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Mechanical strength characterization of recovered azobé timber boards for reuse

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ABSTRACT

Hundreds of kilometers of timber sheet piles protecting the banks of canals of the Netherlands are nearing the end of their service life and need to be replaced. Even though azobé wood is very widely used, little is known about the current state of the azobé timber sheet piles that have been in service for many decades. More information about the current strength is necessary for planning any intervention, maintenance or reuse of the recovered sheet pile boards. This study aims to characterize the current state of azobé sheet piles using destructive techniques such as four point bending tests, compression tests and non-destructive techniques such as micro-drilling and visual assessment. To achieve this objective sheet piles that were in service for over 57 years were pulled out and tested in the laboratory. The non-destructive tests results indicate that the deterioration of azobé sheet piles is concentrated on the superficial layers of the boards. Visual classification and micro drilling techniques did not yield results that support the findings from the destructive tests. The bending strength and modulus of elasticity of in service sheet piles used in current study was found to be lower by about 25 % and 30 % respectively when compared to new azobé sheet piles reported in literature. Based on average values of measured dimensions, density of the sheet piles in this study was in general, lower compared to new sheet piles. Thus, the lower strength could be due to deterioration, lower intrinsic quality of the recovered sheet piles, or simply fall within the natural scatter of the material. In addition an exercise to classify the samples to a strength class is shown for practicing engineers.

1. Introduction

Timber has been historically used in different parts of Europe for various inground geotechnical constructions. Klaassen and Creemers [1] gives detailed historic use of timber piles throughout Europe, for example, Venice with almost all historic buildings from 12th century, Stockholm parliament building from 1890, the Reichstag in Berlin, in middle and St. Petersburg in the east Hermitage.

Another large scale application of timber in the Netherlands, traditionally, was to protect the banks of thousands of kilometers of canals and streams. The bank protection structures often take the form of timber sheet piles or when the retaining depth is small also as

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horizontal sheet members (Fig. 1). Hundreds of kilometers of timber sheet piles are reaching the end of design service life or are in need of maintenance and intervention. In comparison to used timber piles for which detailed methodologies are currently being developed to study their current condition [2], very little is known about the current condition of timber sheet pile wall boards.

Timber sheet piles are loaded by active earth pressure on the back of the wall and passive earth pressure on the front of the wall which resists the active pressure. Often anchoring is used to reduce the required effective embedment depth and the displacement of the cantilever sheet pile. Timber sheet piles are joined using tongue and groove interlocks of trapezoidal or rectangular shape [3]. The maximum shear and moment to be resisted govern the length of the sheet pile and the thickness required.

Azobé (*Lophira alata*), okan (*Cylicodiscus gabunensis*) and treated pine (*Pinus sylvestris*) (treated pine is not used anymore) are commonly used species for timber sheet piles. Azobé wood is red/brown in color and may display interlock grain. Azobé was introduced in Netherlands after the second world war as a durable alternative to organic treated Oak [4]. Azobé, coming from West-Africa is used in extreme conditions as in a bank protection because of its resistance to decay in sweet water. Over time, based on the structures built in last seven decades, the species has given evidence for its performance and durability [5].

Timber sheet piles, similar to other hydraulic structures made of timber such as lock gates, and fenders are exposed to harsh conditions such as drying out, mechanical and wave impact (Gard and Van de Kuilen [6]). These conditions could result in deterioration, which necessitates the need for monitoring of such structures. The extent of deterioration might vary along the length of sheet pile (top of the sheet pile to embedment), vary with respect to the face of the sheet pile (open water side or earth side). Three different sections can be identified in a typical sheet pile (a) section which is completely embedded in the ground and below the waterline (anaerobic), (b) section which has one face completely in water on one side and earth on other side, (c) section which was subjected to air-water-soil environment [7], see (Fig. 2). While, it could be reasonably assumed that the top part of the sheet pile where an air-water-soil interface exist could be more prone to biological deterioration due to favorable circumstances, the parts completely submerged in water are less prone to attack by biological agents. Similarly, the earth face of the sheet pile is less susceptible to mechanical deterioration such as wave impact compared to the face on the water side.

Wealth of information is available in the literature on strength characteristics of recovered or aged wood from above ground applications [9-12]. In addition, there has also been interest for structural reuse of retired timber utility poles [13,14]. However, very little information is available on the mechanical properties of recovered timber sheet piles that have been in service and consequently subjected to mechanical and biological loads. One exception to this is Nowak et al. [7] who investigated wharf timber sheet piles made of *Pinus sylvestris L* by means of non-destructive methods. It is important to note that aging and deterioration impact different species in varying ways [15]. Moreover, unlike softwood species, azobé wood used in ground applications is typically not treated, as it possesses a natural resistance to decay.

To this extent, to the best knowledge of the authors, current study is one of the first attempts to study the state of hardwood timber sheet piles that has been in service for over 5 decades. In Van de Kuilen and Blaß [4], two of the tested samples were recovered from existing structures, but with an age of 15 and 18 years only. For those samples, strength and stiffness values were above average, so a possible negative influence caused by deterioration or long term loading could not be identified. Studies on old structural timber have confirmed the in-service effect on mechanical properties [15]. In addition, load history was seen to have a significant influence on bending strength than modulus of elasticity in old structural timber compared to new wood [15].

Challenges remain on quantifying strength reduction using non-destructive techniques. Nowak et al. [16] suggested that resistance drilling can be useful for qualitative assessment rather than a quantitative one. Moreover, it is not clear, if non-destructive techniques are an effective tool to assess dense hardwood sheet pile which has undergone deterioration. Klaassen and Creemers [17] found large variation in decay in reused azobé in their non-destructive inspection of timber used in artificial island in the marina of Akkrum, the Netherlands. The specific quality of the reused azobé was unknown in their study and the good performance was attributed to the

Fig. 1. a) Existing azobé sheet pile nearing end of service life b) Horizontal wooden elements protecting bank of the canal.

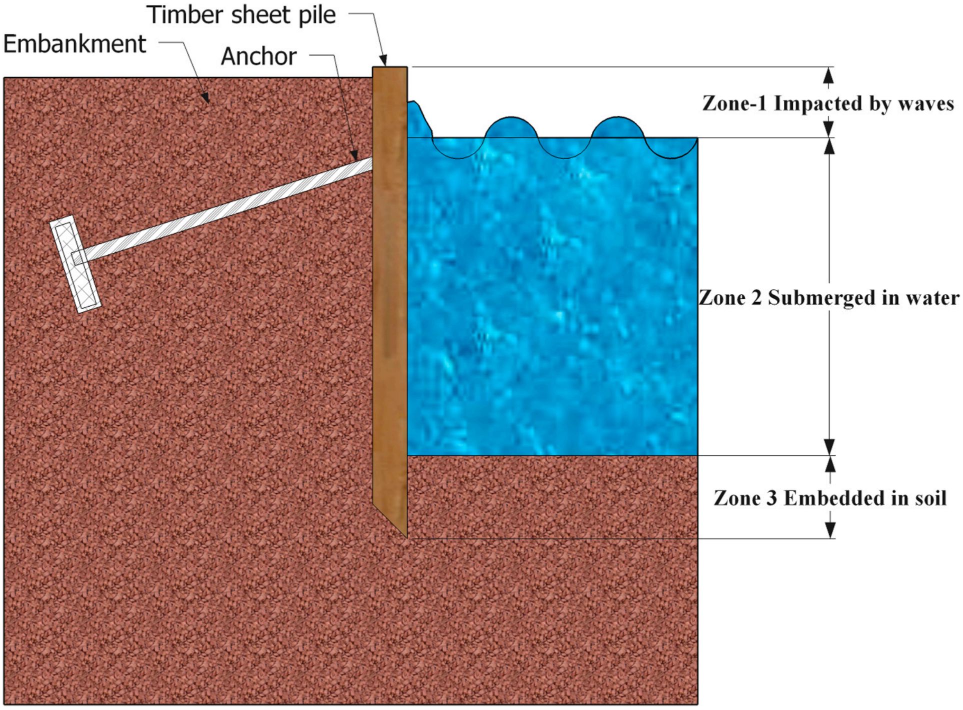

Fig. 2. Different zones in a timber sheet pile in service (modified from Nowak et al. [7] and Van de Kuilen and Van Der Linden [8]).

selection of high-quality timber after it was removed from its original location.

Compared to fresh sawn azobé boards, it is challenging to obtain large quantities of in-service old timber for destructive testing. Thus, the current study provides a unique opportunity to evaluate 152 boards of azobé using both destructive and non-destructive testing.

For the current study, timber sheet piles of azobé which were installed in 1966 in Medemblik, Province of Noord-Holland, the Netherlands were obtained (Fig. 3). The sheets were retrieved in early 2022. This study is aimed at characterizing the current state of these azobé sheet piles, using both destructive and non-destructive techniques. The results are aimed to support practicing engineers in planning maintenance or replacements measures.

2. Materials and methods

2.1. Processing of full length sheet piles

Sheet piles of average length 2.67 m were delivered to the TU Delft Biobased structures and Materials laboratory. The total length of the sheet piles were determined to be varying from 2.1 m to 3 m. The nominal average thickness and width of sheet piles varied from 33.8 to 42.8 mm and 124.4–325.4 mm respectively. When in service the sheet piles were anchored and the bolt holes were observed in the top section in some sheet piles.

It was decided to cut the sheet piles into two boards of 1 m each for non-destructive and destructive analysis. Such a division would aid in determining variation in strength characteristics, along the sheet pile, if any.

The center of the sheet pile was determined, and one meter on either side was marked and cut to obtain a total of two boards of one meter length each (Fig. 4). Thus, for each sheet pile, two boards were obtained, one which was representative of the top part and another representative of the bottom part. Each board was labeled and submerged in water by placing it in a tank few weeks before testing.

2.2. Visual inspection

Each board was closely inspected for visual characteristics such as stripes, holes and any other visible deterioration. As expected, no knots were present in the boards. Preliminary visual inspection, showed that all the boards had erosion deterioration stripes on the water side of varying depths and widths (Table 1). Varying levels of deterioration was also observed in tongue and groove joints. The grooves were disintegrated, brittle and deteriorated, the tongue was reduced in thickness due to deterioration in varying intensity along the length of the board. However, all the above-mentioned deterioration was concentrated on the water side, while groove on the earth side was intact. Holes formed from deterioration, partially or completely passed throughout the thickness of the board. All the

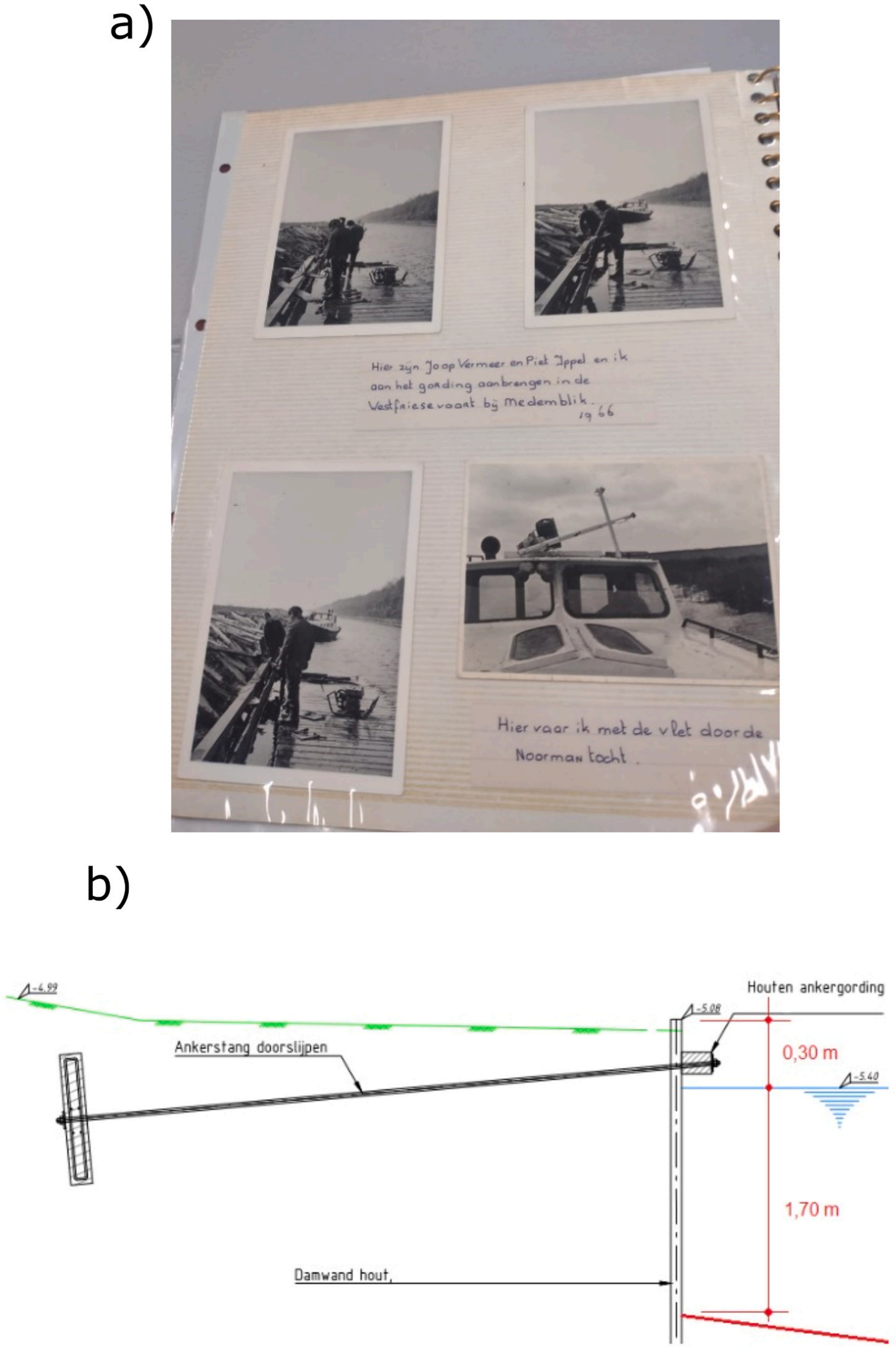

Fig. 3. From archives: a) Picture of installation of azobé timber sheet piles in 1966 b) Installation design of the sheet pile. Courtesy: Province of Noord-Holland.

above-mentioned deformities observed varied in intensities. Further analysis on wood quality is presented in results section.

Since no clear methodology exist for visual assessment of timber boards that were in service, a visual deterioration score (VDS), based on the size and deterioration characteristics of the deformities present was assigned to each board. The boards were visually inspected and given a score from zero to four, zero being an intact sheet pile and deterioration varying in quantity to score four (Table 2).

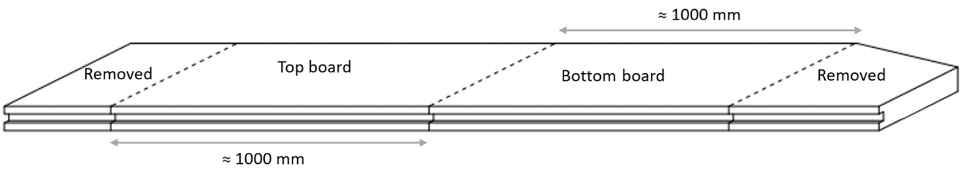

Fig. 4. Processing of full sheet pile into boards for testing.

Table 1
Types of deterioration stripes- shallow, medium and deep.

Deterioration stripes	Shallow	Medium	Deep
Depth [mm]	< 1.3	1.3 –2	> 2
Width [mm]	< 2	2 –4	> 4

Table 2
Visual deterioration score categories.

VDS	Deterioration stripes- depth	Striped deterioration distribution	Deterioration holes	Tongue/Groove condition
1	Shallow or Medium	Sparse 25–75 %	None	Intact
2	Medium & Deep	50 % 75 % 25 %	None	Groove slightly deteriorated but still retains its thickness
3	Medium or Deep	Throughout 50–75 %	Few shallow holes	Groove along the water side deteriorated to 50 % of its original thickness but still intact
4	Deep	50–75 %	Multiple holes through the thickness	Groove deteriorated and chipped away/ extremely thin and brittle

2.3. Acoustic measurements

Acoustic frequency response measurements were used to determine the dynamic modulus of elasticity (MOE_d) parallel to the grain. MOE_d was determined using the mobile Timber Grader MTG (Brookhuis Micro-Electronics BV, the Netherlands). MOE_d was determined as below:

$$V = 2{*}L * f \tag{1}$$

where *V is the velocity of the propagation wave, L* is the length of the board, *f* is the first natural frequency in Hz. Using the velocity of the propagating stress wave, the dynamic modulus of elasticity MOE_d was calculated from the formula:

$$MOE_d = V^{2} * \rho = 4L^2 f^2 \rho \tag{2}$$

where ρ is the wet density.

2.4. Resistance penetration drilling

116 boards with six locations per board were subjected to micro-drilling tests using the IML RESI PD-400 device. At every 0.1 mm, the device records the measurement results as drilling and feed speed power-depth graphs, in which the drill and feed speed power are denoted in terms of their percentage amplitudes. Higher amplitudes represent higher resistance to drilling, higher density and thereby sound wood, while lower amplitudes represent decayed wood. The lowest feed speed possible with the device, 25 cm/min and highest drill speed possible with the device, 5000 r/min was chosen.

Three location points from the earth side to the water side (two edges along length and middle) and another three corresponding locations from water side to earth side were chosen for drilling through the thickness. Resistance Measure (RM), the ratio of the area under the resistance curve in drill resistance with the depth obtained from each drill location point was determined by Eq. 3.

$$RM = \frac{\int_0^T RA.dt}{T} \tag{3}$$

where, *RA* is the drill speed resistance percentage at a given drill depth, *dt* is the depth interval at which the RA values are recorded (0.1 mm) and T is the specimen thickness.

2.5. Four point bending test

According to European standard EN 408 [18] the modulus of elasticity of structural timber can be determined in four point bending tests either by (i) deformation measurements within the zone of constant bending moment, MOE static local ($MOE_{s,l}$) or (ii) deformation measurement of mid span deflection relative to supports, MOE static global ($MOE_{s,g}$). In case $MOE_{s,g}$ is measured, EN 408 [18] suggests a conversion equation to be determined for $MOE_{s,l}$. Thus, a span (S) of 18 times the depth of the thickest board = 750 mm was used, with load applied at 6 times thickness from the support (Fig. 5). The loading mechanism consists of a load cell which measures load applied with an accuracy of 0.1 kN and displacement sensor that records the vertical displacement with an accuracy of 0.001 mm. The load was applied on to the specimen using two steel rollers of diameter 20 mm at a center-to-center distance of 250 mm and equidistant from the center of the specimen.

2.5.1. MOE global

Four point flat wise-bending tests were conducted on 152 specimens to determine $MOE_{s,g}$ and bending strength (MOR). It was decided to conduct the four point bending tests in four different configurations based on the face of the specimen subjected to loading (earth side or water side) and location of the specimen with respect to the total sheet pile (top part or bottom part), see Table 3. For $MOE_{s,g}$ the deflection is measured on the board at mid span relative to the roller supports. Two lasers displacement sensors (LS01 and LS02) placed below the level of the supports at mid span record the vertical displacement of the downward facing surface of the board with an accuracy of 0.001 mm

2.5.2. MOE local

In order to estimate the $MOE_{s,l}$, the deflection within the point loads where constant moment occurs is measured. As specified in EN 408 [18] the central distance between the points of measurements of the displacement had to be kept 5 times the thickness of the specimen tested and was taken as 200 mm. The measurements are taken at limited part of the test piece using a LVDT to estimate $MOE_{s,l}$ see Fig. 6.

2.6. Compression tests

Specimens with a length of 210 mm, which is approximately 6 times the smallest cross-sectional dimension were cut from 20 boards for testing specimens in compression. In addition to the vertical displacement measurements being recorded by the load cell based on its own movement, two LVDTs were placed on either surface of the specimen as shown in Fig. 7. Each LVDT was fixed to the board using two brass clamps that were fixed to the specimen using screws at a distance of at least 140 mm, which is 4 times the thickness of the thinnest specimen (EN 408 [18]). The loading rate was maintained at 0.01 mm/s according to EN 408 [18].

2.7. Data analysis

2.7.1. Influence of geometry

Thickness, width and length were measured 3 times along the sheet pile. Average of the three measurements were used for further calculations of moment of inertia, bending strength, compressing strength and modulus of elasticity.

All boards tested had been in service and had a tongue and groove in various levels of integrity. An equivalent rectangular section was assumed for calculation of moment of inertia with respect to the geometry ($I_{cal,g}$), Fig. 8. This assumption makes the calculations consistent for all the boards irrespective of minor changes in tongue and grooves. This assumption results in an underestimation of the moment of inertia compared to the actual moment of inertia (I_{act})used in determining bending strength and modulus of elasticity.

To estimate the impact of variations in tongue and groove and assumption of rectangular cross section, moment of inertia of two representative extreme cases were checked. A board with deterioration, but still having its tongue and groove intact and a board with one groove completely deteriorated was compared. The former has an actual moment of inertia, I_{act}= 1.06I_{cal} and the latter with an

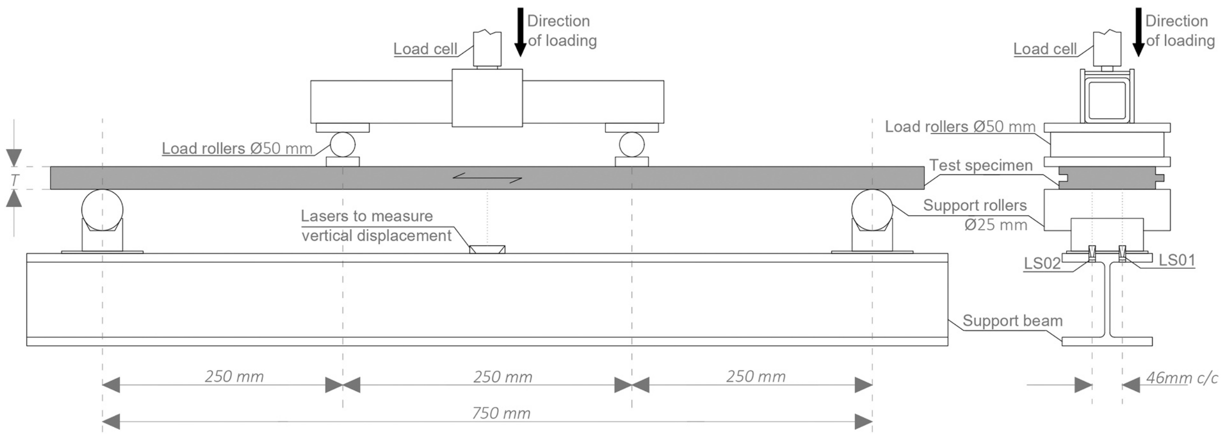

Fig. 5. Four point bending setup for $MOE_{s,g}$ measurements.

Table 3
Four-point bending test configuration of the tested boards with respect to the face at which the load is applied, W-water side, E-Earth side.

Configuration	I	II	III	IV
Top board loading face	W	W	E	E
Bottom board loading face	W	E	E	W

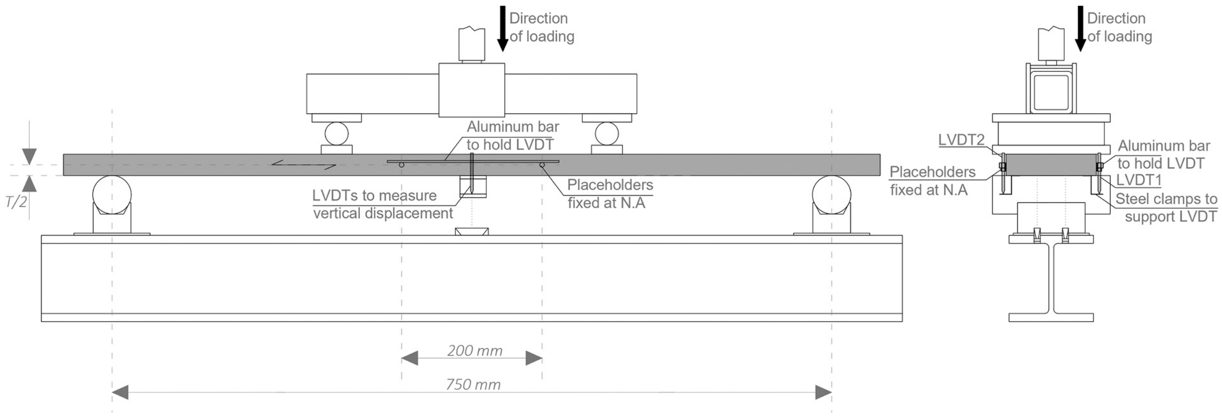

Fig. 6. Four point bending setup for $MOE_{s,l}$ measurements.

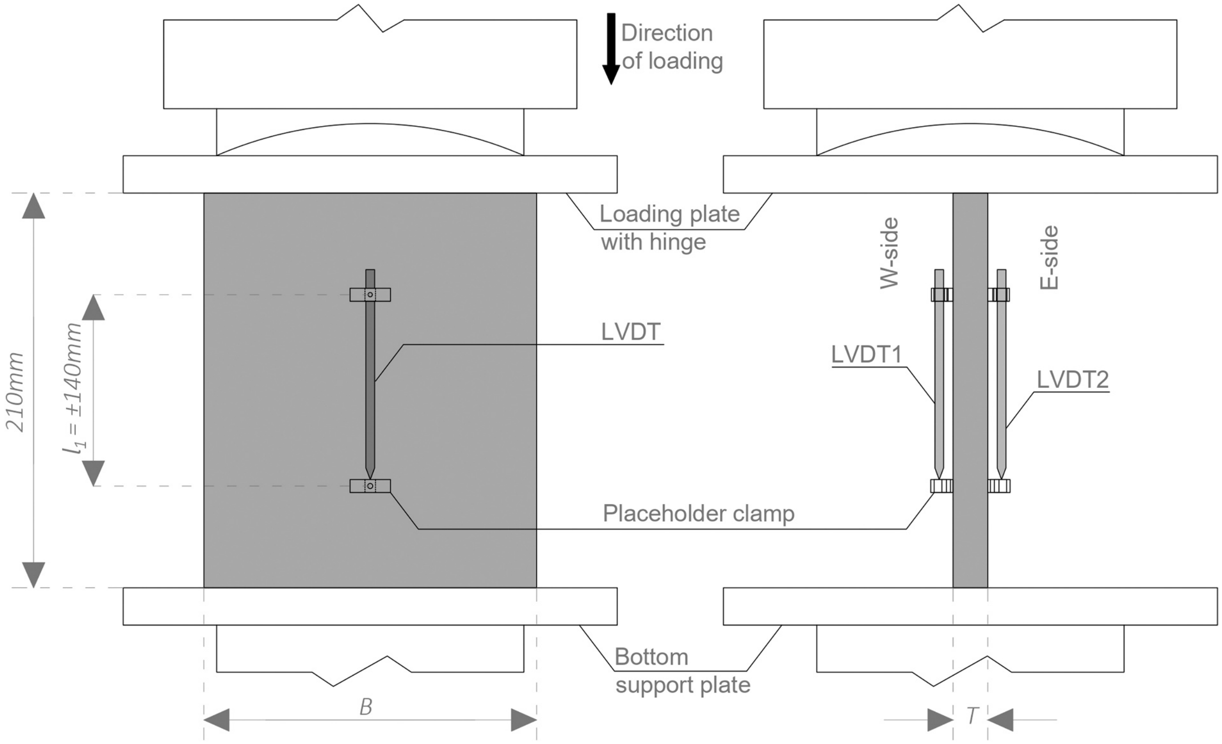

Fig. 7. Compression test setup.

$I_{act}= 1.09I_{cal}$. All the moments of inertia were determined using computer aided drawings software.

2.8. Statistical analysis

Kolmogorov-Smirnov normality test is conducted to check for normal distribution of the data at 0.001 significance level. Significant

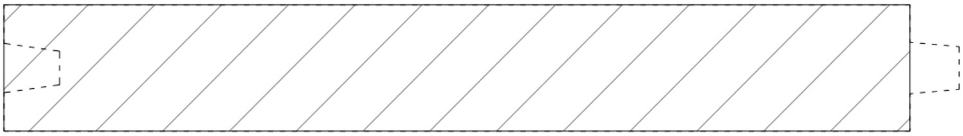

Fig. 8. Cross-sections of the sheet-pile boards, assumed for calculation (hatched) vs real (dotted).

(a) (b) (c) (d) (e)

Fig. 9. Deterioration observed on the recovered azobé boards a)Earth side b)Shallow stripes observed on water side c)Severe water side deterioration d)Water side deterioration of the groove e)Water side deterioration of the tongue.

differences among data sets were assessed with one way ANOVA, followed by post hoc Tukey's test.

3. Results

3.1. Board quality and non-destructive tests

Deterioration stripes were observed in all the boards on the water facing side with varying degree (Fig. 9 **b**). Tongue and groove was found to be intact and had shallow stripes in 18 percent of the tested boards. Highest number of sheets were assigned to VDS 2, 45 %, indicating that majority of the boards had only moderate deterioration (Table 4). Deterioration holes showing a pattern like that of Teredo navalis (shipworm) passing through the full thickness was present in a minority (6 %) of the tested boards and thus assigned to VDS score 4 (Fig. 9 **c)**). In general, the groove edges that were facing the water side were thin and had undergone deterioration or in worst case absent. The tongue was rectangular and about 2 mm thinner compared to the size of groove.

An average MOE_d in wet state of the full population of 152 boards tested was 16800 MPa with 17.9 % CoV. The penetration drilling measurements showed no discerning pattern when compared to the visual deterioration score assigned. No clear pattern was also observed on RPD measurements along the board or from either side of the board. This points towards the lack of potential of the use of RPD measurements for the type of deterioration observed in this study. Distribution of non-destructive parameters measured are shown in Fig. 10.

3.2. Destructive tests

The average $MOE_{s,g}$ was found to be 11500 MPa with a coefficient of variation of 21.2 %. No significant difference was observed in the $MOE_{s,g}$ in any of the I, II, III, IV configurations ($p < 0.05$, one way ANOVA-Tukey test). The bending strength of the population had a mean of 78.8 MPa with coefficient of variation of 21.1 %. No significant difference in peak strength was also observed among four tested configurations. The moisture content (MC) of all but 9 boards was above the fiber saturation point of 28 % for azobé [19]

Eight boards were tested for determining $MOE_{s,l}$, the average local modulus of elasticity was 11750 MPa with coefficient of variance 22.4 %. Twenty samples from the sheet piles were tested in compression and an average compression strength of 46 MPa was obtained. The average modulus of elasticity in compression was determined to be 13300 MPa. Distribution of destructive parameters are shown in Fig. 11.

3.3. Relationships between parameters

A slight general trend of decrease in VDS (from VDS 1 to VDS 4) with respect to decrease in $MOE_{s,g}$ and MOR was observed (Fig. 12**)**. Due to the generic nature of the observation and narrow range of VDS, the methodology used in this study can be used only as a preliminary indicator for the strength of the boards.

MOE_d was correlated to $MOE_{s,g}$ by $MOE_{dyn} = 1.2693$ MOEs,g $+ 2000$ with an R^2 of 0.47. Drilling resistance measurements (RM) was not correlated with any of the mechanical test results of $MOE_{s,g}$ and MOR. Majority (>50 %) of the resistance measures fell in between 22 % and 28 %. $MOE_{s,g}$ was positively and strongly (R^2=0.61) correlated with MOR by MOR $= 0.0065\ MOE_{s,g} + 3.5$. The relationship between local $MOE_{s,l}$ and $MOE_{s,g}$ was found to be $MOE_{s,l} = 1.17\ MOE_{s,g}$, with $R^2 = 0.77$, see Fig. 13.

Testing in four different configurations (Table 3) with the intention of understanding the effect of deterioration on strength on top and bottom boards, water and earth side did not reveal any systematic pattern. A comparison of bending strength for configuration I and configuration III where water side and earth side are on the compression side in a bending test, the mean was around 80 MPa for either configuration. When comparing the properties, MOE_d, $MOE_{s,g}$, MOR and resistance measurements, no significant difference between top and bottom boards was found.

The compressive strength shows good correlation with modulus of elasticity in compression MOE_c as $f_c = 0.0022\ MOE_c + 17.66$, with $R^2 = 0.58$, see Fig. 13. Compressive strength also shows strong correlation with $MOR_{s,l}$, $f_c = 0.56\ MOR_{s,l}$ with $R^2 = 0.76$. The compression strength parameters, MOE_c ($R^2 = 0.33$) and f_c ($R^2 = 0.53$) showed better correlation with RPD measurements than bending parameters.

4. Discussion

While no species is completely immune to deterioration azobé has demonstrated a high resistance to marine borer attack [20]. From observation on sheet piles used in this study, around 6 % of the samples had holes formed by shipworm (*Teredo navalis)* passing through the whole thickness of the boards.

The variations in I_{cal} and I_{act} would result in a strength and stiffness overestimation between 6 % and 9 %. The thickness of the boards varied throughout the length. Additionally, these differences in thickness, though not locally taken into account, are included in the bending strength and stiffness calculated by considering the average thickness of each board. The variation in thickness can also be considered as an indication of quantity of the deterioration the board has undergone. Assuming, the thickest section measured for an individual board represents intact thickness, the maximum % of variation in thickness due to deterioration was below 18 %. (Fig. 14).

Table 4
Overview of test samples and test results.

Config.	No.	Length		Width		Thickness		S/T	Density$_{wet}$		Density$_{mc12\ \%}$		VDS		MOE$_{d}$		RM		MOE$_{s.g}$		MOR		MC	
		[mm]	[%]	[mm]	[%]	[mm]	[%]	[-]	[kg/m³]	[%]	[kg/m³]	[%]	[-]	[%]	[MPa]	[%]	[%]	[%]	[MPa]	[%]	[MPa]	[%]	[%]	[%]
		Avg.	CoV	Avg.	CoV	Avg.	CoV	Avg.	Avg.	CoV	Avg.	CoV	Avg.	CoV	Avg.	CoV	Avg.	CoV	Avg.	CoV	Avg.	CoV	Avg.	CoV
I	44	1000.7	0.6	194.6	21.3	37.1	4.5	20.1	1090	5.8	911	6.8	2.19	40.5	16250	20.2	25.2	9.8	11300	23.5	77.7	20.6	40	18.9
II	36	1000.9	0.6	189.5	20.3	36.8	4.1	20.3	1094	4.2	934	4.8	2.19	40	17250	17.3	25.0	7.6	11700	19.4	79.7	21.0	37	17.5
III	36	998.8	0.9	192.6	22.1	36.6	3.7	20.4	1081	3.5	925	5.7	2.25	44	16950	15.2	24.5	10.2	11500	18.4	81.4	20.4	37	20.2
IV	36	1000.8	0.5	193.8	25.7	36.8	3.1	20.3	1096	4.1	927	7.2	2.31	34.1	16800	18.3	24.9	10.4	11400	23.1	76.7	23.0	38	21.5
Overall	152	1000.3	0.7	192.7	22.2	36.9	3.9	20.3	1090	4.5	924	6.2	2.26	37	16800	17.9	24.9	9.5	11500	21.2	78.8	21.1	38	19.7

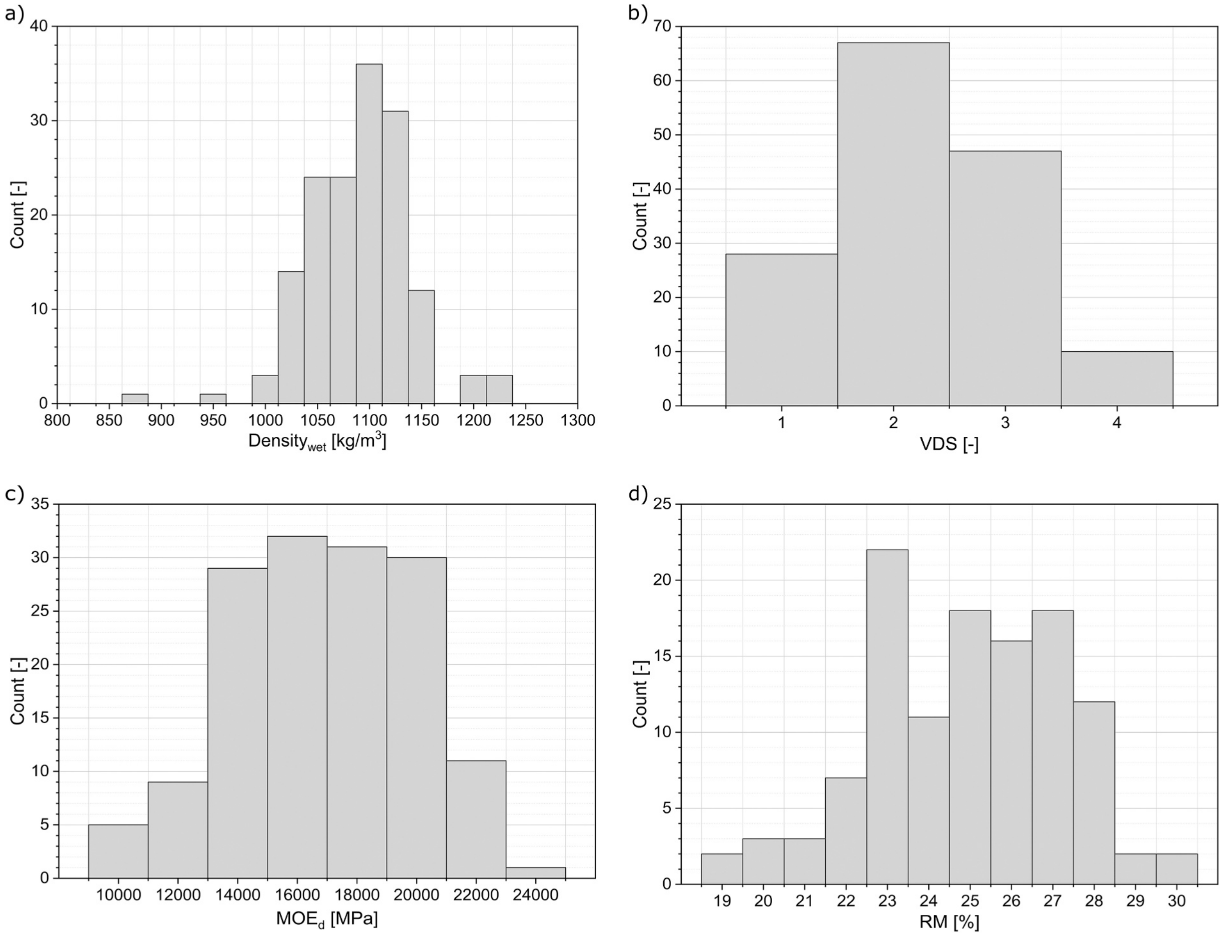

Fig. 10. Distribution of non-destructive measurements a) Wet density, b) Visual deterioration score, c) Dynamic modulus of elasticity, d) Resistance measure according to Eq. 3.

4.1. Non-destructive tests

Resistance measure value in a RPD test depends on tree species, direction of drilling, moisture content of the wood, number of tests, condition of wood etc. ([16,21]. A number of previous researchers have found good correlation of resistance measurements with density, modulus of elasticity in compression, compressive strength and bending strength [22]; Kloiber et al. [23]; Acuña et al. [24]; Faggiano et al. [25]). On the contrary, other researchers have also found lack of strong correlation between drilling resistance, mechanical properties and deterioration or do not validate the usage of drilling for study on deterioration, e.g. change of static bending strength of scots pine due to white rot decay, [26] Tannert et al. [27]). In the current study no clear correlation was found between resistance measure and bending strength (r^2=0.06).

Better correlations were observed in the current study between compression strength (r^2= 0.53) and resistance measure and also between resistance measure and elasticity in compression (r^2= 0.33). Drilling resistance measurements from water side or earth side did not differ, which may point to the deterioration occurring only superficially along the sheet pile on the sheet pile. This can also be confirmed by the previous observations of micro-drilling on azobé, that only cracks of thickness above 0.64 mm with confidence of 99 % could be detected using the RPD technique [6]. Based on the above observations it is recommended that micro-drilling measurements should be used for qualitative assessment with expert judgment in the case of onsite assessment of azobé timber elements which are or were under service. It is also to be noted that micro-drilling technique has been successfully applied primarily in softwoods and medium dense woods and not in dense hardwoods (Density>800 kg/m3) [6].

4.2. Direct comparison of strength properties with literature

The ratio between average value of MOE_d and $MOE_{s,g}$ for azobé timber specimens was reported to be 1.13–1.29 by Ravenshorst [28] when tested in edgewise bending. Similarly, Van de Kuilen and Blaß [4] obtained a ratio of 1.09 for MOE_d and $MOE_{s,g}$. In the current study, the ratio between MOE_d and $MOE_{s,g}$ was found, 1.46. The average of MOE_d of all the boards tested are also below the

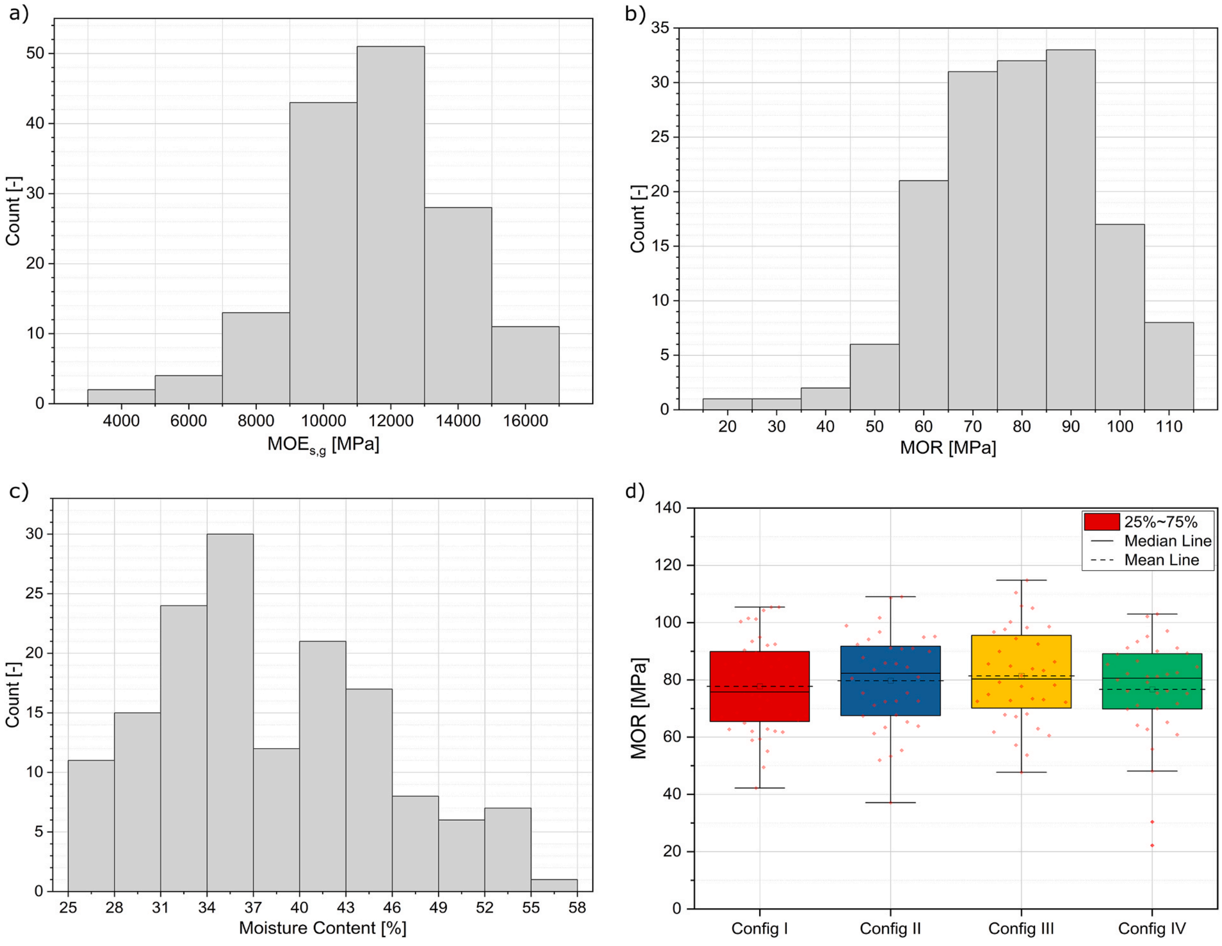

Fig. 11. Distribution of destructive strength parameters a) $MOE_{s,g}$ b) MOR c) Moisture content d) MOR of four configurations tested.

average values reported for new azobé beams [28]. It is to be noted that Ravenshorst [28] results are based on edgewise bending. The decrease in modulus of elasticity could be an indication of deterioration of the azobé boards due to the service of 57 years or lower intrinsic quality of the boards in the study.

Based on 180 samples of new azobé timber tested in both flatwise and edgewise bending an average bending strength of 103 MPa and an average modulus of elasticity of 17600 MPa was found by Blass et al. [29]. Similarly, based on 258 specimens of azobé sheet piles (new and used) tested in both flatwise and edgewise bending, an average bending strength of 96.1 MPa with standard deviation of 18.9 MPa was reported by Van de Kuilen and Blaß [4]. The findings from Van de Kuilen and Blaß [4] serve as a basis for directly comparing average strength values with the results obtained in this study. This is because their study includes reported results for both new and in-service azobé timber sheet piles. New azobé boards tested by Van de Kuilen and Blaß [4] in similar conditions (span to depth ratio, flat wise bending and moisture content) had an average static modulus of elasticity of 16450 MPa and bending strength 104.8 kPa.

Interestingly, the results reported by Van de Kuilen and Blaß [4] consisted of samples having specimens derived from in service sheet piles from different location in the Netherlands. Sheet pile specimens of azobé which were in service for over 15 (sample O2) years and 18 years (sample O3) had an average modulus of elasticity of 18490 MPa and 17380 MPa respectively. It has to be noted that span to thickness ratio for sample O2 was 30–25 and for sample O3 was 30. The bending strength of sample O2 and O3 was 109.4 MPa and 106 MPa respectively [4]. The correlation between modulus of elasticity and bending strength obtained in this study is comparable [28] or better [4] than reported in the literature.

On comparison, the average bending strength and modulus of elasticity in bending in this study was ≈ 25 % and ≈ 30 % lower compared to new azobé boards [4]. When compared with in service boards from Van de Kuilen and Blaß [4] the results of this study in terms of bending strength and modulus of elasticity are ≈ 27 % and ≈ 35 % lower. Direct comparison with new azobé boards tested by Ravenshorst [28] also show a decrease in modulus of elasticity and a slight decrease in bending strength (Table 5). Based on existing literature on old structural timber, it can be seen that in majority of the studies report no change in modulus of elasticity, while few studies show a decrease in modulus of elasticity and none reported an increase in modulus of elasticity [15]. Cai et al. [30] compared 90 year old (*Pinus taeda* L.) joists, to new timber of southern pine in flat wise and edge wise bending and found about 15 % and 42 %

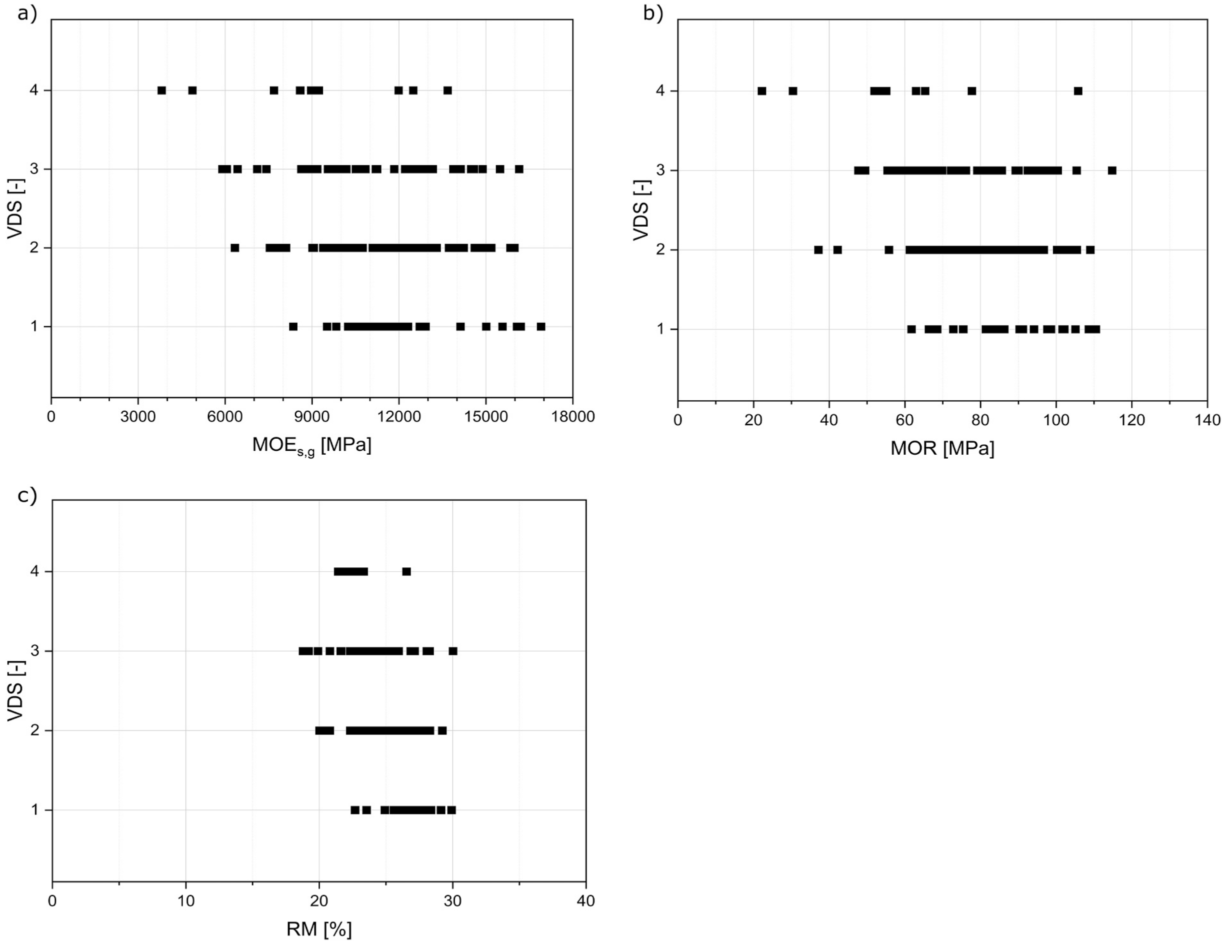

Fig. 12. Relationship between VDS and a) $MOE_{s,g}$ b) MOR c) RM.

decrease in modulus of elasticity. However, large majority of the studies on recovered wood are either from softwoods and above ground applications

The values reported above are based on I_{cal}, i.e on the basis of assumption of rectangular cross section, the actual values for strength and static modulus of elasticity as reported should be lowered by 6–9 %. It has to be noted that nominal average thickness is used for the determining the mechanical properties.

In order to compare the general trend among strength parameters of the boards in this study with fresh azobe boards tested by Ravenshorst [28], $MOE_{s,g}$, MOE_d, MOR and density for both studies were plotted, Fig. 15. It can be observed that the cloud of data from Ravenshorst [28] and this study follow a similar general trend for MOE_d vs $MOE_{s,g}$ Fig. (15**, a)).** However, it can be also observed that density of tested boards in this study are lower than that reported by Ravenshorst [28] for new boards. Given that no information is available about the quality of the boards used in this study during installation five decades back, the lower density at 12 % moisture content ($\rho_{mc12\,\%}$) and superficial deterioration observed, points towards a general lower intrinsic quality of the boards. Again, it has to be noted that the surface of the boards was not planed and the density measurements are based on average values of dimensions measured.

4.3. Example classification strategy for sheets piles in service

Classification of the population of sheet piles tested in this study into a strength class is the essential next step and will act as a vehicle for knowledge transfer for practicing engineers. A non-parametric method and parametric method is used here to determine the characteristic value of strength. It is to be noted that Van de Kuilen and Blaß [4] found that a normal distribution fits the azobé strength distribution the best. It was also shown that the influence of the choice of distribution on the lower fifth-percentile characteristic value of the bending strength is relatively small.

According to EN 384 [31], the 5 % fractile of the sample is in principle a point estimate and is of the order of n/20, where n is the number of samples. Strength class allocation according to EN 338 [32] is based on a reference moisture of 12% and reference height of 150 mm. Based on Houtinstituut [33], Van de Kuilen and Blaß [4] adjusted for the density of azobé by adding 200 kg/m3 to density

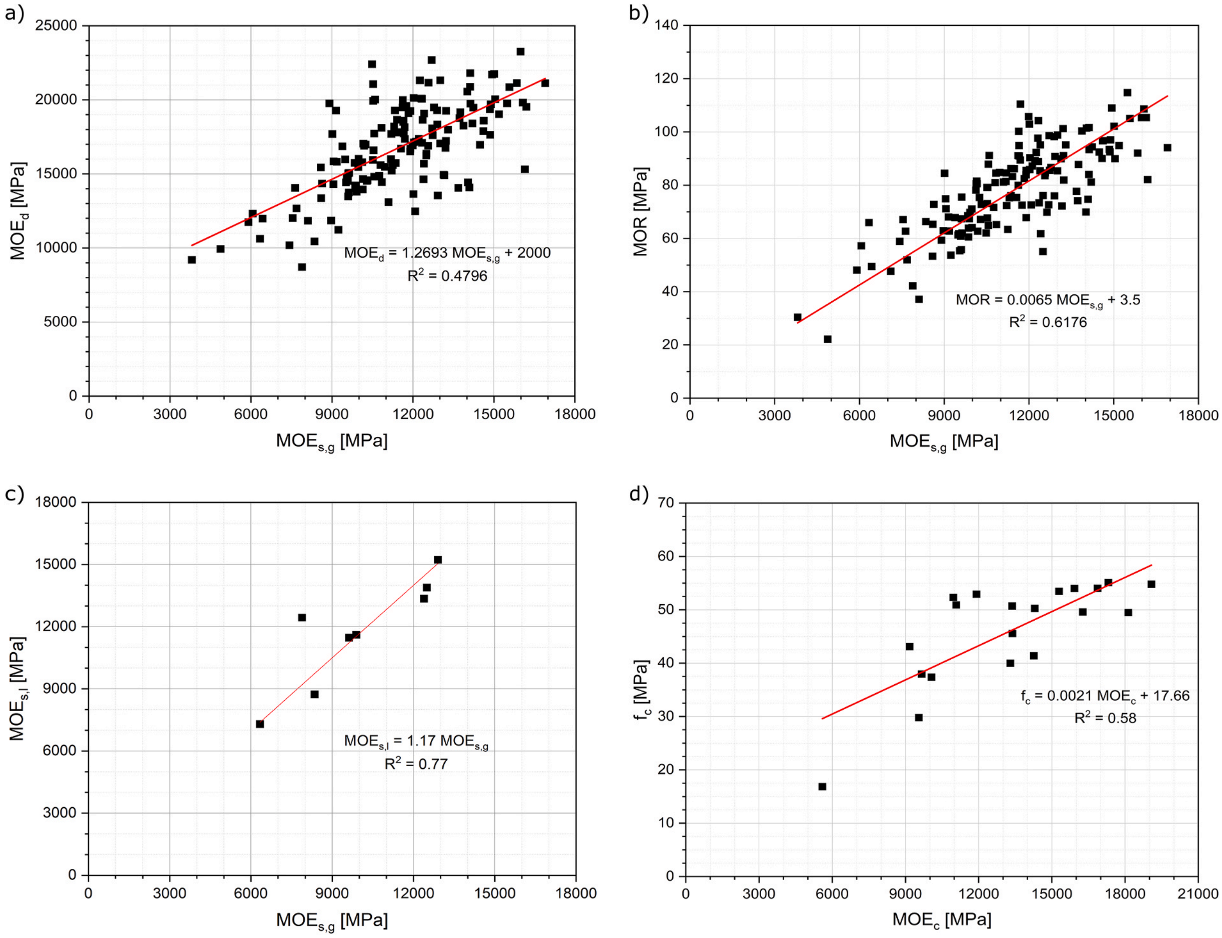

Fig. 13. Relationship between: a) MOE_d vs $MOE_{s,g}$ b) MOR vs $MOE_{s,g}$ c) $MOE_{s,l}$ vs $MOE_{s,g}$ d) f_c vs MOE_c.

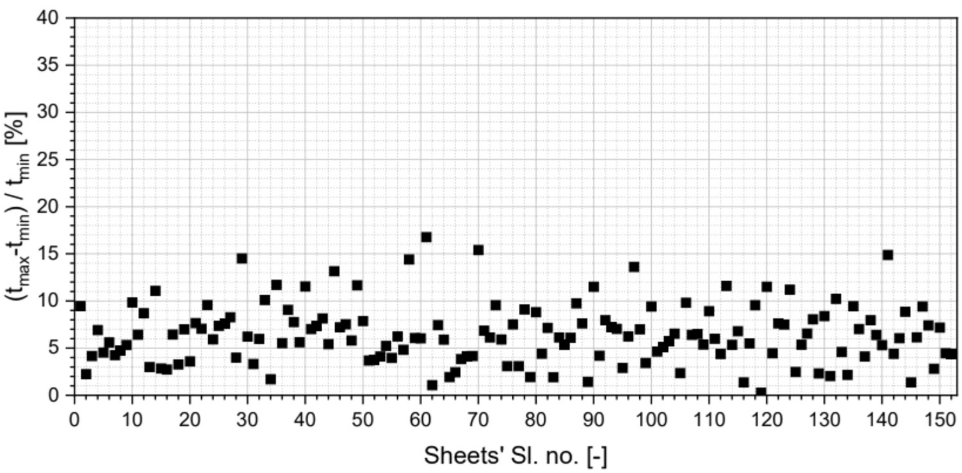

Fig. 14. Percentage difference between maximum and minimum thickness of individual boards.

based on green volume and oven-dry mass. Ravenshorst [28] suggested adjustment factors for strength properties, which was based on tests conducted on wide range of species with different dimensions Eqs. (4–6). The volume change coefficient β takes into consideration the effect of radial, tangential and longitudinal shrinkage and a species-independent average value of 0.5 was used. Adjustment factors for moisture content as suggested by Ravenshorst [28] could be used Eqs. (4–6) for the purpose of strength class allocation of

Table 5
Comparison of experimental data with reported results on azobé from literature (all mean values).

Sample	No.	Width [mm]	Span [mm]	S/T [-]	MC[d] [%]	MOE_d [MPa]	$MOE_{s,g}$ [MPa]	MOR [MPa]
PNH[a]	156	193	750	20.3	>FSP	16,800	11,500	78.8
AZ1[b,c]	46	50	18 + 3 h 5	18 + 3	> 30	20,700	17,000	93.8
AZ2[b,c]	79	65	18 + 3 h 5	18 + 3	> 30	17,700	13,700	80.7
AZ3[b,c]	30	50	18 + 3 h 5	18 + 3	> 30	21,200	18,700	111.6

[a] Results from current study
[b] Results from Ravenshorst [28]
[c] AZ1, AZ2 and AZ3 were tested edgewise with h value of 150, 150 and 110 mm respectively
[d] The moisture content at which the sheet-pile was tested

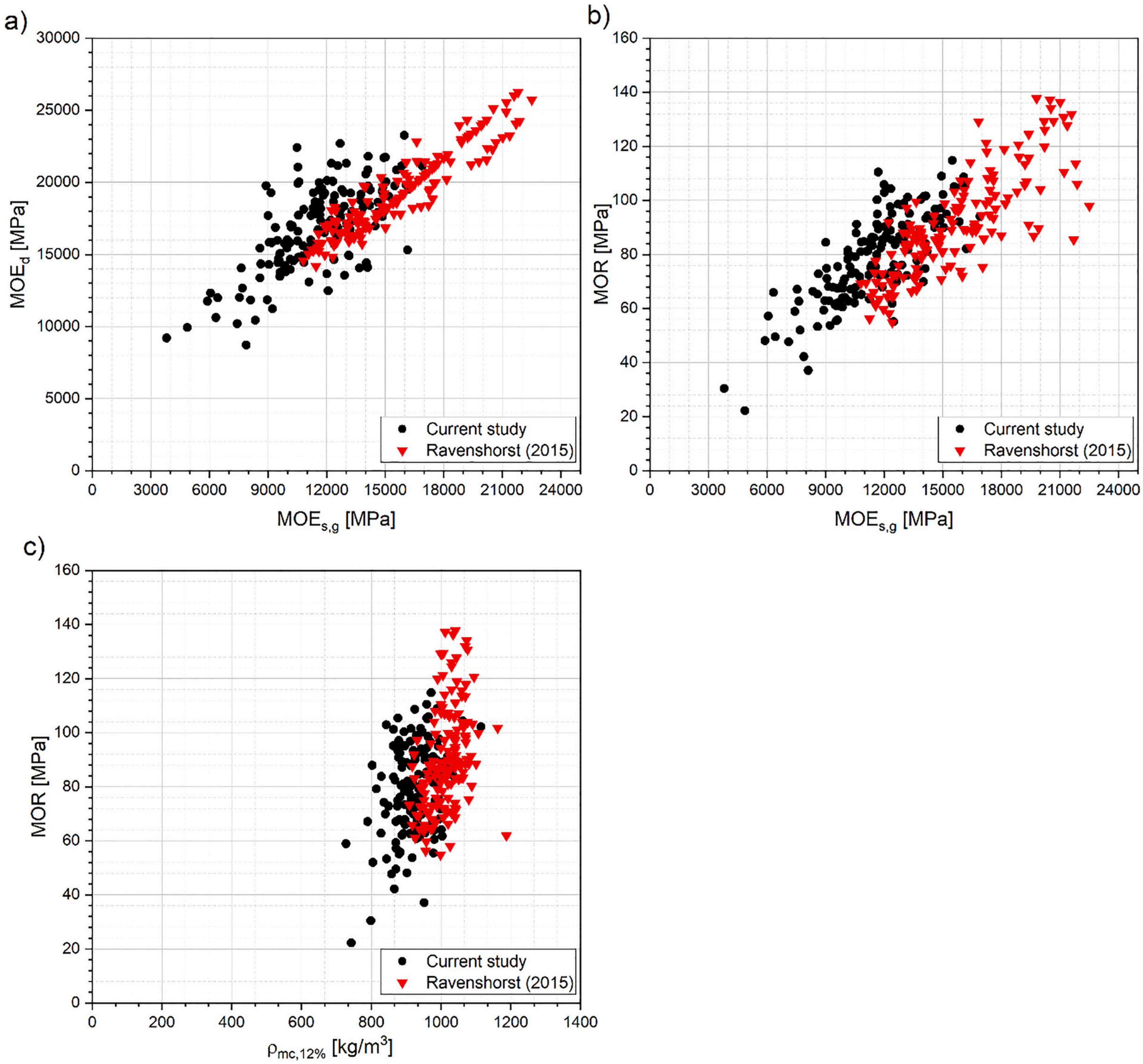

Fig. 15. Comparison of strength parameters between the current study and Ravenshorst [28]. a) MOE_d vs $MOE_{s,g}$ b) MOR vs $MOE_{s,g}$ c) MOR vs $\rho_{mc12\,\%}$.

the used azobé boards.

After moisture corrections and based on EN 338 [32] the azobè sheet piles used in this study have potential to be placed in D50 with mean modulus of elasticity as governing factor, using parametric calculations according to EN 14358 [34] see Table 6. Strength

Table 6
Characteristic strength values of D50 class and current study.

	$f_{m,k}$	$E_{m,mean}$	$\rho_{m,k}$
	MPa	MPa	kg/m^3
D50	50	14,000	620
Non parametric	58	15,210	815
Parametric	60	15,210	826

parameters were normally distributed with a significance level of 0.001. Thus, using parametric method, Eq. 6, in EN 14358 [34] the sheet piles tested have a characteristic strength of 60 MPa and can be placed in class D50 with MOE as governing parameter.

However, from a practical point of view with the factor to adjust test results to the number of samples according to EN 384 [31] the values in Table 6 need to be reduced by factor of 0.7. Bending strength based on Dutch grading standard [3], fresh azobé was classified into strength class D70 [35]. Thus, from a reuse point of view, the large quantity of azobé wood that may become available in the coming years, could be assigned to a lower strength class (D50) than new boards (D70). However, the lower density of the extracted boards and subsequent lower intrinsic quality of the boards also have to be taken into account.

$$\rho_{mc12\%} = \rho_{wet}\frac{1+0.01\beta_v(MC_{25}-MC_{12})}{1+0.01(MC_{wet}-MC_{12})} \tag{4}$$

$$MOE_{mc12\%} = \frac{MOE_{wet}}{1-k_{mc}\left(\frac{\min(MC_{wet};25)-12}{13}\right)} \tag{5}$$

$$MOR_{mc12\%} = \frac{MOR_{wet}}{1-k_{b,mc}\left(\frac{\min(MC_{wet};25)-12}{13}\right)} \tag{6}$$

$\beta_v = 0.5$ is the percentage volume change per percentage MC;
$k_{mc} = 0.13$ is the 12 % MC adjustment factor for MOE;
$k_{b,mc} = 0.15$ is the 12 % MC adjustment factor for bending strength;
MC_{25}, MC_{12}, MC_{wet} is the moisture content at 25 %, 12 % and wet condition respectively.

5. Conclusions

A detailed investigation into current state of azobé sheet piles in service was conducted using destructive and non-destructive testing techniques. Following conclusion can be drawn from this study:

(i) Visual assessment based on deterioration score criterion developed within this study showed that less than 6 % of the boards showed high levels of deterioration, with holes attributed to *Teredo navalis* deterioration passing through the entire thickness. The maximum reduction in thickness due to deterioration was less than 18 %, based on the assumption that the thickest section measured for each board represented intact non-deteriorated thickness. Future research could explore the application of advanced machine learning techniques, such as neural networks, to further refine the correlation between visual inspection findings and mechanical properties.
(ii) No clear correlations were determined between non-destructive measurements and destructive strength parameters. Thus, micro-drilling measurements are recommended to be evaluated for preliminary qualitative assessment with expert judgment only.
(iii) Direct comparison with results reported in literature on new azobé boards show that the azobé boards investigated in this study had 25 % lower bending strength and 30 % lower modulus of elasticity than new azobé boards. However, the relationships between modulus of elasticity and bending strength for new boards and boards from the current study are similar. This indicates a lower quality (also the density is lower) of the boards from the current study, which could be related to the growth area of the boards, which is unknown, or to an influence of the preloading.
(iv) Azobé boards investigated in the current study were assigned to strength class D50 with modulus of elasticity as governing parameter.

CRediT authorship contribution statement

Abhijith Kamath: Writing – original draft, Validation, Methodology, Investigation, Funding acquisition, Conceptualization. **Ganesh Shri Raam Kalaichelvi Senthil Kumar:** Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis. **Jan-willem van de Kuilen:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Geert Ravenshorst:** Writing – review & editing, Visualization, Supervision, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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