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Advancing Timber for the Future Built Environment

STRENGTH GRADING OF SATURATED ROUND TIMBER FOR STRUCTURAL APPLICATIONS

Giorgio Pagella[1], **Michele Mirra**[2], **Geert Ravenshorst**[3], **Jan-Willem van de Kuilen**[4]

ABSTRACT: The lack of strength values for timber foundation piles in the current Eurocode 5 hinders their appropriate engineering design and assessment. Timber piles, often submerged for their entire service life, endure high moisture levels, highlighting the need to define strength parameters of round wood under fully saturated conditions. To ensure reliable material properties, a large-scale study was conducted on 70 European softwood piles, determining strength and stiffness through axial compression tests on saturated segments extracted along the pile. Mean and characteristic wet compressive strength and stiffness values were derived, applicable to the whole pile and/or its parts. The mechanical properties of the piles were analysed in relation to grading parameters that may influence the saturated compressive strength, leading to the classification of three strength classes for visual grading. Additionally, two regression models were developed—one based on the most influencing visually graded parameters, and the other on the dynamic modulus of elasticity. The saturated compressive strength values and grading boundaries presented in this study contribute to the engineering design of European softwood foundation piles in the context of a new circular construction ecosystem, and support the integration of reliable design values into future versions of Eurocode 5.

KEYWORDS: timber, grading, timber foundation piles, strength classes, round timber.

1 – INTRODUCTION

Historically, timber foundation piles were designed on experience and trial-and-error techniques to determine their optimal length and load-bearing capacity [1], as formal methods for soil analysis and geotechnical engineering had not yet been established. Despite current advancements in geotechnical and structural engineering, European standards and guidelines for the design of timber piles remain limited. In the current Eurocode 5 (EC5) [2], which provides regulations for the design of timber structures, timber piles are not mentioned. In the Netherlands, where timber piles were extensively utilized across the country, the present Dutch National Annex to EC5 [3] and NEN 5491 [4] provide a single "dry" compressive strength design value (at 12% moisture content) based on historical data [5],[6], and grading rules for saturated timber piles and their application in soil. The design of saturated timber piles in the ground, enduring high moisture contents, starts from the "dry" strength value in [3], factoring in climate conditions and load durations using codified modification factors (k_{mod}) in the calculation, according to the design practice in the EC5. This is because the mechanical properties of timber are dependent on moisture content [7], where climate conditions with high moisture levels (such as saturated piles in the ground) result in lower strength and stiffness [8]. However, the modification factors in the standards were determined on the basis of edgewise bending tests conducted on timber boards [9], which may have different behaviour than round wood such as timber piles, as indicated in previous studies [7],[8]. In addition, the load duration is typically accounted for 50 years in the modification factors. However, the service life of timber pile foundations can be much longer than modern design, up to 300 years or more [10]-[15]. These aspects highlight that the current procedure outlined in the standards, may not be adequate for the design of timber piles in wet conditions, suggesting the need for conducting research on the material properties of saturated timber piles. In the existing literature [5],[6],[7], large uncertainties are present with regard to the material properties of saturated timber piles. The provided compressive strength and stiffness properties are not fully comprehensive for a correct design or assessment of timber piles, since they are based on a limited dataset, without providing grading boundaries and strength parameters spanning from the head to the tip of the pile. Since the piles are typically sourced from softwood trees [1],[16], their material properties inherently vary from the lower section of the tree trunk (butt-log) to the tip [17]. Their tapered shape implies larger diameters at the butt-log (head) and smaller diameters at the tip (tapered end). The tip is especially critical as it features the poorest mechanical properties [10],[17]. Moreover, depending on soil conditions, it corresponds to the critical cross section of the pile during service, primarily due to the high stresses associated with its smaller cross section.

To enable engineers to adequately design timber foundation piles, verification rules, reliable material properties and grading specifications are required. These aspects have to be considered alongside the fact that

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wooden foundation piles used under buildings, bridges and quay walls, remain submerged under the water table for their whole service life, enduring high moisture levels. The design procedure in the standards has to start from saturated design values, as suggested in the draft of the new Eurocode 5, prEN 1995-1-1 (2023) [18]. Moreover, the given k_{mod} values in the draft of the new EC 5 are only to be used for load duration effects in a newly defined service class 4, for fully saturated conditions. In this context, this research has the following objectives:

a. Providing saturated strength and stiffness parameters along the entire length (from the head to the tip) of 70 softwood piles, characterized with large-scale compression tests.
b. An investigation in the relationships of visual grading (as described in the Annex Q of the prEN 1995-1-1 2023) and the dynamic modulus of elasticity with the saturated compressive strength the piles, to investigate the potential determination of conservative strength classes applicable to European-grown softwood species, and possible prediction models for their compressive strength.

This research contributes to the incorporation of accurate design values for timber piles in the future Eurocode 5. Moreover, promoting the use and reuse of timber pile foundations offers new solutions for circular construction ecosystems, potentially minimizing the environmental impact of conventional concrete foundations and advancing the realization of fully biobased buildings.

2 – MATERIALS

The test material comprised 253 pile segments sawn from full-scale logs subdivided in:

- 38 spruce (*Picea abies L.*) piles from a forest in Holterberg, The Netherlands;
- 32 pine (*Pinus sylvestris L.*) piles from a forest in Nuremberg, Germany.

The piles were selected based on an average tip diameter (Size 14 and 15 according to Annex Q of prEN 1995-1-1 2023), measured on the top part of the tree trunk, and pile length between 12-14 m. The timber piles were cut at the lower section of the tree trunk ("butt log") close to the base [19]. This specific portion is generally favoured due to its characteristics of being broader, straighter, and having a more consistent diameter compared to the upper part of the tree [19],[20], also ensuring the optimal utilization of the material during harvesting, minimizing material waste. The trees were cut approximately 25 cm from the ground, as close as possible to the ground. The first 2 meters of the trunk were cut off, since this part is typically considered as low quality material due to the natural growing deviation of the grain of the trunk at the base as observable in Figure 1b (Director of RHS Rondhout, Hierden (NL); personal communication, November 28, 2023). The remaining 14-m portion of the tree was taken for the piles tested in this work (Fig. 1a).

Figure 1. (a) timber piles after cutting; (b) typical deviation of the bottom part of a tree trunk.

2 – METHODOLOGY

The piles were cut into head, middle, and tip segments with a length of approximately 6 times the smallest diameter of the tapered log sections, according to EN 408 (Figure 2). This was done to investigate the mechanical properties over their length, with average moisture content (MC) higher than 70%, well above fiber saturation point [8]. MC was determined with the oven-dry method, according to EN 13183 [21], for two 30-mm-thick discs taken from both sides of each selected segment. The global MC values were related to the full cross-section of the pile.

Compression tests were performed to determine the saturated compressive strength ($f_{c,0,sat}$) and and static modulus of elasticity ($E_{c,0,sat}$) in direction parallel to the grain of the pile segments.

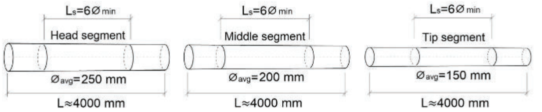

Figure 2. Subdivision of the full-scale pile into head, middle, and tip segments for mechanical testing.

The strength affecting parameters and geometrical properties listed in Table 1 were visually graded according to the limits outlined in Annex Q of prEN 1995-1-1 (2023).

In particular, the diameter (D) of the pile was measured at the pile head and the tip section and classified in sizes. Based on the minimum tip diameter selected for pile, prEN 1995-1-1 (2023) provides sizes ranging from 8 to 16. Annual ring width (ARW) was calculated by counting the number of growth rings over the outer 75% of the representative radius of the cross section. The knot-ratio (KR) was calculated as the ratio between the sum of the knot diameters perpendicular to the longitudinal axis of the log, over a 150 mm length, and the circumference of the log in that section.

The correlation between visual grading and $f_{c,0,sat}$ was studied along the spruce and pine piles, in order to derive possible strength classes for the design of timber piles. Limits for characteristic values (mean $E_{c,0,sat}$ and the 5-percentile value of $f_{c,0,sat}$ and density at 12% moisture content ρ_{12}) were determined for spruce and pine piles, according to the parametric calculation in NEN-EN 14358 [23].

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Table 1. Grading parameters for softwood piles and relative grading boundaries according to NEN 5491 2010 and prEN 1995-1-1 2023.

Choice of wood species	- Norway spruce (Picea abies) and Scots pine (Pinus sylvestris)
Evaluation of geometrical properties	- Length of 6 times the smaller diameter (according to EN 408). - Diameter of tapered end. Range of size classes between 11 and 16. - Taper below 15 mm/m. - Straightness below 1% of the length.
Strength affecting parameters	- No more than 2 bore holes per m length - Slope of the grain ≤ 1/10 ($\alpha = 5.7°$) - Knots calculated with Knot-Ratio[a] (KR) with KR < 0.5 - No mechanical damage - No fissures (the piles were tested in saturated conditions) - No fungal decay - No soft sapwood - Sagging related to a straight line between both log ends < 1/2 times the diameter of the log at mid-length improve - Annual ring width, ARW < 5.0 mm/year

ρ_{12} was calculated in order to have a standardized value comparable with results in the standards and literature. ρ_{12} was determined from the calculated mass m_{12} (Eq. 1) and the volume V_{12} at MC = 12% (Eq. 2). In order to determine V_{12}, the volumetric shrinkage at MC = 12% was calculated on the basis of the following three assumptions according to [22]: (a) shrinkage starts at the fiber saturation point (MC = 30%); (b) the dimensions of the pile decrease linearly with decreasing MC; (c) variability in volumetric shrinkage can be expressed using a coefficient of variation of approximately COV = 15 %, accounting for wood's intrinsic growth characteristics. Based on this, Equation 3 was used to calculate the volume V_{12} at MC = 12%.

$$\rho_{12} = \mathrm{m}_{12} / \mathrm{V}_{12} \qquad (1)$$

$$\mathrm{m}_{12} = \mathrm{m}_{\mathrm{dry}}\,(1 + \mathrm{u}_{\mathrm{ref}}) \qquad (2)$$

$$\mathrm{V}_{12} = \mathrm{V}_{\mathrm{wet}} \cdot (1 - \mathrm{S}_0) \cdot (1 - \mathrm{u}_{\mathrm{ref}} / \mathrm{u}_{30}) \qquad (3)$$

Where:

u_{30} is MC at fiber saturation point (assumed 30% [22])

u_{ref} is MC at 12%.

S_0 is the volumetric shrinkage from green (MC = 30%) to ovendry (MC = 0%) assumed to be 12% [22] for both pine and spruce.

Finally, the dynamic modulus of elasticity $E_{\mathrm{c,0,sat,dyn}}$ was determined through the frequency response method with Equation 4, using a Timber Grader (MTG) [24]. This measurement was performed on every segment of the pile prior to mechanical testing when all the specimens were above fiber saturation. This was done to assess the possibility of machine grading the saturated timber piles based on $E_{\mathrm{c,0,sat,dyn}}$.

$$E_{c,0,sat,dyn} = 4\,\rho_{sat}\,f^2\,L_S^2 \qquad (4)$$

With ρ_{sat} = wet density, f = frequency, and L_S = length of the pile segment.

The most influencing visually-graded properties on $f_{c,0,wet}$ were used to calculate one or several Indicating Properties (IPs) by means of multiple linear regression. By choosing predefined limits of the IPs, the pile segment was either assigned to a graded class or rejected. The tested European spruce and pine piles were considered for grading together as one category, given the good overlapping of their mechanical properties (See Results). Each IP limit was chosen on the basis of the minimum samples for each grading class (≥ 40). The pile's $f_{c,0,k,sat}$ values below the IP limit were calculated with the parametric method in EN 14358 [23]. The calculation is based on Parametric Tolerance Limit (PTL) approach. PTL was defined as the value for which, with a probability of α (95% confidence level). The approach works with the assumption that the population of data is normally distributed.

3 – RESULTS

3.1 Mechanical characterisation

Saturated characteristic values ($f_{c,0,k,sat}$, $E_{c,0,sat}$, and $\rho_{12,k}$) of all pile segments are reported in Table 2 in accordance with NEN-EN 14358 (2016), for pile sizes from 11 to 16.

The characteristic values were calculated for grading boundaries (according to NEN 5491 2010 and Annex Q of prEN 1995-1-1 2023) listed in Table 1. Six segments did not comply with the grading limits in Table 1, leaving 247 standardized samples (Table 2). The tips featured the lowest saturated strength, stiffness, and density. Head and middle segments had similar mechanical properties. Therefore, they were presented as one category.

Correlation matrixes were presented both for spruce piles (Tab. 3) and pine piles (Tab. 4). A strong correlation was found between $f_{\mathrm{c,0,sat}}$ and $E_{\mathrm{c,0,sat}}$ of spruce and pine. Visually graded parameters such as KR and ARW exhibited the highest correlation with $f_{\mathrm{c,0,sat}}$ (Fig. 3a-b), indicating that factors such as growing conditions and the geographical areas where trees are located can significantly influence these growth characteristics. Contrarily, diameter and taper had a very weak correlation with $f_{\mathrm{c,0,sat}}$, indicating a significant variability

Table 2: . $f_{c,0,k,wet}$, $E_{c,0,wet}$, and $\rho_{12,k}$ determined with the parametric calculation in EN14358 for spruce and pine piles.

Wood species	Pile part(s)	No. of tested samples	Size[a]	$E_{c,0,sat}$ (MPa)	$f_{c,0,k,sat}$ (MPa)	$\rho_{12,k}$ (kg/m^3)
Spruce (*Picea abies*)	Head + Middle	81	14	10500	12.6	410
	Tip	47		8900	11.2	380
Pine (*Pinus sylvestris*)	Head + Middle	72	15	11100	15.5	420
	Tip	47		8700	13.0	400

[a] The labelling of the sizes is based on the diameter of the logs at their tapered ends according to Annex Q of prEN 1995-1-1 2023.

in the material properties, even among piles of similar diameter and length. These findings highlight the importance of measuring strength-influencing parameters in wood for an accurate mechanical characterisation. All the tested pile segments had SoG < 1:10, higher deviation of grain direction was not measured. Thus, SoG was not included in the correlation analysis. All the other parameters were measured according to Table 1, and complied with the maximum limits provided by prEN 1995-1-1 2023.

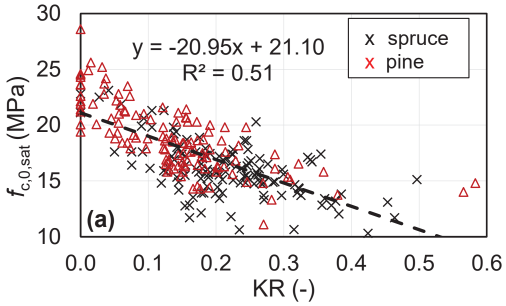
Finally, a good correlation was found between $f_{c,0,sat}$ and $E_{c,0,sat,dyn}$ (Fig. 3c), indicating that the stiffness measured with frequency response measurements is a good indicator for the compressive strength. This implies that frequency response measurements can be efficiently employed to estimate the modulus of elasticity of saturated timber piles.

Table 3. Correlation matrix for all spruce piles

	$f_{c,0,sat}$	$E_{c,0,sat}$	ρ_{12}	KR	ARW	MC	Taper	D
$f_{c,0,sat}$	1							
$E_{c,0,sat}$	0.76	1						
ρ_{12}	0.53	0.54	1					
KR	-0.60	-0.48	-0.24	1				
ARW	-0.68	-0.54	-0.29	0.53	1			
MC	-0.14	-0.19	-0.49	0.02	0.0	1		
Taper	-0.22	-0.34	0.04	0.37	0.23	-0.05	1	
D	0.27	0.34	0.10	-0.48	-0.12	0.01	-0.26	1

Table 4. Correlation matrix for all pine piles

	$f_{c,0,sat}$	$E_{c,0,sat}$	ρ_{12}	KR	ARW	MC	Taper	D
$f_{c,0,sat}$	1							
$E_{c,0,sat}$	0.89	1						
ρ_{12}	0.64	0.70	1					
KR	-0.72	-0.66	-0.46	1				
ARW	-0.52	-0.47	-0.32	0.52	1			
MC	-0.24	-0.36	-0.28	0.21	0.14	1		
Taper	-0.31	-0.32	-0.17	0.38	0.30	0.34	1	
D	0.46	0.46	0.29	-0.49	-0.09	-0.28	-0.32	1



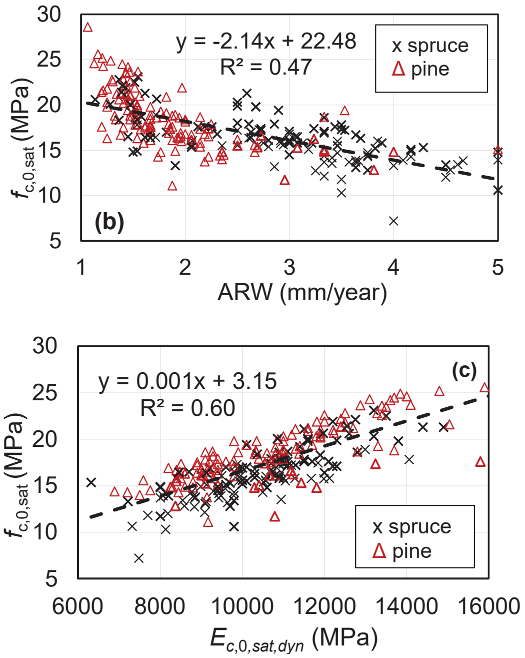


Figure 3. Relationship between fc,0,sat and (a) KR; (b) ARW, (c) Ec,0,sat,dyn.

3.2 Strength classes

Based on the knot-ratio (KR) and annual ring width (AWR)—identified as the most influential grading parameters for the saturated compressive strength of spruce and pine piles—three grading classes (A, B, C) were defined in Table 5 accordance with prEN 1995-1-1 (2023) and the parametric calculations outlined in NEN-EN 14358:2016.

The derived strength classes are applicable to the whole pile and/or its parts: head, middle-part, and tip. However, the grading has to be conducted at the tip section, since it corresponds to the critical cross section of the pile, featuring the lowest compressive strength and subjected during service to higher stresses due to its smaller cross section. The strength classes proposed in this study are also applicable when a pile needs to be cut in shorter parts to be used for different design purposes; the shorter part can be re-graded to be assigned to a possible different strength class.

Table 5. Grading classes A, B, C, for visual grading of European spruce and pile piles according to prEN 1995-1-1 2023 and NEN-EN 14358 2016

Species and Size	Possible grading classes	No. of samples	KR (-)	AWR (mm/year)	$f_{c,0,sat}$ (MPa)			$E_{c,0,sat}$ (MPa)		ρ_{12} (kg/m^3)		
					mean	COV	x_{05}	mean	COV	mean	COV	x_{05}
EU spruce & pine (Size 14-15)	**A**	75	< 0.15	< 1.5	21.0	10%	17.1	11500	12%	520	10%	430
	B	108	0.15 < KR < 0.3	1.5 < ARW < 3.0	17.0	7%	14.8	9800	14%	480	9%	400
	C	64	0.3 < KR < 0.5	3.0 < ARW < 5.0	14.0	11%	11.4	8700	13%	460	9%	380
	Rejected	6	>0.5	> 5.0	-	-	-	-	-	-	-	-

4 – PREDICTION MODELS FOR THE COMPRESSIVE STRENGTH

4.1 Visual model

The possibility of combining spruce and pine for the regression model based on visually graded properties is studied with Equation 5 and detailed in Table 6. IP$_{\mathrm{VM}}$ (VM stands for visual model) is calculated based on the most strength influencing visually-graded independent variables for spruce and pine: KR and ARW according to prEN 1995-1-1 2023. The multiple regression model of IP$_{\mathrm{VM}}$ ($f_{c,0,sat}$) for spruce and pine had a F-value = 198.7 (n = 252), a multiple coefficient of determination (adjusted R^2) of 0.62, and a standard error of 1.9, indicating a high level of correlation of $f_{c,0,sat}$ with KR and ARW. All multipliers were significant and the residuals had relatively equal variances.

$$IP_{VM}\left(f_{c,0,sat}\right) = 23.02 - 15.97\,KR - 1.19\,ARW \quad (5)$$

Table 6: Multipliers and statistical parameters for 95% confidence interval in regression IP$_{SP}$ for combined spruce and pine.

Variables	Coeff.	Standard Error	t-stat	p-value	Lower 95%	Upper 95%
Intercept	23.02	0.32	70.9	7.6E-165	22.4	23.66
KR	-15.97	1.58	-10.0	3.76E-20	-19.1	-12.84
ARW	-1.19	0.16	-7.51	1.08E-12	-1.50	-0.87

The visual model is graphically shown in Figure 4. The model can be applied to spruce and pine piles with 11-16 sizes (tapered end diameter between 110-160 mm). The grading is based on KR and ARW, making sure that the piles comply with all the other grading parameters and boundaries in Table 1.

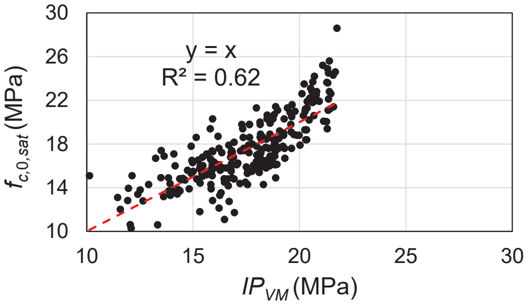


Figure 4: Multiple regression model IP$_{VM}$ for spruce and pine piles.

4.1 Model based on dynamic modulus

A regression model is proposed in Equation 6 and detailed in Table 7 based on the dynamic modulus of elasticiy $E_{c,0,sat,dyn}$. IP$_{\mathrm{MGM}}$ (DM stands for dynamic modulus) estimates $f_{c,0,sat}$ based on $E_{c,0,sat,dyn}$ (in MPa) of spruce and pine. The regression model of IP$_{\mathrm{DM}}$ ($f_{c,0,sat}$) for spruce and pine had a F-value = 407.8 (n = 252), a multiple coefficient of determination (adjusted R^2) of 0.62, and a standard error of 1.95, indicating a strong correlation of $f_{c,0,sat}$ with $E_{c,0,sat,dyn}$. All multipliers were significant and the residuals had relatively equal variances.

$$IP_{DM}\left(f_{c,0,sat}\right) = 2.77 + 0.00138\,E_{c,0,sat,dyn} \quad (6)$$

Table 7: Multipliers and statistical parameters for 95% confidence interval in regression IP$_{DM}$ for combined spruce and pine.

Variables	Coeff.	Standard Error	t-stat	p-value	Lower 95%	Upper 95%
Intercept	2.771	0.731	3.78	0.00019	1.33	4.21
$E_{c,0,sat,dyn}$	0.00138	6.85E-05	20.19	1.91E-54	1.25E-03	1.52E-03

The model based on dynamic modulus is graphically shown in Figure 5. The model can be applied after conducting frequency response measurements to spruce and pine piles with 11-16 size (measured at the tapered end) and complying with the grading limits in Table 1.

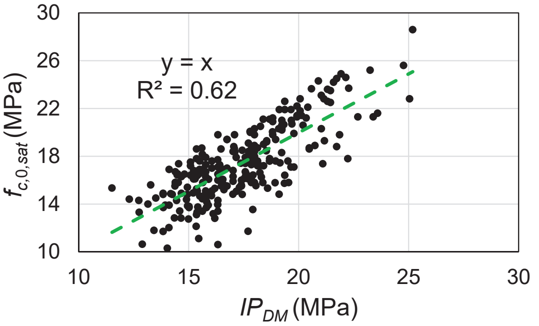


Figure 5: Multiple regression model IP$_{DM}$ for spruce and pine piles.

6 – CONCLUSIONS

The compression tests conducted on 132 spruce (*Picea abies*) and 121 pine (*Pinus sylvestris*) pile segments—extracted from the head, middle section, and tip of full-sized tapered piles—enabled a comprehensive characterization of the saturated material and mechanical properties along the length of the piles. These tests provided valuable insights into the grading of the piles for engineering applications based on the requirements provided in the draft of the new Eurocode 5: prEN 1995-1-1 (2023).

The mechanical properties of both spruce and pine piles were found to be governed by the tips, as the distribution of saturated compressive strength decreased from the head to the tip in both species. Higher KR values were associated with lower saturated compressive strength of the piles, due to the grain deviation around the knots. From the head to the tip of the pile, both decreasing diameter and increasing ARW were observed, which correlated with reductions in density and saturated compressive strength.

The good correlation with visually-graded parameters, such as KR and ARW, opened up the opportunity for grading of multiple strength classes for combined visual grades, combining spruce and pine piles. The derived strength classes are applicable to the whole pile and/or its parts: head, middle-part, and tip. This is important especially for tips, since depending on soil conditions, they correspond to the critical cross section of the pile during service, primarily due to the high stresses associated with its smaller cross section. In addition, the strength classes are also applicable in case where a pile needs to be cut in a shorter part to be used for different design purposes; the shorter part can be re-graded to be assigned to a possible different strength class.

Two regression models were developed to predict the saturated compressive strength of European spruce and pine piles. The first model relies on visually graded properties, specifically KR and ARW, enabling strength prediction based on a visual assessment. The second model utilizes the dynamic modulus of elasticity, determined with frequency response measurements (e.g., MTG grader). These models enhance the characteristic strength classifications established in this research by providing a means to predict the saturated compressive strength of piles using both visual and machine grading methods.

The saturated compressive strength values and grading boundaries presented in this study contribute to the engineering design of European softwood foundation piles in the context of a new circular construction ecosystem, and support the integration of reliable design values into future versions of Eurocode 5.

7 – REFERENCES

1. Klaassen, R.K.W.M. et al. (2005). Preserving cultural heritage by preventing bacterial decay of wood in foundation poles and archaeological sites. Final report EVK4-CT-2001-00043. Wageningen 2005.
2. EN 1995-1-1 (2010)+AC (2006)+A1 (2008) Eurocode 5: design of timber structures–part 1-1: General–common rules and rules for buildings. CEN.
3. NEN-EN 1995-1-1/NB:2013. Dutch National annex to EC 5: Design of timber structures-Part 1-1: General-Common rules and rules for buildings. NEN.
4. NEN 5491: Quality requirements for wood (KVH 2010) - Piles - European softwood. NEN. (In Dutch).
5. Van de Kuilen, J.W.G.: Bepaling van de karakteristieke druksterkte van houten heipalen. Toegepast-Natuurwetenschappelijk Onderzoek (TNO), order Nr. 94-con-RO271. Delft, The Netherlands. (1994) (in Dutch) .
6. Buiten, H., Rijsdijk, J.F.: Compressive strength of larch, Douglas fir and spruce piles (in Dutch). Rapport HI 82.1140, Houtinstituut TNO, Postbus 151, 2600 AD Delft, order Nr.: 30.01.1.0002 (1982).
7. Aicher, S., Stapf, G.: Compressive strength parallel to the fiber of spruce with high moisture content. Eur. J. Wood Prod. 74, 527–542 (2016)
8. Kollmann F., Côté, W.A. (1968). Principles of Wood Science and Technology. Springer-Verlag, Berlin · Heidelberg 1968, Ed. 1, 1968, 592 p, ISBN 978-3-642-87930-2.
9. Sørensen, J.D., Stang, B.F.D., Svensson, S. (2002). Calibration of Load Duration Factor k mod . Dept. of Building Technology and Structural Engineering. Structural Reliability Theory Vol. R0223 No. 222
10. Pagella, G., Mirra, M., Ravenshorst, G., Gard, W., van de Kuilen, J.W. 2024. Characterization of the remaining material and mechanical properties of historic wooden foundation piles in Amsterdam. *Construction and Building Materials*, 450, Article 138616. https://doi.org/10.1016/j.conbuildmat.2024.138616
11. Mirra, M., Pagella, G., Lee, M., Gard, W., Ravenshorst, G., van de Kuilen, G.J.W. 2024. Characterisation of bacterial decay effects on wooden foundation piles across various historical periods. *Construction and Building Materials*. 421: 135670. https://doi.org/10.1016/j.conbuildmat.2024.135670
12. Pagella, G., Urso, T., Mirra, M., Naldini, S., van de Kuilen, J.W.G., 2025. Traditional wooden foundation piles in Amsterdam and Venice: techniques for the assessment of their state of conservation. *Wood Material Science and Engineering.*
13. Pagella, G., Struik, M., Mirra, M., van de Kuilen, J.W. 2024. Small-scale testing of water-saturated wooden discs for determining the strength properties of timber foundation piles. *Wood Material Science and Engineering*. https://doi.org/10.1080/17480272.2024.2426070
14. Pagella, G., Ravenshorst, G., Mirra, M., Gard, W., van de Kuilen, J.W., 2024. Innovative application of micro-drilling for the assessment of decay and remaining mechanical properties of historic wooden foundation piles in Amsterdam, *Developments in the Built Environment*, Volume 19, 2024, 100514, ISSN 2666-1659. https://doi.org/10.1016/j.dibe.2024.100514
15. Felicita, M., Pagella, G., Ravenshorst, G.J.P., Mirra, M., van de Kuilen J.W.G., 2024. Assessment of in-situ stress distribution and mechanical properties of wooden foundation piles instrumented with distributed fiber optic sensors (DFOS). *Case Studies in Construction Materials. Vol. 20.* https://doi.org/10.1016/j.cscm.2024.e03139
16. F3O (2011) F3O Richtlijn: Onderzoek en beoordeling van houten paalfunderingen onder gebouwen. Rapportnummer: 978-90-816732-1-1 (in Dutch).
17. Wilkinson, T.L. (1968). Strength evaluation of round timber piles. Forest products laboratory, U.S.D.A. forest service, U.S. Department of Agriculture. Madison Wisconsin U.S.A. Research paper FPL 101, 1968.
18. prEN 1995-1-1:2024. Draft of Eurocode 5: Design of timber structures - Common rules and rules for buildings - Part 1-1: General. NEN.
19. Ramage, M.H. et al. (2017). The wood from the trees: The use of timber in construction, Renewable and Sustainable Energy Reviews, Volume 68, Part 1, 2017, Pages 333-359, ISSN 1364-0321.

https://doi.org/10.52202/080513-0523

20. Bažant, Z.P. (1979). Chapter 15 - Piles, Developments in Geotechnical Engineering, Elsevier, Volume 24, 1979, Pages 327-406, ISSN 0165-1250, ISBN 9780444997890.
21. NEN-EN 13183-1 (2002). Moisture content of a piece of sawn timber - Part 1: Determination by oven dry method. NEN.
22. Ross, R.J. (2021). Wood handbook wood as an engineering material. Forest Products Laboratory. General Technical Report FPL-GTR-282. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 543 p.
23. EN 14358 (2016). Timber structures – Calculation and verification of characteristic values. CEN.
24. Ravenshorst, G.J.P., Van de Kuilen, J.W.G. (2009). Relationships between local, global and dynamic modulus of elasticity for soft- and hardwoods. CIB W18, proceedings paper 42-10-1, Dubendorf, Switzerland, 2009.