.2.2 Computer tomography (CT) scanning

The CT scanner may be used for specimens with a radius of 350mm (Figure 5). CT scans have been used as reference for the micro drillings. The course of the mico-drillings though the cross section could exactly followed. The grey values of the CT scans had been calibrated with the density of the wood.

- 140 kV
- 250mAs
- 0,6 mm slices
- 0,6 mm pitch
- 0,5 mm per rotation
- Kernel B50f

Resolution and settings:
0,6 mm in z-direction
x,y-direction depends on the test sample

Figure 5: *Somatom Philips CT scanner with settings for the present investigation.*

3 DRILLING MEASUREMENTS

Resistance measurements are able to spot internal defects and/or areas with a significant deviating density such as juvenile wood, decay. These areas can affect the mechanical properties of the structural timber member.
Drilling measurements were not used to determine the density. Only relative resistance fluctuations were analysed to determine defects.

From both eucalypt and azobé, 2 samples each have been investigated with in total 820 drillings.
The resistance of the drilling into the material is expressed as consumption of electrical energy (amplitude of power). The drilling resistance depends on several parameters which are reliant on the material and the drilling tool (Table 1).
Increased wood moisture content lowers the strength properties of the fibres and vessels of the wood, whereby the cutting energy decreases.
Own preliminary investigations (unpublished) have shown that the wood moisture content in the range of 10% to fibre saturation have a significant influence (0.2%/% moisture content) on the feed but not on the drilling (rotation) resistance. Therefore, the test specimens were conditioned at the standard climate 20°C/65% to avoid any influence of wood moisture differences. The mean wood moisture content was 12%± 2% for both species.

Table 1: *Parameters influencing the drilling resistance*

Material dependent	Tool dependent
Anatomy of wood	Geometry of the drill
Moisture content	Shaft shape
Depth of the drill hole	Feed speed
	Drilling speed
	Slenderness of the drill

3.1 FUNCTIONING OF THE DRILL

Depending on the size of the chips and the length of the drilling channel, friction occurs, which can greatly increase the drilling resistance [8]. With large feed, the friction becomes high between the chip and the tool, which leads to heating of the cutting edge. This can soften the pre-cutter and 'burn' the wood [9].

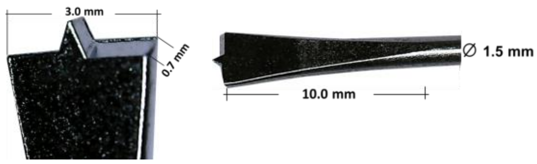
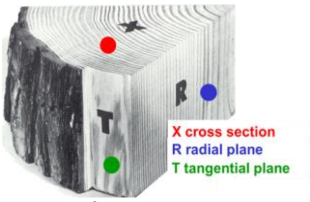


Figure 6: *Geometry of the drill needle.*

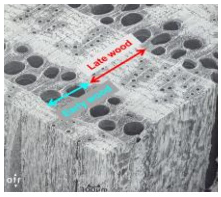
Shaping a chip is complex. It depends on the mechanical and physical properties of the material (e.g. wood fibre, wood moisture content), the cutting conditions (e.g. feed, depth of cut, chip thickness), geometry of the cutting head, and the sharpness of the drill [10].
The influence on the resistance of the sharpness of the particular needle has not been investigated separately. To neglect this influence, the needle has been exchanged after a total drilling length of 500mm.
To be able to drill in wood, two forces are needed, pressure and torsion force. Pressure force ensures friction between the drill head and the wood, so that the drill can cut the wood under the influence of torsional force. The pressure force therefore has a leading role.
The energy needed for shearing of the fibres in the wood depends on the direction. Cutting the fibre parallel to the fibre direction requires only a fraction of the energy needed to cut the fibre perpendicular to the grain [11]. Therefore, it makes sense to drill always exactly perpendicular to the grain direction. As a result, interpretation errors can be avoided.

3.2 WOOD MICRO STRUCTURE

Wood is a highly inhomogeneous and anisotropic material with a complex morphology. The wood 'composite' consists of plant cells such as fibres and vessels with a hollow core and cell wall. The density of the cell wall (wood substance) varies in hardwoods where the average is about 1500kgm^{-3} [12]. The local density of the material depends on the particular location.
Natural variations in density of wood are due to growth rhyme and anatomical directions (Figure 7). In the present study, drillings are conducted exclusively in the radial and tangential direction, i.e. perpendicular to the fibre direction.
Types of wood with ring-pore structure show significant density scatter in radial direction compared to tangential direction (Figure 7).



a) slice of wood

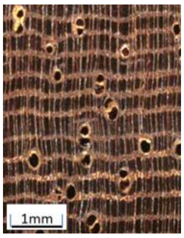


b) cross section

Figure 7: *Anatomical directions of wood (a), microscopic view of growth rhyme (early and late wood) of a ring-pore wood species (b).*

From own research (unpublished) it can be concluded that in diffuse-pore wood species the scatter of density in tangential relative to radial direction is marginal (Figure 8).

a) eucalypt

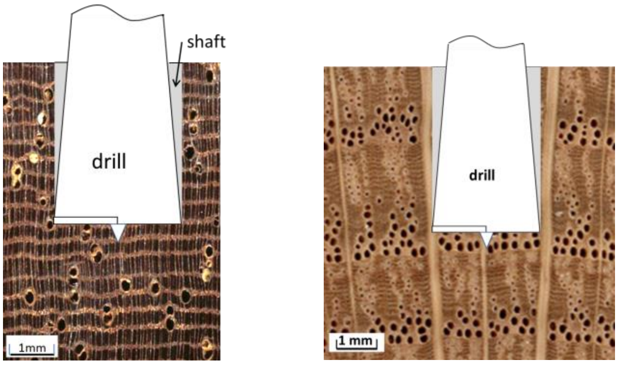


b) azobé

Figure 8: *Microscopic cross section of diffuse-pore wood species (a),(b)*

Another aspect that affects the accuracy of the measurements is the arrangement and cross sectional diameter of the fibres and vessels, and the sample size. of the measurements. The used equipment, samples at every 100µm. Thus, only cell diameters greater than 100µm can be detected in the measured curves.
Since in azobé the vessels are arranged diffusely, they cannot be recognized by the measured curves. However,

in the case of oak (Figure 9) where the vessels are arranged in wide bands in the early wood, this low resistance areas are clearly distinct in the resistance curves.



a) azobe, difuse-pore b) oak, ring-pore

Figure 9: *Microscopic cross section with drill resolution at scale.*

In summary, it can be concluded that both eucalyptus as well as azobé show no significant differences in the radial and tangential directions. Thus, the drilling results are not significantly dependent on the drilling direction. Because of the relatively small pore size, the drilling resistance is composed of a mixture of fibres and vessels density.

3.3 FEED AND DRILLING SPEED

The feed speed can be adjusted from 15cm/min to 200cm/min depending on wood hardness. The rotation speed (drilling speed) of the drill needle ranges from 1500r/min up to 5000r/min.

Needle and feed speed have to be phased with each other. High feed speed can lead to a deformation of the needle and damage the needle tip. Low rotation speed of the needle can lead to deformations of the drill head in particular in hardwoods with a high drilling resistance (high density). In the present study with eucalypt and azobé the optimal drill speed was found at 5000r/min and feed speed 500mm/min. The offset is about 0.2mm (Figure 10).

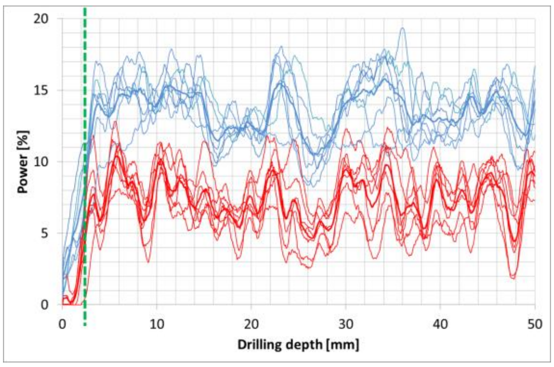


Figure 10: *Micro-drilling chart(8 specimens): feed speed at 500mm/min (red line), drill speed at 5000r/min (blue line); the darker thick lines are the average of the individual measurements; offset depth (dashed green line)*

From the graphs (Figure 10) it can be seen that both amplitudes are almost synchronized.

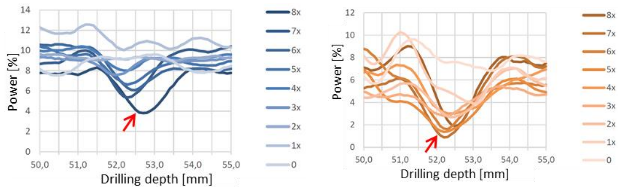
3.4 CRACK DETECTION

Usually cracks have a drilling speed of zero. Due to the needle geometry, the feed speed, the slenderness of the needle and the sampling frequency of the measurements, the recognition of thin cracks is not always assured. Side effects which may cause friction resistance cannot completely be neglected.

An artificial gap between two specimens was created with a thickness of 0.08mm and the drilling was performed. The gap was increased by a multiple of the initial gap.

Neither the feed speed nor the drilling speed reach the limit value '0' (Figure 11). The feed speed shows a greater sensitivity than the drilling speed.

After statistical analyses, it seems that a gap/crack can be recognized as of 0.64mm width, with a confidence of 99%.



a) drilling speed b) feed speed

Figure 11: *Micro-drilling with an artificial gap/crack in a sample; lowest energy consumption is pointed by the red arrow; light colours represent small gaps, dark colours thicker gaps.*

3.5 SHAFT FRICTION AND SLENDERNESS OF THE NEEDLE

Shaft friction was mainly observed in hardwoods with high density (> 800kgm^{-3}) [8]. The reason for this may be the development of heat at the tip of the needle, which softens both extractives/gums in the wood and the lignin in the cell walls, which may have an adhesive effect.

This glue effect can cause the cut chips to clump on both the needle tip and within the shaft, which increases the resistance of the feed and drill speed.

The deeper the drilling hole in the wood, the greater the risk that the shaft friction significantly increases for the reasons mentioned.

Due to the slenderness of the needle, it may bend and deviate from the intended drilling trajectory if there are knots (very high resistance) or gaps (very low resistance).

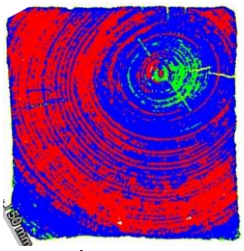
This problem can be addressed by drilling several holes from different sides of the structural element. As a result, points of intersection of the drill holes can be identified, whereby a deviation of the bore direction can be determined.

4 RESULTS

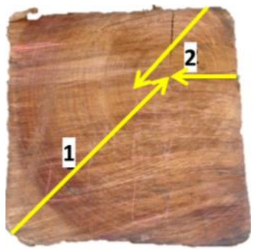
4.1 AZOBÉ MEASUREMENTS

The azobé pile has a distinct core that lies outside the middle of the pile. Around the core, the juvenile wood is

located which usually has a lower density than the mature wood. For control reasons, 2 pieces with a length of 350mm from the wooden pile were scanned in 3D using a computerized x-ray imaging (CT scanning). By means of the scans, zones in the wood with significant density variation could be identified (Figure 12). The colours in the picture symbolize grey values, which represent the density. The density of the red areas are about 30% higher than those of the blue zones.
From this mapping it can be concluded that the core area is juvenile wood and decay is at the outer zones of the pile.



a) azobé cross section CT scan



b) azobé cross section (naturel)

Figure 12: *Azobé cross section: 3D CT scan, red=high density, blue and green low density (a); indication of drilling lines and drilling direction: yellow lines (b)*

These results of the CT scan are confirmed by the micro-drilling (Figure 13). The offset of the drilling, a few tenth of millimetres at the surface of the pile, can be neglected (Figure 13, left part).
All drilling measurements were done perpendicular to the grain of the pile. In total 245 micro drillings were conducted on azobé.

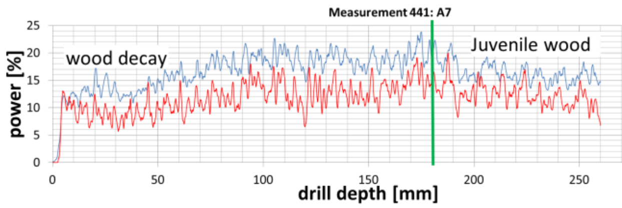


Figure 13: *Resistance profile of azobé cross section along the yellow line in figure 12 b);red line = feed speed amplitude, blue line=drill speed amplitude.*

4.1.1 Shaft friction

Shaft friction was detected during drilling in azobé. Firstly, a deep hole was drilled of 260mm (Figure 14, yellow line), which ran through both mature wood and juvenile wood. Secondly, a hole was drilled from the opposite side of the pole cross section of 90mm length (Figure 14). The second drilling ran mainly through juvenile wood which overlaps partly with the 'long drilling' in the area of juvenile wood (Figure 15).
In the area where the measurements overlap it shows that the drilling resistance of the shorter drilling distance is significantly lower than that of the longer drilling distance (Figure 15, green line). The resistances are almost twice as high for the 'long' drilling as for the 'short' one (Table 2). In the long drilling, the juvenile wood cannot be identified based on the drilling resistance. The deviation of the juvenile wood is not significant with regard to the mature wood (Table 2).

Figure 14: *Azobé cross section indicating drilling lines: yellow (line 1), blue (line 2); the dashed black circle line indicates the area of juvenile wood.*

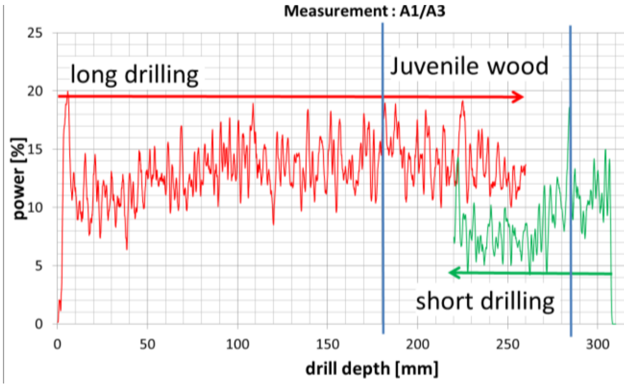


Figure 15: *Resistance profile of azobé cross section: along the yellow and blue line in figure 14); red line = feed speed amplitude of drilling 1, green line = feed speed amplitude of drilling 2; arrowhead indicates the drilling direction; between the vertical blue lines the juvenile wood is located.*

Table 2: *Relative power consumption of drilling in azobé*

	Power [%]	
	Average	Stdev.
Long drilling: mature and juvenile wood	13.4	2.0
Long drilling: mature wood	12.8	2.6
Long drilling: juvenile wood	13.9	2.1
Short drilling: juvenile wood	7.7	1.7

In summary, the shaft friction has a significant impact on the discrimination of juvenile vs mature wood. The shaft friction dependents mainly on the length of the drilling and the composition of the wood. Therefore, it is necessary to calibrate the resistance drilling taking into account the wood species and cross sections (drilling depth).

4.1.2 Decay and cracks

The drilling resistance in decayed parts of the pole can vary a lot. Depending on the degree of decay the amplitude of the resistance may have the same level of juvenile wood (Figure 13). Only because of the location in the cross section it can be concluded that this is due to decay (e.g. fungi, erosion).

Cracks detection with a resolution of 0.64mm was possible in azobé (Figure 16). The feed speed is most sensitive to crack detection than the drill speed (Figure 16). The high amplitude in the graphic caused by cracks can be recognized in most cases, even when shaft friction happens. That's because a 'gap' has no drilling resistance. But it is possible that the resolution of 0.64mm may decrease, because the crack can be clogged with chip parts.

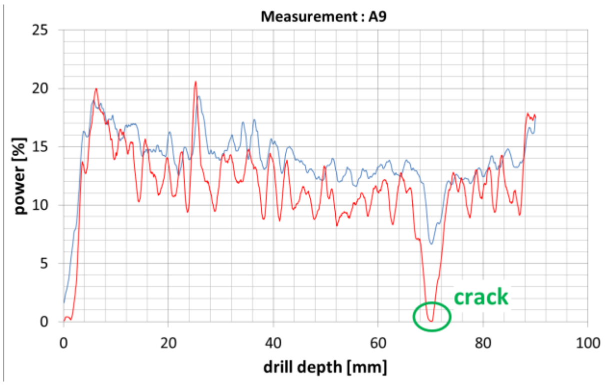
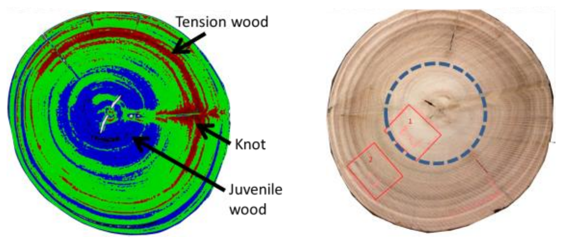


Figure 16: *Resistance profile of azobé cross section with crack; red line = feed speed amplitude, blue line = drill speed amplitude.*

4.2 EUCALYPT MEASUREMENTS

The eucalypt pile has a circular cross section with a distinct pith in the middle. Around the core, the juvenile wood is located (Figure 17) with a lower density than the mature wood. From the wooden pile 2 sections with a length of 500mm were scanned in 3D using a computerized x-ray imaging (CT scanning). By means of the scans, zones in the wood with significant density variation could be identified (Figure 17). The colours in the picture represent density levels. The density of the red areas are about 50% higher than those of the blue zones.

From this mapping the low dense juvenile wood can be identified. In addition, a semi-annular zone of high density is visible, surrounded by mature wood (Figure 17). This is probably tension wood, which has a significant higher density than 'normal' wood. Another high density zone can be spotted in radial direction. This a offshoot of a knot.



(a) cross section CT scan (b) cross section natural

Figure 17: *Eucalypt cross section: 3D CT scan, relative density: high density red>green>blue low density (a); indication of juvenile area, blue dashed line (b)*

All drilling measurements were done perpendicular to the grain of the pile. In total 189 micro drillings were conducted on eucalypt. The micro drilling graphs in this paper are typically for all measurements on the particular eucalypt piles.

The micro drillings confirm the density profile of the cross section of the eucalypt pile (Figure 18). The high dense 'ring' (tension wood) surrounded by lower dense material in the pile cross section can be identified (Figure 18). The area of the juvenile wood has a low density and is clearly bordered from mature wood.

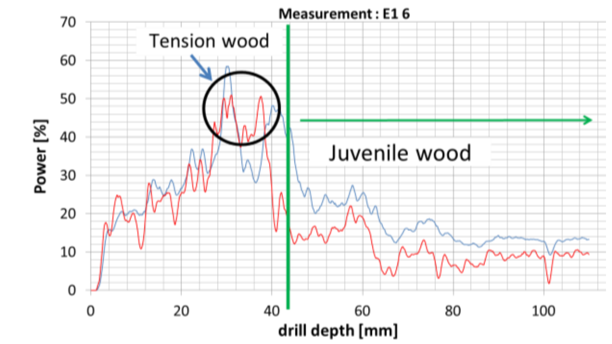


Figure 18: *Resistance profile of eucalypt cross section; red line = feed speed amplitude, blue line = drill feed speed amplitude; high dense area (tension wood).*

4.2.1 Shaft friction

Shaft friction could not be observed during the drilling. Two opposing holes were drilled, which overlap in the juvenile wood area (Figure 19). The resistance levels of the two measurements are not significantly different in that area (Figure 19, Table 3).

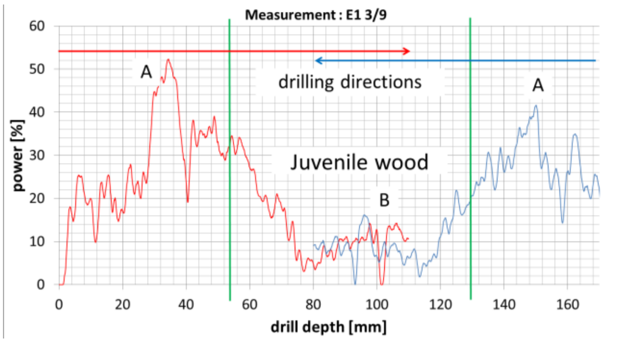


Figure 19: *Resistance profile of eucalypt cross section:; red line = feed speed amplitude of drilling 1, blue line = feed speed amplitude of opposing drilling; arrowhead indicates the drilling direction; between the vertical green lines the juvenile wood is located; A = high dense area (tension wood), B=crack.*

Table 3: *Relative power consumption of drilling in eucalypt in the juvenile wood area*

	Power [%]	
	Average	Stdev.
Drilling: juvenile wood area	9.3	3.6
Opposing drilling: juvenile wood area	8.8	3.0
Short drilling: juvenile wood	7.7	1.7

The reason for the insignificant effect of the shaft friction compared to azobé, is probably the much lower density of eucalypt and the shorter drilling depths (max 115mm). Due to the drastic density differences between mature and juvenile, the boundaries between the two areas become clearer, whereby a possible low shaft friction effect is no longer recognizable.

4.2.2 Tension wood

Especially in young trees, tension wood is formed near the core/pith. Tension wood has deviant mechanical properties to 'normal' wood. The stiffness and the bending strength is lower than normal wood. These can have negative consequences for the performance of the structure.

These areas can easily identified by micro drillings, because of the high density of tension wood (Figure 18).

5 CONCLUSIONS

Assessment of large, dense hardwood cross sections with the aid of micro-drilling gives reliable results regarding decayed areas, cracks and juvenile wood. Wood decay in an early stage cannot be detected. Only areas that differ significantly from one another may be considered in the analysis.

Knowledge of the material and morphology of the wood are necessary for the interpretation of micro drilling results in order to avoid incorrect conclusions.

However, for high dense wood species the measuring device has to be calibrated taking into account: feed and drilling speed, shaft friction, slenderness of the drill, resolution of the drill, wood species, dimension of the cross section and wood moisture content.

- *Juvenile wood*

It is necessary to drill through the cross section from several sides to get points of intersection. Based on the intersection points, the position of the core/pith can be determined. This information is necessary for calibration on juvenile wood.

- Decayed wood

The early stage of decay caused by fungi cannot be detected by micro-drilling because the mass loss of the wood is not significant vs sound wood. This implies that the drilling resistance doesn't change considerably.

- *Shaft friction*

Shaft friction is one of the most important phenomena that occur in high dense hardwood species. In order to keep the effect as small as possible, the drilling depths should be limited, otherwise low dense areas cannot be identified due to shaft friction.

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