Effect of a Longitudinal Cut on the Mechanical Properties of Small-Diameter Roundwood of *Pinus nigra* Arnold

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The use of roundwood in structures has drawbacks that include tapering and lack of flatness, which can be overcome by making a longitudinal cut to flatten one side. The aim of this work was to compare the mechanical behavior of roundwood *vs.* roundwood with one flat face, comparing pieces of small-diameter roundwood from young trees of *Pinus nigra* Arnold. Half the samples were given a longitudinal cut. Specimens taken from these pieces were tested for bending and compression parallel to the grain to determine their modulus of elasticity and strength. The modulus of rupture by bending was 22% lower in roundwood with one flat face (59.0 MPa) than in roundwood (75.6 MPa). It has been observed that the smaller cross section in the roundwood with one flat face is not the only explanation for the decrease in the bending strength. In contrast, no significant differences were observed for the other three mechanical properties studied (compression strength parallel to the grain and modulus of elasticity in bending and compression).

Keywords: Mechanical properties; MOE; MOR; Rafter; Roundwood with one flat face

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INTRODUCTION

The timber used in the building industry in Europe today is predominantly in the form of sawnwood. A substantial proportion of the Eurocode 5 regulation is dedicated to defining the material and the calculations for either solid or laminated pieces with a rectangular section (European standard EN 1995 (1-1, 1-2, and 2) 2004).

Roundwood is a material that is commonly found in traditional structures (Wolfe 2000), and its use continues to be widespread in certain geographic areas today (Wolfe and Murphy 2005). Some authors have highlighted the structural advantages of roundwood over sawnwood, including particularly its lower cost (Wolfe and Murphy 2005) and its greater mechanical strength (Ranta-Maunus 1999). The use of small-diameter roundwood in simple structures would represent a means to obtain greater profitability in the early stages of forestry production, which currently has very limited applications (Wolfe and Moseley 2000) and where sometimes material flow is affected by accidental felling (Parobek *et al.* 2014). This interest in the use of roundwood in structures has led to the publication of the European standard EN 14251 (2003), which defines the tests for determining the mechanical resistance of roundwood.

One of the drawbacks of using roundwood in structures is that it has a somewhat irregular outer surface because of its curves, tapering, knots, *etc*. This makes it more difficult to assemble, as the joints are more complex than in sawnwood (Wolfe 2000).

Another feature of roundwood is that flat surfaces can only be achieved by adding elements with different thicknesses. To avoid this effect, some companies offer roundwood with one flat face to make it easier to incorporate surface elements, particularly in the case of rafters (Green *et al.* 2004). The main advantage of this material is that it provides a flat face that facilitates the assembly of roof boards. Evidently, making a longitudinal cut implies a decrease in the section and thus in bending strength. It is necessary to establish whether the loss of bending strength is due exclusively to the reduction of the section or whether there are other similar supplementary effects to those indicated by other authors (Ranta-Maunus 1999).

The aim of this work was to establish whether there are differences in mechanical behavior in terms of bending and parallel compression between roundwood and roundwood with one flat face in small-diameter pieces of *Pinus nigra*.

EXPERIMENTAL

Material and Methods

General observations

The material analyzed was obtained from the timber depot of a sawmill located in Lleida (Spain). Forty-two pieces of *Pinus nigra* Arnold (from Cellers, Spain, 40°04’N, 0°52’E) with a length of 4.5 m and an average diameter of 118 mm (maximum 140 mm, minimum 100 mm) were extracted from the basal part of the trunk of young trees (50 years). The samples were then separated into two groups of 21 elements in a strictly random manner.

Each piece in the first group was given a flat surface with an average width of 68 mm (FF, roundwood with one flat face); the second group remained uncut (RW, roundwood). The samples were debarked and stored outdoors in the shade for eight months until they reached an estimated moisture content of 16%. The moisture was obtained by oven drying (at 103 ºC) slices with a thickness of 20 mm, extracted at a distance of 500 mm from the end of the log.

First, the samples were prepared for parallel compression testing by making a cut with a chainsaw 0.5 m from the end with the greatest diameter. Two parallel transversal cuts separated by 300 mm were then carefully made using a band saw (Fig. 1). Samples were then produced for the bending tests by cutting the remaining part of the pieces at a distance of 20 times the greatest diameter, measured from the thickest end.

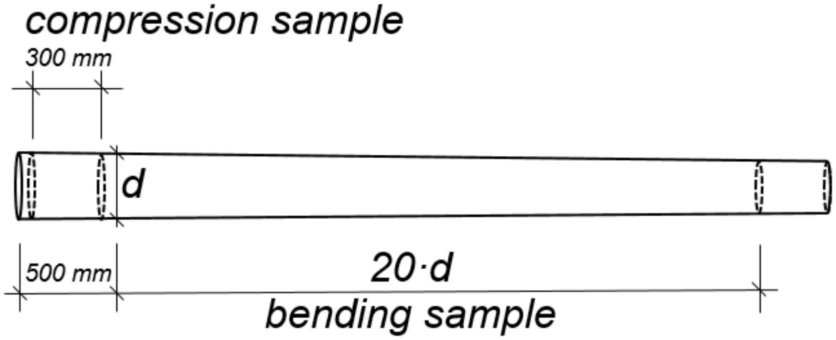

Fig. 1. Sample preparation

Mechanical tests

The bending test was performed with a 50-kN bending testing machine (Cohiner, Spain) with supports placed at 18 times the nominal diameter of the samples and with two loads located in the central thirds, according to standard EN 14251 (2003; Fig. 2). The supports consisted of pieces of wood with a thickness of 100 mm with a semicircular gap, 150 mm in diameter, to ensure the stability of the samples during testing. The FF samples were placed cut face up. Once each test had been completed, a slice with a thickness of approximately 20 mm was extracted from an area near the rupture to estimate the moisture and density.

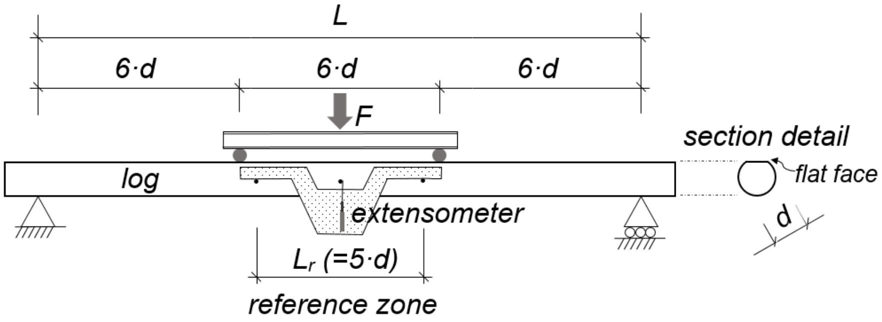

Fig. 2. Bending test scheme

The compression test for the samples with a length of 300 mm was done with a 1500-kN H11 universal testing machine (Matest, Italy). The displacement of the plates was measured with an extensometer to obtain the modulus of elasticity in compression. Once each test was completed, a slice with a thickness of approximately 20 mm was extracted to estimate moisture and density.

Data acquisition was done with LabVIEW 7.1 (National Instruments, USA).

Bending strength

The modulus of rupture (MOR) in RW was calculated using the procedure specified in standard EN 14251 (2003; Eq. 1),

$$f_{m,0} = \frac{16\, F_{max}\, L}{3\pi d^3} \tag{1}$$

where $f_{m,0}$ is the MOR, F_{max} is the maximum total load obtained from the test sample, L is the distance between supports, and d is the average diameter of the sample.

In calculating the MOR of FF, the equations were fitted based on the same assumptions as in the case of roundwood. Given the asymmetry with respect to the neutral axis, the term of inertia in the intermediate section was deduced and applied in Eq. 2, and the MOR value was taken as the one corresponding to the maximum tensile bending stress,

$$f_{m,0} = \frac{F_{max}\,Lz_t}{6I} \tag{2}$$

where $f_{m,0}$ is the MOR, F_{max} is the maximum total load obtained from the test sample, L is the distance between supports, z_t is the distance from the neutral axis to the bottom of the cross section, and I is the moment of inertia of the intermediate section.

Modulus of elasticity in bending

The modulus of elasticity in bending (MOE) of RW was calculated using the equations provided in standard EN 14251 (2003; Eqs. 3, 4 and 5), which analyze the behavior in the reference zone (central zone of the piece with a length equal to five times the diameter). Bending was assessed based on the assumption that the ends of this zone follow a simultaneous vertical displacement. The log diameter was also assumed to have a linear variation. The quotient between the increase in force ($F_2 - F_1$) and the increase in deflection ($w_2 - w_1$) was deduced from the slope of the regression curve of the values observed. $R^2 > 0.95$ was observed for all cases. The data interval for the regression curve was obtained from the window formed by percentiles 25% and 75% for both the force (y-axis) and the deflection (x-axis); it was thus possible to delimit systematically the initial straight section of the graph even for tests with dual rectilinear behavior.

$$E_{m,0} = \frac{(F_2 - F_1)L^4}{36(w_2 - w_1)I_{sr}}\left[\frac{-1}{(c + L_r/2)^2} - \frac{D}{2} + \frac{1}{c^2}\right] \tag{3}$$

$$c = \frac{L_r d_{sr}}{\left(d_{gr} - d_{sr}\right)} \tag{4}$$

$$D = \frac{1}{c^2} - \frac{1}{(c + L_r)^2} \tag{5}$$

where $E_{m,0}$ is the MOE, $F_2 - F_1$ is the increase in force during the test, $w_2 - w_1$ is the increase in deflection during the test, L is the distance between supports, L_r is the length of the reference zone, I_{sr} is the smallest moment of inertia of the cross-section in the reference zone, d_{sr} is the smallest diameter of the reference zone, and d_{gr} is the greatest diameter of the reference zone.

Standard EN 14251 (2003) does not include roundwood with one flat face; thus, the equations for estimating the value of MOE were adapted taking into account –as in the case of roundwood– that the cross-section is not constant along the length of the log. Given the asymmetry of the cross-section, the moment of inertia was estimated by segregating the log into virtual slices 1 mm thick. The inertia values were fitted to an exponential function according to their position along the length of the log (Eq. 6). The MOE (Eq. 8) was obtained from the twofold integration (Eq. 7) and imposition of boundary conditions (zero relative deflection for the reference points),

$$I_x = ae^{bx} \tag{6}$$

$$\frac{\partial^2 w}{\partial x^2} = \frac{FL}{6E_{m,0}I_x} \tag{7}$$

$$E_{m,0} = \frac{(F_2 - F_1)L}{2(w_2 - w_1)ab^2}\left[e^{\left(\frac{-bL_r}{2}\right)} - \frac{1}{2}\left(1 + e^{(-bL_r)}\right)\right] \tag{8}$$

$$a = I_{sr} \tag{9}$$

$$b = \left(\frac{1}{L_r} ln \frac{I_{gr}}{I_{sr}}\right) \tag{10}$$

where $E_{m,0}$ is the MOE, a and b are adjustment parameters for the estimation of inertia in the reference zone, w is the deflection of the log axis in the reference zone, x is the position on the longitudinal axis in the reference zone, F is the total force during the test on the sample, $F_2 - F_1$ is the increase in force during the test, $w_2 - w_1$ is the increase in deflection during the test, L is the distance between supports, L_r is the length of the reference zone, I_x is the adjusted function of the moment of inertia, I_{gr} is the greatest moment of inertia of the cross-section in the reference zone, and I_{sr} is the smallest moment of inertia of the cross-section in the reference zone.

Parallel compression strength

Compression strength parallel to the grain of RW was calculated using Eq. 11,

$$f_{c,0} = \frac{4F_{max}}{\pi d_g d_s} \tag{11}$$

where $f_{c,0}$ is the compression strength parallel to the grain, F_{max} is the maximum total load obtained from the test sample, d_g is the greatest diameter of the cross-section, and d_s is the smallest diameter of the cross-section.

In the case of FF, the missing part of the cross-section was taken into account by subtracting the circular segment removed by the cut from the theoretical area of the circle.

Modulus of elasticity in parallel compression

The modulus of elasticity in compression parallel to the grain ($E_{c,0}$) of the samples was calculated according to Eq. 12. For these cases, the quotient between the increase in compression force ($F_2 - F_1$) and shortening ($w_2 - w_1$) was deduced from the slope of the regression curve for the values observed (using windows with a similar shape to the one used in the bending test).

$$E_{c,0} = \frac{h(F_2 - F_1)}{A(w_2 - w_1)} \tag{12}$$

where $E_{c,0}$ is the modulus of elasticity in compression parallel to the grain, $F_2 - F_1$ is the increase in load during the test, $w_2 - w_1$ is the shortening during the test, h is the length of the specimen, and A is the area of the cross-section.

Statistical analysis

Although the samples were distributed in a strictly random manner between the RW and FF groups, we tested to determine whether these groups showed significant differences in diameter, moisture, density (at 12% moisture), and number of knots. This was done with an analysis of variance, except when the samples showed a lack of normality (Shapiro-Wilk test) or homoscedasticity (Bartlett test), in which case the Kruskal-Wallis non-parametric test was applied. The following procedure was used for the strength test. A value smaller than 0.05 was considered significant. The statistical calculation was done with the R package (R Core Team 2013).

In the test samples with moisture different from 12%, corrections were applied as indicated in standard EN 384 (2010) and used by other authors (Ranta-Maunus 1999). According to this criterion, the parallel compression strength was modified by –3% for each 1% increase in moisture. The percentage was –1% in the case of the modulus of elasticity (for both parallel compression test and bending test). As indicated in the standard, the bending strength was not corrected. These values are similar to those obtained by Green *et al.* (2007) for *Pinus contorta*. In any case, the difference in moisture between samples RW and FF was small.

RESULTS AND DISCUSSION

The analysis of possible bias between the samples of roundwood (RW) and roundwood with one flat face (FF) showed no significant differences, confirming the correct random distribution of the pieces. The values are shown in Table 1. In the case of moisture, the differences are close to significance.

Table 1. Analysis of Variance for the Detection of Possible Biases between the Samples

	RW	FF	p-value
Diameter of sample (mm)	111 (9.07)	108 (8.86)	0.321
Moisture (%)	11.63 (2.71)	10.46 (1.34)	0.089
Density ($g \cdot cm^{-3}$) (at 12% moisture)	0.546 (0.094)	0.520 (0.062)	0.312
Knots (n)	6.2 (4.36)	7.5 (3.03)	0.292

The values in brackets indicate the standard deviation. RW = roundwood; FF = roundwood with one flat face

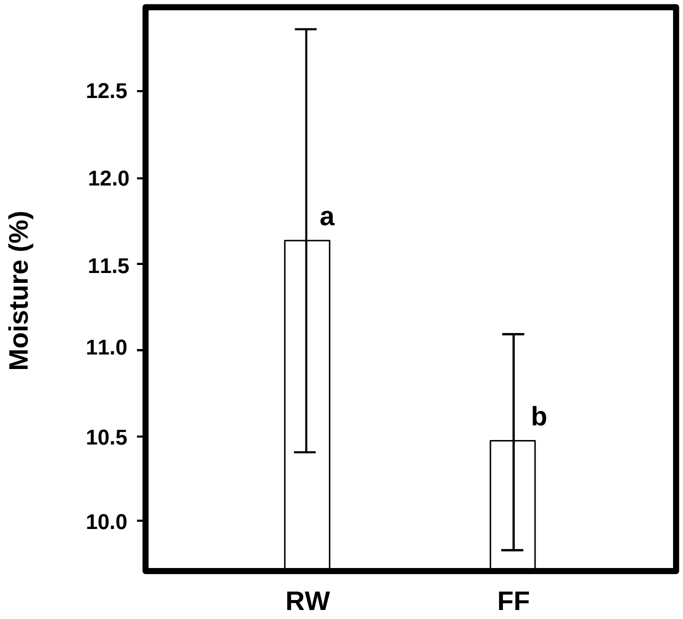

Fig. 3. Moisture content of samples of roundwood (RW) and roundwood with one flat face (FF) at the time of testing (mean ± SE). The different letters showed a significant difference using Tukey's mean separation test (p = 0.05).

The mean diameters of the samples in groups RW and FF were very similar (only 4 mm difference) and no significant differences were detected between them. It can therefore be considered that the size-scale effects were correctly shared between the two groups.

The confidence intervals are shown in Fig. 3. These differences may be due to the faster drying speed through the cut face than in the case of uncut roundwood. This effect is more evident for wood with a longer length because the central areas are at a significant distance from the end grain. Although the differences are limited and represent around 1% of the moisture, the strength values were corrected according to the criterion in standard EN 384 (2010).

An analysis of variance was applied to infer the values of MOR, as the samples fulfilled the requisites of normality and homoscedasticity. The results for the MOR (Table 2) indicated significant differences between RW and FF, with an estimated decrease in bending strength of 22% in the FF samples (Fig. 4).

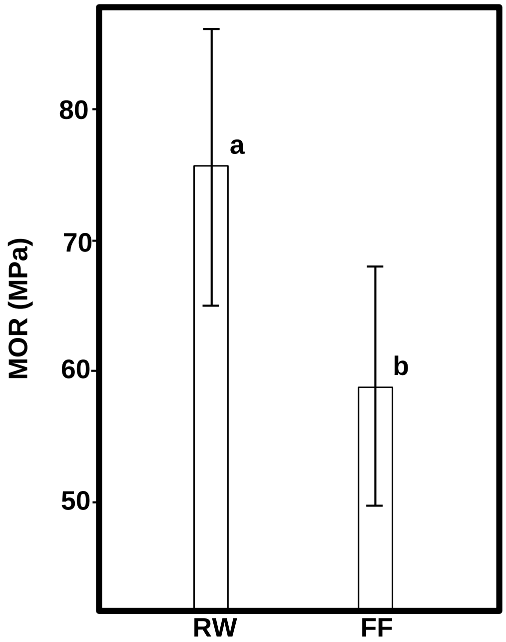

Fig. 4. MOR of samples of roundwood (RW) and roundwood with one flat face (FF). The different letters showed a significant difference using Tukey's mean separation test (p = 0.05).

In contrast, the analysis for the rest of the variables revealed no significant differences between RW and FF (Table 2). The analysis of variance was used, as MOE and parallel compression complied with the criteria of normality and heteroscedasticity. However, the non-parametric Kruskal-Wallis test was applied in the case of the modulus of elasticity in parallel compression as the requisites of normality (p-value of RW samples = $5.2 \cdot 10^{-5}$) and homoscedasticity (p-value = 0.0011) were not fulfilled.

The values of MOR obtained exceeded those in the works of Ranta-Maunus (1999) on *Pinus sylvestris*, which were 50 MPa (in wood from Finland) and 54 MPa (in wood from the UK). Elsewhere, the results obtained by Høibø and Vestøl (2010) (67 and 64 MPa) in *Pinus sylvestris* were closer to those of the present work. According to Fernandez-Golfin *et al.* (2001), *Pinus nigra* has a 20% greater MOR than *Pinus sylvestris*. This agrees with the findings of this work (for *Pinus nigra*).

Table 2. Average Values for Mechanical Properties of Roundwood (RW) and Roundwood with One Flat Face (FF) in *Pinus nigra*

	RW	FF	p-value
MOR (MPa)	75.60 (23.12)	58.95 (19.46)	0.017(av)
MOE (MPa)	13154 (3616)	11689 (5195)	0.307(av)
Compression strength parallel to the grain (MPa)	32.62 (5.63)	30.38 (4.06)	0.178(av)
Modulus of elasticity in compression parallel to the grain (MPa)	6520 (2560)	5652 (1063)	0.257(kw)
The values in brackets indicate the standard deviation. MOR = modulus of resistance in bending, MOE = modulus of elasticity in bending; (av) = value obtained by analysis of variance; (kw) = value obtained by the Kruskal-Wallis test			

The work of Fernandez-Golfin *et al.* (2007) found a MOR of 44 MPa for roundwood in the same species (*Pinus nigra*) with a uniform diameter of 120 mm. The difference in bending strength is explained by the effect of machining to a uniform diameter (Larson *et al.* 2004), causing the values to be nearer to those obtained in the FF samples.

The MOE values coincided with the results of Ranta-Maunus (1999) for *Pinus sylvestris*. The values obtained for RW in the present study are between these authors' findings for wood from Finland (11,900 MPa) and the UK (14,900 MPa). The same is true of the parallel compression strength (28 and 33 MPa, respectively).

The significant differences between roundwood (RW) and roundwood with one flat face (FF) detected in the bending tests concurred with other works comparing roundwood and sawnwood (Ranta-Maunus 1999). One of the explanations for the lower strength of FF was the discontinuity of the wood fibers as a result of the cut (Wolfe 2000). This effect is singularly important in the samples in the present work because the sawcut occurs in a zone that is very far from the neutral axis, where there are significant compression tensions (upper part) that overload the tension area in the lower part when they exceed the elastic limit. Another interesting aspect was the presence of a substantial percentage of juvenile wood in the central part of small roundwood (Ranta-Maunus 1999). In the case of FF, mature wood was eliminated from the periphery; thus, the compressed area at the top has a greater quantity of juvenile wood with lower mechanical strength (Wolfe and Murphy 2005). The four flat faces were generated by making four cuts in sawnwood, which several authors associated with losses in strength compared with roundwood (Ranta-Maunus 1999). Only one cut is made in the case of FF, however, the loss of bending strength in RW (22%) was significantly higher than expected. Ranta-Maunus (1999) found a 50% decrease in sawnwood (with four flat faces) compared to RW. This is because the cut face was placed in the area with the highest stress during the bending test. It is likely that if the test were conducted with the flat face placed vertically (in the same direction as the loads), the moment of inertia would be likely to be greater (26.5%) due to the geometry of the section, and the deflection would be substantially less. The works of Larson *et al.* (2004) also detected significant losses in bending strength of 20% when roundwood was machined to a uniform diameter by removing the mature outer wood.

No significant differences were detected in the modulus of elasticity in bending between RW and FF. However, significant differences were detected in bending strength. This behavior can be explained by the fact that in the case of bending strength, the test was done up to the rupture (beyond the elastic limit of the compressed zone), whereas only the linear area of the load/deflection diagram was studied for modulus of elasticity in bending, where the elastic limit was not exceeded. Beyond the elastic limit, the rupture was reached earlier in the cut zone because of the presence of juvenile wood and cut fibers. These results coincided with the works of Larson *et al.* (2004), which compared roundwood and wood with a uniform diameter in tip logs.

No significant differences were detected in parallel compression or in modulus of elasticity in parallel compression. Although part of the mature wood was removed from the outer rings in the FF samples, the effect was negligible as it was not eliminated from a critical area and the pressure was evenly spread throughout the entire cross-section.

CONCLUSIONS

1. While MOR is affected by a longitudinal cut on small roundwood from *Pinus nigra*, MOE and parallel compression is not. The decrease in bending strength in roundwood with one flat face is not sufficiently explained by the reduction of the cross section.

2. It is therefore not recommended that the resistance classification assigned to roundwood should be extrapolated to roundwood with one flat face.

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