Reuse of Wooden Utility Poles Through the Combination of New and Old Elements

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Wooden utility poles are crucial in supporting overhead telecommunication lines in Portugal. Maritime pine (*Pinus pinaster* Aiton) is the most common wood species used for this purpose. The durability of the poles is typically determined by the deterioration observed in their ground line. Aiming to reduce the use of new sound wooden poles, reducing the economic costs involved, and the environmental impacts, the reuse of those old wooden poles by removing the degraded part is one possible solution. This study aimed to develop and validate solutions with composed poles, specifically for the connections between the wood members, so that it is possible to more efficiently incorporate used parts into the remanufactured poles. Two types of connections were used: members joined by a cylindrical steel tube, and members joined by finger joints. The static bending moduli of elastic and rupture were tested. The mechanical properties of the reused wooden utility poles showed to be in line with the values of new sound wooden poles made of different wood species. Finally, both proposed solutions proved to be practical for use in the production of reused utility poles, which are mostly made from old timber poles.

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INTRODUCTION

The use of timber in construction has been increasing in Portugal, from the traditional solid timber products with circular or rectangular cross-sections to newly engineered wood products such as cross-laminated timber or glued laminated timber (Martins *et al*. 2019). Despite the great evolution that took place in recent years, rectangular and roundwood products are still used for many reasons. Christoforo *et al*. (2016) explain that scientists in different regions of the world have developed research aimed at expanding the range of technical and scientific knowledge related to round wood. Among these applications, one of the most relevant is the roundwood utility poles (Morgado *et al*. 2009).

Despite the various wood species available and studied in Portugal, such as poplar (*Populus alba* L.), cryptomeria (*Cryptomeria japonica*) (Hodoušek *et al*. 2017), blue gum (*Eucalyptus globulus* Labil.) (Martins *et al*. 2020), and blackwood (*Acacia melanoxylon* R. Br.) (Martins *et al*. 2020), wooden poles are mostly produced out of maritime pine (*Pinus* *pinaster*) (Morgado *et al*. 2009; Marques *et al*. 2016). Wood is a material of natural origin with appreciated quality. It requires a minimal level of processing, which can lead to low costs in economic and energetic terms, including low environmental impacts. Utility poles have been widely used in various countries in North America and Australia, where 80% of the total utility poles are made of wood (Tallavo *et al*. 2012; Bandara *et al*. 2019).

A pole is specifically designed to withstand the environmental load that is caused by wind, the live loads that occur during the installation and inspection process, as well as the forces that result from an imbalance in cable loads (or a broken cable condition) (Datla and Pandey 2006). Regarding the environmental conditions and biological degradation, the wood poles may suffer from degradation due to decomposition, insect infestation, and exposure to harsh weather conditions (Tallavo *et al*. 2012). The lifetime of these utility poles is usually governed by damage in the ground line area of the pole. Indeed, the pole part without soil contact is usually sound, with adequate conditions to be maintained in service (Marques *et al*. 2016). Despite this, typically the entire pole is replaced once it does not meet the necessary service requirements (Datla and Pandey 2006; Tallavo *et al*. 2012).

One alternative is recycling and transforming them into fencing materials, parking curbs, retaining walls, guardrail posts, or landscaping supports (Khademibami and Shmulsky 2022). Another possibility to overcome this problem is the removal of the degraded part, with the introduction of a new, sound wood component with similar characteristics. This approach could save sound wood material, reduce the amount of wood preservative treatments (reducing costs), and reduce disposal of contaminated wood material (treated wood) that might potentially become classified as hazardous waste.

It is important to highlight that the present environmental issues have garnered significant interest globally, prompting endeavors to foster initiatives that seek to mitigate the consequences of human actions on the environment (Duan *et al*. 2022). Therefore, the carbon storage capacity of wooden poles is significant due to their extended utilization and widespread implementation on a global scale (May *et al*. 2019).

When materials and components exhibit acknowledged longevity, the elements made from them experience an extended period of use, resulting in a reduction of environmental impacts caused by maintenance (Emídio *et al*. 2014). Enhancing the lifespan of structures is also crucial in reducing energy consumption, and the environmental effects of products (Emídio *et al*. 2014). Therefore, reusing wooden utility poles by combining two elements from distinct wooden poles into one might lead to lower expenses and environmental impacts. To achieve this goal, the critical issue is the connection between the wood components, located in a high-demanding zone regarding bending and shear stresses. Hence, the focus of this study is on the connection between wood components. Despite some studies that have been carried out (Huybers 1996; Lukindo *et al*. 1997; Wolfe 2000; Morgado *et al*. 2013), the connections between round wood elements have always been a complex issue, being one of the reasons for the relatively low use of circular cross sections. Furthermore, for utility poles, there is hardly any research available, being one of the few examples of the work presented by Morris *et al*. (2006).

Currently, there are no recognized viable and robust technical solutions that allow the production of composed poles made from two roundwood elements. Hence, the main objective of this research work is to develop and validate such solutions for the connection and, consequently, to allow the production of more efficient utility-composed wooden poles and contribute to a circular economy.

METHODOLOGY

Selection of the Wooden Poles

The choice of wooden poles removed from service began based on certain criteria, namely, having information on the type of treatment used, time in service, and reason for removal from service. Figure 1 shows examples of poles that met such criteria, allowing their usage in the present study.

Fig. 1. Used wooden poles

In total, 22 utility wood poles of Portuguese maritime pine from the central region of Portugal were used, and their information is shown in Table 1.

Table 1. Visual Characteristics of the Wooden Poles Removed from Service

	Length (mm)	Nominal Diameter (mm)
Mean	7506	168
Max	9130	224
Min	5525	125
Std	1116	26
COV (%)	14.9	15.5
Number of tests	22	22

The survey of the characteristics of the poles included their time in service, length, effective length for mechanical testing, dimensions of the base, zone B, nominal diameter based on the maximum and minimum diameter at ground line, zone A (Fig. 2) 1 m from the ground line and at the top, fiber inclination, the presence of knots, curvature, and the existence of mechanical damage. The defects were based on those mentioned in the European standard EN 14229 (2010). The wood preservative product applied in the poles was Tanalith E 8001.

A Resistograph (IML-RESI PD400; Instrumenta Mechanik Labor System GmbH, Wiesloch, Germany) equipment was used to define the deteriorated area for identification of the replacement length (deteriorated wood pole volume). Six holes were made in the wooden poles in different positions: a) 1 m from the height of the post (not indicating rot) – Reference profile; b) in the superior limit of zone A; c) at ground level; d) in the inferior limit of zone B; and e) in the zone above ground (zone A) where visual assessment did not detect signs of rot. In this zone, holes were made in the region still showing signs of rot and 10 cm above the zone with signs of rot (Fig. 2). The holes were made in areas that do not contain defects, such as knots or resin pockets. At each height, two holes were drilled in orthogonal directions in the transverse plane of the pole.

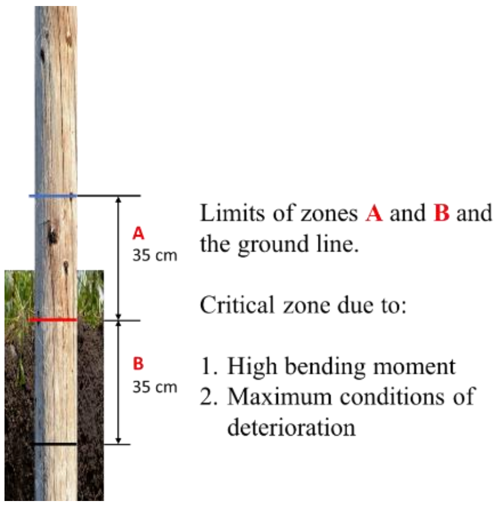

Fig. 2. Procedure to identify the degradation in the wooden poles

Fig. 3. Measurements made with Resistograph

Measurements of drilling resistance were conducted on each wooden pole at different heights and locations to evaluate the presence of biological degradation and, if observed, its extent. After conducting an analysis of the poles based on the specified procedures, the sound wood sections were obtained and then subjected to visual and mechanical analysis to determine their mechanical properties. The frequency *f* was obtained using the Machine Timber Grader (MTG), a non-destructive method (Table 2).

Table 2. Mechanical Properties of Wooden Poles Removed from Service

	MOE (MPa)	MOR (MPa)	*f* (Hz)
Mean	8235	40	318
Max	13875	83	454
Min	4348	18	215
Std	2796	16	52
COV (%)	30.0	41.5	16.5

MOE is the static bending modulus of elasticity, and MOR is the modulus of rupture

Therefore, given the results presented in Table 2, it is possible to conclude that the wooden poles removed from service were mechanically suitable for later reuse in the manufacture of composite poles.

Studied Connection Solutions

The choice of the possible connections to be used followed three requirements: to be resistant to bending moment, to present a good fatigue behavior, to have adequate cost, and to require a low execution complexity. Then, as a first approach, several possible connection systems were considered, with existing timber structure solutions as a starting point. Each solution was analyzed, leading to two final solutions: timber members inserted in a cylindrical steel tube and finger joint configuration (Fig. 4).

(a) (b)

Fig. 4. Studied solutions: (a) wood pole members inserted in a cylindrical steel tube; and (b) finger joint

The finger joint connection offers the benefit of avoiding metallic elements, which when subjected to prolonged intense fire tend to have lower fire resistance than wood. While steel loses strength and stiffness rapidly when subject to high temperatures, wood subject to the same conditions undergoes a charring process that, when advancing at a constant rate, will lead to the gradual loss of wood cross-section and thus, depending on the cross-section, provide a slower loss of strength and stiffness over time and therefore a higher resistance to fire of the wood pole. In addition, depending on the glue used, it may have fire-retardant properties, which improves the fire performance of the connection compared to the solution involving the cylindrical metal tube. Additionally, it requires less processing of the ends to be joined, making it a simpler connection to implement compared to the steel tube connection, which requires the top ends to be processed to perfectly rounded sections.

Two sets of testing were performed for each type of connection: a preliminary and a final one. For each one, the bending strength and stiffness were measured. The preliminary and final tests of the solution with the wooden members inserted in a steel tube were named “P_ST” and “F_ST”, respectively. The wooden poles connected by finger joints tested in the preliminary and final sets were named “P_FJ” and “F_FJ”, respectively.

Concerning the external steel tube connection, commercial steel tubes with external diameters of 168.3 mm and 600 mm long were used in both sets of tests (Fig. 5). The difference was in the thickness of the tube, 4 and 3 mm, and the type of commercial tube and its internal diameter were linked to the thickness. The tubes with 4 mm thickness had an internal diameter of 160.3 mm and steel of class S275. Contrastingly, the tubes with 3 mm had an internal diameter of 162.3 mm and steel of class S235.

(a) (b)

Fig. 5. The wooden poles (a) before insertion; and (b) with the cylindrical steel tube

In the tests, 4-mm and 3-mm-thick steel tubes were used in the preliminary and final test series, respectively. The wooden poles with the members inserted in a cylindrical steel tube of 4 mm (preliminary tests) had an average cantilever length of 6389 mm. Those with 3 mm (final tests) had an average cantilever length of 6390 mm. It was decided to reduce the thickness of the tube and change the resistance class from the preliminary tests (P_ST) to the final ones (F_ST) because with the 4 mm tube, the ruptures were always caused by the wood, and in this way, it is possible to increase the section of wood. Additionally, by reducing the thickness of the tube, there is a reduction in the connection cost.

For the finger joint connection (Fig. 6), the commercial configuration used for glued laminate timber was chosen, which corresponds to a length (l_j) of 20 mm and a pitch *p* of 6.2 mm. The glue polyurethane (PUR) Loctite HB S709 was used in the preliminary tests. In the final tests, the glue phenol-resorcinol-formaldehyde (PRF) was used. In both cases, it is required that the wood members have a moisture content (*W*) between 8% and 18%, and the *W* of each wood member cannot have a difference superior to 5%.

Fig. 6. The wooden poles with finger joints

Different pressures were investigated to assemble the wood elements in the wooden poles with finger joints until the pressure of 10 N/mm^2 was chosen. The maritime pine wooden poles used in the preliminary tests with finger joints had an average length of 4000 mm, and the final set had an average cantilever length of 6187 mm.

Mechanical Testing

Prior to the preliminary mechanical tests, the poles were placed in a climatic chamber, being exposed to a relative humidity of 65% ± 5% and 20 ± 2 °C of temperature until the equilibrium moisture content was achieved. As explained before, preliminary tests were conducted for both studied connection systems, and then, based on the analysis of the results obtained, a new set of tests was prepared and conducted to validate the final tests.

Destructive static tests were made to determine MOR (Eq. 1) and MOE (Eq. 2). The preliminary tests of the wooden poles with finger joints were completed following procedures defined in standards EN 14251 (2005) and EN 408 (2012),

$$\mathrm{MOR} = \frac{16 \cdot F_{max} \cdot a}{\pi \cdot d_h \cdot d_v^2} \tag{1}$$

$$\mathrm{MOE} = \frac{3 \cdot a \cdot l^2 - 4 \cdot a^3}{\left(\frac{3 \cdot \pi \cdot D^4}{8}\right) \cdot \left(2 \cdot \frac{w_1 - w_2}{M_1 - M_2}\right)} \tag{2}$$

where F_{max} is the maximum total load of both loading heads; a is the distance between the loading position and the support; d_h is the diameter in the direction of the load at mid-span; d_v is the diameter perpendicular to the load direction at mid-span; l is the pole length measured from butt to tip; $w_1 - w_2$ is the displacement increment; and $M_1 - M_2$ is the increment in bending moment in the linear portion of the force × displacement curve.

The MOR (Eq. 3) and MOE (Eq. 4) values of the final wooden poles with finger joint and the preliminary and final wooden poles with the external steel tube were determined according to standard EN 14229 (2010) (Figs. 7 and 8). This type of test is specifically suitable for evaluating utility wooden poles but presents a higher degree of complexity and cost. Hence, it was not employed during the preliminary phase of testing.

Fig. 7. Bending test in accordance with EN 14229 (2010)

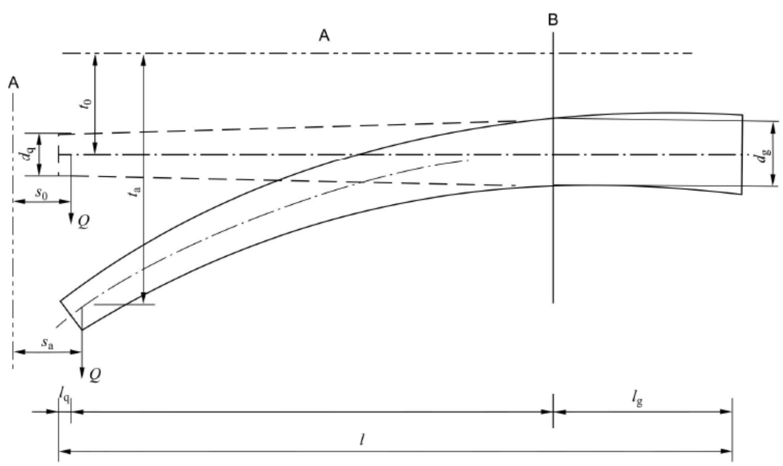

Fig. 8. Bending test diagram in accordance with EN 14229 (2010)

$$\text{MOR} = \frac{32 \cdot Q \cdot (l - l_{max} - (s_a - s_0))}{\pi \cdot d_{max}^3} \tag{3}$$

$$\text{MOE} = \frac{Q \cdot (l - l_{max} - (s_a - s_0))^3 \cdot d_q^3}{3 \cdot I_q \cdot (t_a - t_0) d_{max}^3} \tag{4}$$

In the preceding equations, Q is the applied load; l_{max} is the distance from butt to section of maximum stress or ground line, whichever is the greater; $s_a - s_0$ is the movement of load application point parallel to longitudinal axis of the pole during testing; d_{max} is the nominal diameter at section of maximum stress; l_q is the distance from tip to position of applied load; $t_a - t_0$ is the deflection at point of load application.

Pearson's correlation coefficient (r) was used to analyze the relationship between the d_g, the nominal diameter at the assumed ground-line, d_q, the nominal diameter at the point of load application, modulus of rupture (MOR), and modulus of elasticity (MOE) of the analyzed connections. The scope of correlation values extended from -1 to +1, where a value of 0 signifies the absence of correlation, while the presence of low, moderate, or strong correlation remains within the realm of possibility (Nowicki *et al*. 2021). It is acknowledged that Pearson's correlation solely elucidates the correlation between each pair of variables without considering their interaction with other parameters. Thus, regression models were utilized to investigate the relation among the variables implicated in the determination of MOR and MOE (d_q, d_g, and the thickness of the steel tube). The aim was to examine the combined impact (interactions) of each studied parameter on the values of MOR and MOE in the final set of tests.

The evaluated differences among the examined mechanical properties were assessed through the conventional analysis of variance (ANOVA) with a significance level of 5%. In accordance with the ANOVA formulation, the results can be deemed dissimilar if the p-values are lower than the significance level (p-value < 0.05). The statistical analysis was conducted using the Minitab software (Minitab, LLC, Version 18, State College, PA, USA).

RESULTS AND ANALYSIS

The results of the preliminary tests in 9 wooden poles (P_ST) with 4 mm are shown in Table 3. Both MOE and MOE of P_ST had high coefficients of variation, approximately 27.6% and 42%, respectively, which showed high variability among the results.

Table 3. Results of the Static Tests of the P_ST

	MOE (MPa)	MOR (MPa)
Mean	7849	33.7
Max	10869	54.5
Min	347	14.0
Std	2168	14.1
COV (%)	27.6	41.7
Number of tests	9	9

Max: Maximum value; Min: Minimum value; Std: Standard deviation; COV: Coefficient of variation

Recognizing the occurrence of the rupture within the zone of connection with the steel tube, specifically the area where the wooden poles possessed the smallest diameters, equivalent to the diameter of the steel tube (160.3 mm for tubes with a thickness of 4 mm), it is plausible to regard this value as the diameter at ground level, referred to as d_g. Consequently, the outcomes pertaining to the final set of tests conducted on the wooden components joined by the steel tube were recalibrated, taking into account a d_g equal to 160.3 mm, and denoted as the sample labeled "P_ST_160" (Table 4).

Table 4. Results of the Static Tests of the P_ST_160

	d_q (mm)	MOE (MPa)	MOR (MPa)
Mean	144.4	10345	43.0
Max	157.6	12459	71.8
Min	127.3	8070	20.8
Std	10.8	1463	18.8
COV (%)	7.5	14	43.7
Number of tests	10	10	10

The quantity d_q is the nominal diameter at the point of load application; std is standard deviation.

With a reduction in the average value of d_g, from 178.3 mm (actual *d*g diameter of the poles) to 160.3 mm of 10%, the MOE and MOR values of P_ST_160 were approximately 32% and 27% higher than those of P_ST, respectively.

Table 5 shows the results of the final tests of 10 wooden poles inserted in a cylinder steel tube (F_ST) with 3 mm of thickness, and Fig. 9 shows some of the ruptures that were observed. In all wooden poles with steel tubes, the rupture occurred due to exceeding the tensile strength of the wood, and in all cases, the metallic element did not show any damage. The coefficient of variations of both diameters were small, as well as the COV of MOR and MOE decreased compared to those from the P_ST tests, showing that there was a reduced variability among the tested poles.

Table 5. Results of the Static Tests of the F_ST

	d_g (mm)	d_q (mm)	MOE (MPa)	MOR (MPa)
Mean	171.5	146.2	7881	44.7
Max	186.0	171.9	10162	57.2
Min	156.0	134.6	5458	29.6
Std	7.9	13.5	1548	7.9
COV (%)	4.6	9.2	19.6	17.7
Number of tests	10	10	10	10

The parameter d_g is the nominal diameter at the assumed ground line.

Fig. 9. Ruptures observed in the wooden elements inserted in the steel tube

A strong negative correlation coefficient was identified between the quantity d_g and MOE (r = -0.643), and it was statistically significant (a significance level of 0.05), meaning that higher values of the d_g resulted in a smaller MOE. In contrast, a non-statistically significant (at a significance level of 0.05) correlation (r = 0.221) was found between the nominal diameter at the point of load application and MOE.

An insignificant (at a significance level of 0.05) correlation (r = -0.609) was found between MOR and d_g. It was also identified a non-statistically significant correlation between d_q and MOR, with a correlation coefficient of 0.332. Finally, a positive and statistically significant correlation was identified between MOR and MOE, r = 0.675, meaning that the bending MOE could be an adequate property to estimate the MOR (Crespo *et al*. 2020). Analyzing the combined effects of the parameters that potentially influence the variations in MOE, considering the data of P_ST and F_ST, it was identified that at a significance level of 5%, only d_g (p-value = 0.005) was statistically significant in the changes that the MOE had from preliminary to final tests.

Regarding the variations in the MOR values between P_ST and F_ST (considering the combined effect of the variables), only d_g (p-value = 0.034) was statistically significant (at a significance level of 5%), and the ANOVA analysis indicated that the smaller values of d_g resulted in higher values of MOR. This result is important because only based on Pearson's correlation it was not possible to identify the significance of d_g.

Acknowledging that the rupture occurred in the zone of the connection with the steel tube, *i.e.*, the zone in which the wooden poles had the smallest diameters, which is the diameter of the steel tube (162.3 mm for the tubes with 3 mm thickness), it is possible to consider this value as the diameter at ground-line, d_g. Therefore, the results regarding the final set of tests of the wooden members joined by the steel tube were recalculated considering a d_g equal to 162.3 mm and the sample named "F_ST_162". An increase in the MOE and MOE values of F_ST_162 compared to F_ST were obtained (Table 6). With a reduction of 5% in the value of d_g from 171.5 mm (real diameter of the poles) to 162.3 mm, the average MOE and MOR of F_ST_162 were 16.7% and 21.8% higher than those of F_ST, respectively.

Table 6. Results of the Static Tests of the F_ST_162

	d_q (mm)	MOE (MPa)	MOR (MPa)
Mean	146.2	9196	54.4
Max	171.9	11678	68.8
Min	134.6	6889	43.1
Std	13.5	1451	8.0
COV (%)	9.2	15.8	14.7
Number of tests	10	10	10

Table 7 shows the average results of MOE and MOR of P_ST and F_ST.

Table 7. Comparison between the Mechanical Properties of Wooden Poles from P_ST and F_ST Considering the Actual d_g

	Average MOE (MPa)	Increase in Relation to Preliminary (%)	Interval of Confidence (IC) of 95%	Average MOR (MPa)	Increase in Relation to Preliminary (%)	IC of 95%
P_ST	7848^{A}	-	(6650; 9047)	33.7^{B}	-	(26.7; 40.8)
F_ST	7881^{A}	0.4	(6744; 9018)	44.7^{A}	32.7	(38.0; 51.4)

From ANOVA tests, values followed by different letters differ significantly at α = 0.05

The MOE values of P_ST and F_ST were considered statistically equivalent, and there was a slight increase of 0.4% of F_ST compared to P_ST. Additionally, the final set of tests showed important improvements in MOR values for the wooden poles with the cylindrical steel tube compared to the preliminary tests, and this difference was statistically significant.

Table 8 shows the comparison of the results obtained for MOE and MOE between the preliminary and final tests, considering the diameter d_g as the internal diameter of the steel tube, P_ST_160 and F_ST_162.

Table 8. Comparison between the Mechanical Properties of Wooden Poles from P_ST_160 and F_ST_162 Considering the New Values of d_g

	Average MOE (MPa)	Increase in relation to Preliminary (%)	Interval of Confidence (IC) of 95%	Average MOR (MPa)	Increase in relation to Preliminary (%)	IC of 95%
P_ST_160	10345^{A}	-	(9320; 11369)	43.0^{A}	-	(33.0; 52.91)
F_ST_162	9196 ^{A}	-11.1	(8224; 10168)	54.4^{A}	26.7	(45.0; 63,9)

From ANOVA tests, values followed by different letters differ significantly at α = 0.05

For both situations represented in Tables 7 and 8, it is possible to conclude that the decrease in the thickness of the steel tube demonstrated its efficacy regarding the mechanical properties of the wooden poles, particularly in the increase of the MOR value. Hence, it is the favored option due to its best cost-effectiveness.

Concerning the wooden poles with finger joint configuration, Table 9 shows the results of the preliminary tests in the ten wooden poles (P_FJ).

Table 9. Results of the Static Tests and Moisture Content of the P_FJ

	MOE (MPa)	MOR (MPa)
Mean	9180	26.6
Max	14333	38.9
Min	4895	15.3
Std	3024	9.5
COV (%)	32.9	35.6
Number of tests	10	10

From the analyses of the ruptures, it was observed that the finger configuration in the preliminary tests was not correct. The fingers were thinner than the desired configuration, which was probably caused by the vibration of the machine developed to make the finger joints in round sections. Moreover, according to the manufacturer, the PUR glue used on the P_FJ for optimal performance on maritime pine requires the application of a primer, which was not available at the time of the study. The glue was changed to a PRF type for the F_FJ, and the finger joint machine was modified to reduce vibrations during work. Hence, Table 10 shows the results of the final tests in the 12 wooden poles with finger joint configuration (F_FJ), and Fig. 10 shows some rupture modes that occurred.

Table 10. Results of the Static Tests of the Final Tested Wooden Poles with Finger Joints – F_FJ

	d_g (mm)	d_q (mm)	MOE (MPa)	MOR (MPa)
Mean	177.5	142.9	11860	41.2
Max	212.3	158.5	14602	62.5
Min	149.0	129.0	8670	25.9
Std	17.7	10.1	1882	11.6
COV (%)	10.0	7.1	15.9	28.1
Number of tests	12	12	12	12

Fig. 10. Ruptures observed in the finger joint connections

Pearson's correlation coefficient (r) was used to assess the correlations between the different properties of the wooden poles with finger joints in the final configuration. There was a negative moderate to high correlation coefficient (r = -0.498) regarding nominal diameter at the assumed ground-line, d_g, and MOE. In contrast, the correlation coefficient between the nominal diameter at the point of load application, d_q, and MOE was negative and weak (r = -0.030). The correlations in both cases were not statistically significant (at a significance level of 0.05), meaning no notorious correlation was identified between MOE and nominal diameter at the ground line and the point of load application. Similar results were found by Marques *et al*. (2016).

Concerning MOR, the highest correlation coefficient was found for d_g (r = -0.286), followed by the correlation with dq (r = 0.074), a very weak correlation. It was determined that neither of the correlations exhibited statistical significance (at a significance level of 0.05), indicating that the observed r values were statistically equal to zero and that no remarkable correlation was observed between MOR and nominal diameter at the groundline and load application point.

Regarding the mechanical properties, there was a moderate to strong correlation between MOR and MOE (r = 0.736), and it was statistically significant (p-value = 0.006). The correlation coefficient for the wooden poles with finger joints was better than that found by Marques *et al*. (2016) and similar to that found by Morgado *et al*. (2009) for new wooden poles of maritime pine.

The values of MOE and MOR obtained in the preliminary tests and those in the final ones for the wooden poles with finger joints were statistically different, as shown in Table 11. These results show that the modifications made from the preliminary to final tests resulted in statistically significant improvements in the stiffness and strength of the reused wooden poles. Additionally, from the preliminary to the final tests, there were adjustments to the notches of the finger joints.

Table 11. Comparison between the Mechanical Properties of Wooden Poles with Finger Joints in the Preliminary and Final Tests

	Average MOE (MPa)	Increase in Relation to Preliminary (%)	Interval of Confidence (IC) of 95%	Average MOR (MPa)	Increase in Relation to Preliminary (%)	IC of 95%
P_FJ	9180^{B}	-	(7555; 10804)	26.7^{B}	-	(19.6; 33.7)
F_FJ	11860^{A}	29.2	(10377; 13343)	41.2^{A}	54.3	(34.7; 47.6)

From ANOVA tests, values followed by different letters differ significantly at α = 0.05

When comparing both studied solutions (Table 12), it is possible to see that the finger joint connections gave the best result in terms of bending stiffness. The MOE values of the finger joints (F_FJ) were 1.5 and 1.2 times higher than the MOE of the S_ST and F_ST_162, respectively, and they were statistically different. In contrast, the solution involving steel tubes, considering the pole and the steel tube diameter, exhibited the highest values of MOR. The MOR values of F_ST were deemed to be statistically equivalent to those of F_FJ as well as those of F_ST_162.

Table 12. Comparison between the Mechanical Properties of Wooden Poles with Finger Joints and Cylindrical Steel Tubes

	Average MOE (MPa)	IC of 95%	Average MOR (MPa)	IC of 95%
F_ST	7881^{B}	(6894; 9146)	44.1^{AB}	(38.0; 51.4)
F_ST_162	9196^{B}	(8464; 10625)	54.4^{A}	(48.3; 50.8)
F_FJ	11860^{A}	(10883; 12837)	41.2^{B}	(33.6; 48.7)

From ANOVA tests, values followed by different letters differ significantly at α = 0.05

The results of MOR and MOE of both studied connections and the values of other wood species present in the literature with sound and new wooden poles are shown in Table 13. Regarding the comparison between the values of this study (reused wooden poles) and sound new poles of Portuguese maritime pine, the MOR values of the studied solutions were smaller, but the MOE of wooden poles with finger joints were acceptable and competitive compared to sound new wooden poles of Portuguese maritime pine.

Table 13. Comparison of Roundwood Species with the Reused Wooden Poles

Wood Species	MOR (MPa)	MOE (GPa)
Maritime pine – Finger joint[a]	41	11.9
Maritime pine – Steel tube[a]	44	7.9
Maritime pine – Steel tube (dg = 162.3 mm)[a]	54	9.2
Maritime pine - Portugal[b]	83	14.1
Maritime pine - Portugal[c]	74	13.0
Scots pine (*Pinus sylvestris*) – United Kingdom[d]	54	14.9
Scots pine – Finland[d]	50	11.9
Norway spruce (*Picea abies*) - Austria[c]	61	12.9
Norway spruce - Finland[d]	60	12.9
Sitka spruce (*Picea sitchensis*) – United Kingdom[d]	58	16.1
Douglas (*Pseudotsuga menziesii*) - France[d]	52	11.1
Douglas-fir – USA (Oregon)[e]	46	9.7
White fir (*Abies concolor*) – USA (Oregon)[e]	46	8.3
Radiata pine (Pinus radiata) – USA (Oregon)[e]	39	5.6
Radiata pine – Chile[f]	52	10.5
Ponderosa pine (*Pinus ponderosa*) – USA (Arizona)[g]	56	10.7

[a] Data from this work; [b] Morgado *et al*. (2009); [c] Martins and Dias (2012); [d] Ranta-Maunus (1999); [e] Wolfe and Moseley (2000); [f] Cerda and Wolfe (2003); [g] Larson *et al*. (2004)

Compared with other pine wood species, it becomes evident that the MOR values exhibited by F_FJ, F_ST, and F_ST_162 were either similar or surpassed the values observed in those other species. Furthermore, it is noteworthy that the MOE values obtained by the reused wooden poles from this work are deemed acceptable and align with the values documented in existing literature.

Therefore, based on the results, both connection solutions for reuse poles (finger joint and steel tube) proved viable and can be adopted depending on the availability of machinery to produce either or another in the production of utility-composed wooden poles. Safeguarding the benefits inherent to each type of connection used, better performance in fire situations is expected of poles with finger joints.

CONCLUSIONS

Among the different connection methodologies that were tested to connect new parts to existing poles, two were selected for production: external steel tube and finger joint.

1. The tests and subsequent analysis allowed the improvement of the methodologies, with significant improvement in the poles' performance in terms of their mechanical properties. The correlation analysis showed positive and statistically significant correlations between MOR and MOE of the wooden poles with steel tube, r = 0.675, and finger joint MOE, r = 0.736.
2. The mechanical properties obtained in the recovered utility poles, especially MOE, are in line with those obtained in other studies for new poles from the same and other wood species.
3. Both approaches proved viable for use in the production of recovered utility poles, mostly from used timber poles, with significant deterioration on the part of their

length. The choice of the connection method (external steel tube or finger joint) might depend on the machinery availability and involved production costs.

4. Further investigations regarding the weathering and biological durability of the proposed solutions of the composed wooden poles should be carried out.
5. Finally, further studies testing both typologies of connections are recommended using different wood species to verify their efficiency and applicability, in regards to their widespread utilization in different countries.

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