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Measurement of the shear properties of clear wood by the Arcan test

José Xavier[1,*], Marcelo Oliveira[1,2], José Morais[1] and Tiago Pinto[1]

[1] CITAB/UTAD, Engenharias I, Vila Real, Portugal

[2] DEMAD/ESTV, Campus Politécnico, Repeses, Viseu, Portugal

*Corresponding author.
CITAB/UTAD, Engenharias I, Apartado 1013, 5001-801 Vila Real, Portugal
Phone: +351-259-350356
Fax: +351-259-350356
E-mail: jmcx@utad.pt

Abstract

In this work, the identification of the shear properties of maritime pine (*Pinus pinaster* Ait.) wood was investigated by applying the Arcan test method. For this purpose, an ad hoc Arcan fixture was designed for which clear wood samples could be tested along all the material planes of symmetry – *LR*, *LT* and *RT* planes. For the accurate evaluation of the shear moduli, correction factors taking into account the non-uniformity of the shear stress and the shear strain distributions at the gauge section were determined with finite element analyses. Experimentally, two 0/90 rosettes were glued on both frontal and back surfaces of the specimens in order to take into account any through-to-thickness shear strain variation. It was found that the Arcan test is suitable for the identification of the shear moduli of wood in all its natural planes. The failure of the Arcan specimens systematically occurred under a concentrated stress state nearby the V-notches. Nevertheless, it was shown that an accurate estimation of the shear strengths of wood can be achieved by the Arcan test.

Keywords: Arcan test; mechanical properties; mechanical testing; wood.

Introduction

The mechanical behaviour of wood can be analysed hierarchically over a spectrum of length scales. At the macroscopic scale (0.1–1.0 m), clear wood (i.e., defects-free and straight-grained wood) is normally assumed as being a continuous and homogeneous material. Besides, three planes of symmetry are locally defined by the longitudinal (*L,1*), the radial (*R,2*) and the tangential (*T,3*) directions of the elongated wood cells (tracheids representing approximately 90–95% of the softwood volume). Consequently, independent mechanical tests are required for the characterisation of the shear behaviour of clear wood in its principal planes of symmetry (i.e., *LR*, *LT* and *RT*). Moreover, current standard test methods (EN 408 2003; ASTM D143 2007) for measuring the shear properties of clear wood have some limitations and drawbacks (Xavier et al. 2007; Gupta and Siller 2005a,b; Denzler and Glos 2007). Therefore, particular attention should be focused on the investigation of appropriate shear test methods for clear wood. Usually, these tests are intended to simultaneously quantify both the shear moduli and the shear strengths of the material.

During the last decades, several shear test methods have been proposed and developed for anisotropic and heterogeneous materials, such as polymer composite materials and wood. Among those tests applied to clear wood, there are, e.g., the off-axis tensile test (Sliker and Yu 1993; Yoshihara and Ohta 2000; Liu 2002), the Iosipescu shear test (Yoshihara et al. 1999; Dumail et al. 2000; Xavier et al. 2004), the Arcan shear test (Liu 1984; Liu et al. 1996; Liu and Ross 2005), the in-plane shear test using a thin specimen (Yoshihara and Matsumoto 2005), the quasi-simple shear test (Naruse 2003) and the square-plate twisting test (Yoshihara and Sawamura 2006). Tests using full-size structural wood samples – e.g., torsion and bending tests – have also been carried out, namely from the evaluation of strength properties, with the advantage that they can provide more representative values for structural applications (Riyanto and Gupta 1998; Gupta et al. 2002; Gupta and Siller 2005a,b).

This work focuses on the Arcan test, which has been one of the less studied tests. Initially, the Arcan test was proposed for the shear characterisation of plastic materials (Goldenberg et al. 1958). Several improvements were achieved afterwards in the field of fibre-reinforced composite materials (Voloshin and Arcan 1980; Hung and Liechi 1997; El-Hajjar and Haj-Ali 2004) and cellular solids (Mohr and Doyoyo 2003). This work presents a comprehensive study about the suitability of the Arcan test to simultaneously determine the shear moduli and the shear strengths of maritime pine (*Pinus pinaster* Ait.) wood, in all its natural planes of symmetry.

The Arcan test

The specimen employed in the Arcan test has a typical rectangular shape with two symmetrical V-notches at its centre (Figure 1a). This specimen is mounted into an ad hoc fixture, which has two anti-symmetrical parts as illustrated in Figure 1b. The fixture can be rotated such that the direction of the applied load (*P*) is coincident with the specimen transverse axis ($\alpha=0°$ in Figure 1b). In this configuration, a predominant shear stress is generated in the minimum cross-section of the specimen – the geometry of the V-notches provides a quasi-uniform shear stress distribution. Therefore, the Arcan test is suitable for the characterisation of the shear modulus and the shear strength.

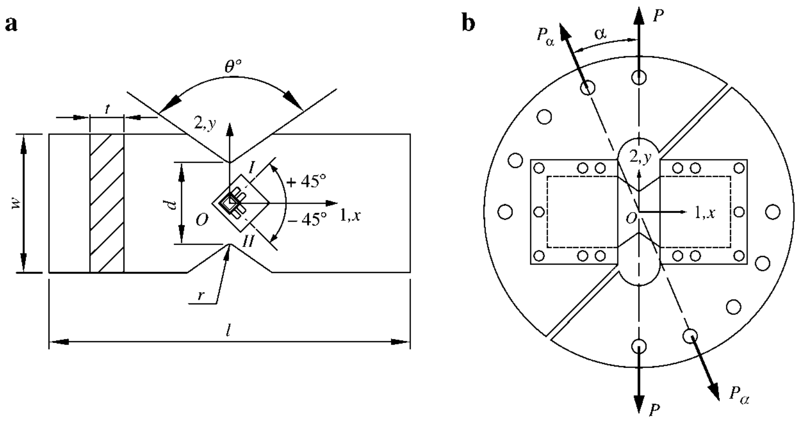

Figure 1 Schematic representation of the Arcan (a) specimen and (b) test configuration.

An average engineering shear strain, in the (*1,2*) material principal axes, can be determined from the linear strains measured by a two-element rosette glued at the centre of the specimen at an angle of $\pm 45°$ with regard to its longitudinal axis (Figure 1a):

$$\varepsilon_6^{av} = \varepsilon_I^{+45^\circ} - \varepsilon_{II}^{-45^\circ} \quad (1)$$

The average shear stress at the cross-section between V-notches is given by:

$$\sigma_6^{av} = \frac{P}{A} \quad (2)$$

where A is the initial cross-section area between notches and P is the resultant applied load measured by the load cell of a testing machine. An apparent shear modulus can be determined directly from the experimental data [Eqs. (1) and (2)]:

$$G_{12}^a = \frac{\sigma_6^{av}}{\varepsilon_6^{av}} \quad (3)$$

Under the assumption of uniformity of the shear stress and shear strain at the gauge section, this value would represent the true shear modulus of the material. However, such an ideal state is unlikely to occur when testing orthotropic materials (Pierron and Vautrin 1997; Xavier et al. 2004). Nevertheless, a corrected shear modulus can be determined according to the following equation:

$$G_{12} = \left(\frac{\sigma_6^O}{\sigma_6^{av}}\right)\left(\frac{\varepsilon_6^{av}}{\varepsilon_6^O}\right) G_{12}^a = CSG_{12}^a \quad (4)$$

where the factors C and S are correction terms taking into account, respectively, the non-uniformity of the shear stress distribution (σ_6^{av}) with regard to its value at the gauge central point O (σ_6^O) (Figure 1a), and the non-uniformity of the engineering shear strain (ε_6^{av}) compared to its values at the specimen central point O (ε_6^O). These factors must be determined by a finite element analysis.

The data reduction presented so far is based on the implicit assumption of a uniform distribution of shear stress and shear strain through the thickness of the specimen. However, strain measurements on both front and back surfaces of the specimen can be significantly different. Nevertheless, this effect can be minimised by measuring the shear strain on both faces of the specimen and considering the average value (Pierron 1998; Xavier et al. 2004).

The ultimate shear stress carried out by the specimens can be defined as:

$$\sigma_6^{ult} = \frac{P_f}{A} \quad (5)$$

where P_f is the applied load at the occurrence of failure. If the shear stress state is not pure over the gauge section then the ultimate shear stress defined above [Eq. (5)] cannot be taken as the material shear strength.

Finite element analyses

A two-dimensional finite element (2D FE) model of the Arcan test was developed in the ANSYS® code, which includes the non-gripped region of the specimen and the fixture, with perfectly bonded interfaces (Figure 2). In the analyses, clear wood was modelled as a linear elastic

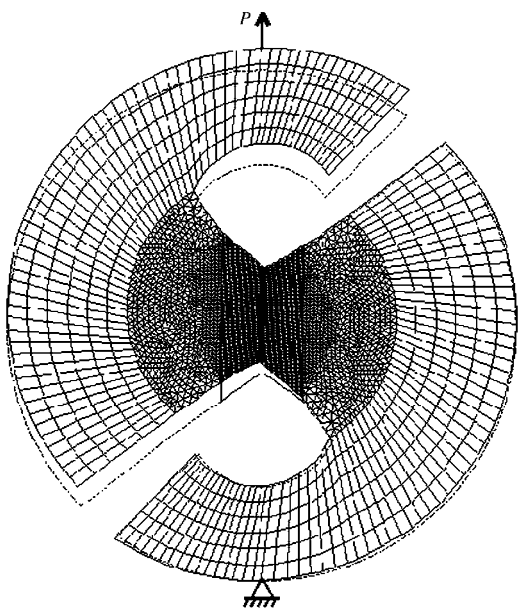

Figure 2 Finite element model of the Arcan test: mesh and boundary conditions.

orthotropic material, whilst the fixture was assumed as a linear isotropic material (aluminium). The boundary conditions and the geometries of the specimens were similar to the ones tested experimentally (Figure 3b,c). Further details about the finite element analyses of the Arcan test on wood specimens can be found in a paper by Oliveira et al. (2003).

The correction factors *C* and *S* were evaluated according to Eq. (4). The global force *P* was evaluated by the vertical reaction force at the prescribed pinned nodal point of the upper grip (Figure 2). The engineering shear strain ε_6^{av} was defined as the average of the engineering shear strains calculated at the nodes circumscribed by the strain-gauge grid area. σ_6^O and ε_6^O are the shear stress and shear strain taken at the central point *O* of the specimen, respectively. The correction factors for the shear moduli are reported in Table 1. As it can be seen, the values of *S* are practically equal to one for all planes of symmetry. Therefore, the *CS* correction factor [Eq. (4)] mainly describes the heterogeneity of the shear stress distribution along the critical section. According to the *CS* value for the *LR* and *LT* specimens (Table 1), the apparent shear moduli measured directly from the experimental data is overestimated by 8.1% and 9.5%, respectively. These values are in the order of magnitude of the scatter associated to experimental results (see Table 3). On the other hand, the *CS* value for the *RT* specimen (Table 1) suggests that there is no need for numerical correction for the proper evaluation of the shear modulus in this plane.

Table 1 Correction factors for the shear moduli of *Pinus pinaster* Ait. determined by finite element analyses of the Arcan test.

Material planes	*C*	*S*	*CS*
LR	0.92	1.0	0.92
LT	0.90	1.0	0.90
RT	0.98	0.99	0.97

Experimental work

Materials and specimens

The wood material tested in this work was manufactured from a single *P. pinaster* tree, aged 74 years old (geographic origin: Portugal). From a log selected between 2.5 and 5.0 m from the basal plane of the tree, quarter-sawn and plain-sawn boards were cut and dried in a kiln to approximately 12% moisture content. Several specimens oriented along the *LR*, *LT* and *RT* planes were then sampled in the outermost part of these boards (mature wood). The nominal dimensions of the specimens are shown in Figure 2b,c. The *LR* and *LT* specimens were reinforced at the grip regions by gluing Kambala wood (*Chlorophora Excelsior* Ait.) end-tabs (with a thickness of 2 mm) with Wurth WB3® adhesive (Figure 2b). End-tads were not used for the *RT* specimens (Figure 2c). During testing, the temperature and the relative humidity of the laboratory were around 23°C and 45%, respectively. The moisture content of the specimens was in the range of 9–12%, as determined by the oven-dry method (ASTM D4442 2003). The oven-dry density of the specimens (i.e., the oven-dry weight divided by the green volume) was found to be between 0.571 and 0.685 g cm^{-3}.

Arcan fixture

Previous versions of the Arcan fixture for wood testing used two different grip systems: one considered that the specimen was directly glued at the fixture (Liu 1984), and the other considered that the load was transferred into the specimen by bolts (Liu et al. 1996). In this work, an Arcan fixture was designed in which the shear stress is transferred to the specimen by means of frictional forces along its grip surfaces (Figure 3). Striated grips (2 in Figure 3a) guided by three bolts are used to tighten the

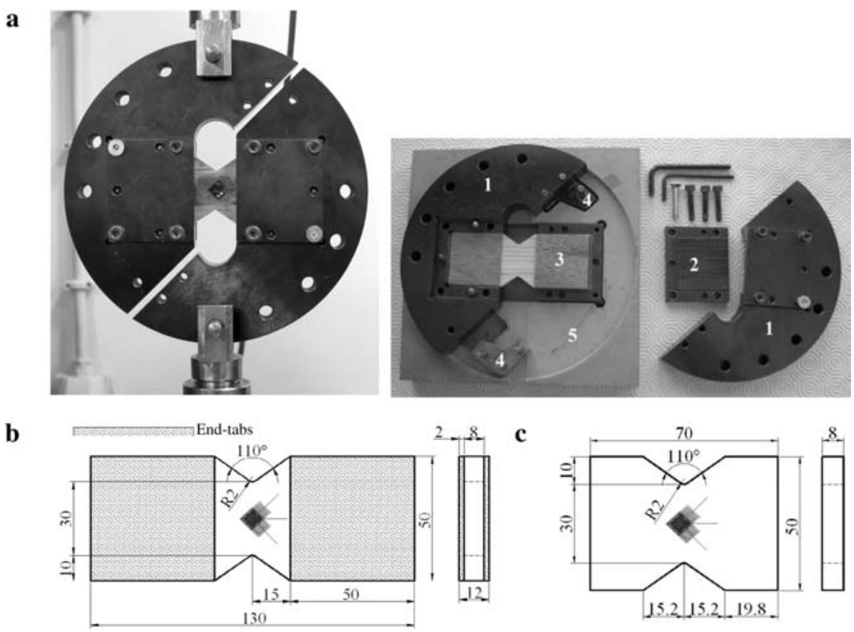

Figure 3 (a) Mechanical set-up of the Arcan test (fixture components: 1, left and right parts of the fixture; 2, tighten grips; 3, specimen; 4, stopping plates; 5, mould); (b) *LR* and *LT* specimens; (c) *RT* specimen.

specimen by means of fastening screws. For mounting the specimen into the fixture (1 in Figure 3a) a special mould made of medium density fibreboard (MDF) was employed (5 in Figure 3a) and stopping plates (4 in Figure 3a) prevent the damage of the specimen during the fixture set-up. The Arcan fixture was made of aluminium and was linked to the testing machine through clevis pins to reduce the parasitic out-of-plane forces and moment effects.

Arcan tests

The Arcan tests were carried out on an INSTRON 1125 universal testing machine, with a cross-head displacement rate of 2 mm min^{-1}. The applied load was measured with a 5 kN load cell. The frontal and back surfaces of each specimen were instrumented with 0/90 biaxial rosettes (MicroMeasurement CEA-06-062WT-350; the grid dimensions are 3.05×5.97 mm^2), fixed at its centre at $\pm 45°$ (see Figure 1a). The M-Bond AE-10 adhesive was used for the gauge fixing. Both load and linear strain outputs were recorded on a personal computer by a HBM SPIDER 8 data acquisition system. Before testing, the *LR* and *LT* specimens were loaded and unloaded five times up to a force of 400 N, in order to accommodate the specimens into the fixture; for the *RT* specimens the load-unload cycles were not performed due to their low strength.

Results and discussion

Experimental data

The raw data measured directly in the Arcan test (i.e., the load measured by the load cell and the linear strains measured with the strain gauges glued on both faces of the specimen) are illustrated in Figure 4. As it can be seen, the $\pm 45°$ linear strains recorded on the two surfaces of the specimen are not symmetrical, showing that some out-of-plane movement may have occurred due to twisting and/or bending induced by the gripping system. From these data, both the shear stress [Eq. (1)] and the engineering shear strain [Eq. (2)], on both surfaces of the specimen, were determined. Furthermore, in order to account to eventual through-to-thickness variation, an average engineering shear strain was determined from the back-to-back strain measurements.

The apparent shear stress-average shear strain curves are shown in Figure 5 (for all specimens and planes of symmetry). The mechanical response for all the material

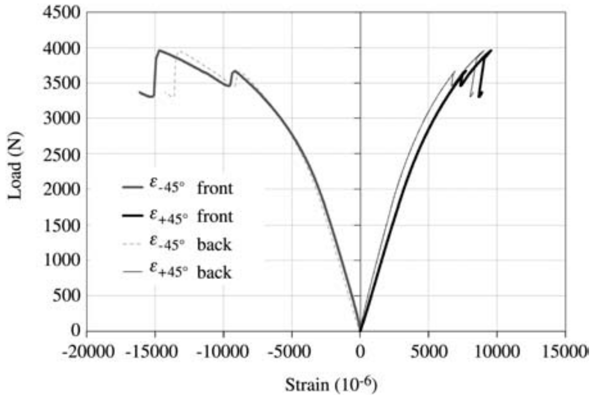

Figure 4 Load as a function of the linear strain gauge readings measured in the Arcan test on both frontal and back faces of a *LR* specimen.

planes is non-linear. However, some amount of this non-linearity may not represent the intrinsic material behaviour but the geometrical non-linearity due to the change of grain orientation during the test (this is particularly visible in the *LR* specimens, see Figure 7). The complete analysis of shear stress-strain curves is not addressed in this work, which is concerned with the identification of the shear moduli and shear strengths. However, in view of the results of the present work (Figure 5), the Arcan test is a promising test method to completely characterise the non-linear shear behaviour of wood. This issue needs to be investigated further. The strain gauges were damaged before the ultimate failure of the specimens occurred, preventing the measurement of the ultimate shear strain. Alternatively, the complete load-time curve was recorded, allowing the measurement of the applied load until failure.

Shear moduli

In order to assess the effect of the through-to-thickness variation of the shear strain on the shear modulus, this parameter was determined taking separately the frontal ($G_{ij}^{a,f}$), the back ($G_{ij}^{a,b}$) and the average (G_{ij}^{a}) engineering shear strain (with $ij = LR$, LT and RT). This study is summarised in Table 2. As it can be concluded, the coefficient of variation associated with the shear modulus determined from the average shear strain can be significantly lower than the ones obtained just by measuring the shear strain at one of the surfaces of the specimen. This is the case particularly for the *LR* specimen where a reduction of the coefficient of variation of approximately 10% was observed. Besides, the apparent shear moduli

Table 2 Frontal (*f*), back (*b*) and average (*avg*) apparent (*a*) shear moduli of *Pinus pinaster* Ait. determined by the Arcan test (moisture content of approximately 11%).

	LR plane			*LT* plane			*RT* plane		
	$G_{LR}^{a,f}$	$G_{LR}^{a,b}$	$G_{LR}^{a,avg}$	$G_{LT}^{a,f}$	$G_{LT}^{a,b}$	$G_{LT}^{a,avg}$	$G_{RT}^{a,f}$	$G_{RT}^{a,b}$	$G_{RT}^{a,avg}$
Mean (GPa)	1.70	1.31	1.45	1.46	1.06	1.20	0.219	0.301	0.246
CI[a]	±0.18	±0.12	±0.06	±0.10	±0.05	±0.04	±0.04	±0.04	±0.04
CV[b] (%)	17.0	15.3	6.5	11.4	7.9	5.7	23.4	19.1	19.8

[a]Confidence interval (CI) at 95% confidence level (determined from the *t*-distribution after checking the normality by the Shapiro-Wilk test).
[b]Coefficient of variation (CV).

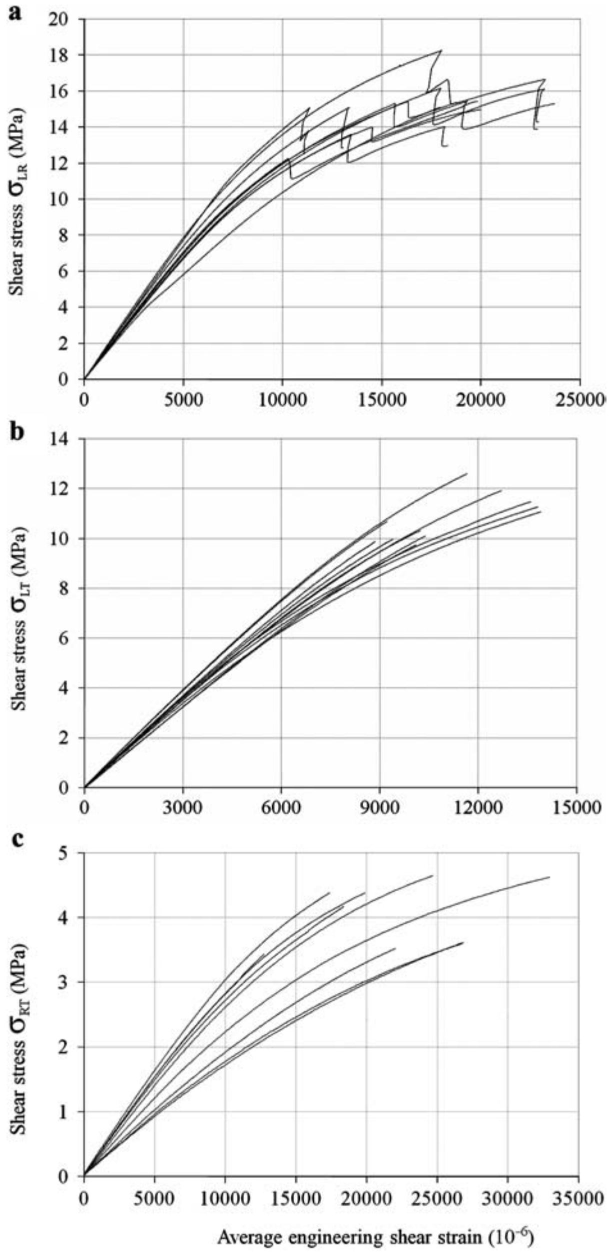

Figure 5 Apparent average shear stress-strain curves: (a) *LR*, (b) *LT* and (c) *RT* material planes.

measured directly from the experimental data can be overestimated or underestimated depending on which surface the measurements are taken.

The apparent shear moduli measured directly from the experimental data [Eq. (3)] were corrected according to Eq. (4) (Table 3), in which the *C* and *S* factors were evaluated by finite element analyses (Table 1). The difference between apparent and corrected shear moduli (9%, 10% and 3% for *LR*, *LT* and *RT* material planes, respectively) is in the order of magnitude of the coefficient of variations associated with the mean shear moduli. Besides, the coefficient of variations associated to both *LR* and *LT* specimens are relatively low, considering the inherent variability among wood specimens; although, the one for the *RT* specimens is slightly high.

The shear modulus-density relationship for all planes of material symmetry is shown in Figure 6a. A linear

Table 3 Corrected shear moduli of *Pinus pinaster* Ait. determined by the Arcan test (moisture content of approximately 11%).

Specimen	*LR* plane		*LT* plane		*RT* plane	
	ρ g•cm^{-3}	G_{LR} GPa	ρ g•cm^{-3}	G_{LT} GPa	ρ g•cm^{-3}	G_{RT} GPa
1	0.598	1.15	0.598	0.96	0.668	0.261
2	0.605	1.30	0.605	1.19	0.670	0.268
3	0.611	1.42	0.611	1.05	0.664	0.281
4	0.613	1.39	0.613	1.18	0.666	0.206
5	0.618	1.32	0.618	1.12	0.665	0.280
6	0.575	1.51	0.575	1.10	0.660	0.297
7	0.607	1.29	0.607	1.05	0.685	0.198
8	0.582	1.35	0.582	1.07	0.670	0.184
9	0.612	1.28	0.612	1.11	0.594	0.176
10	0.629	1.27	0.629	1.14		
11	0.620	1.37	0.620	1.09		
12	0.612	1.32	0.612	1.03		
13	0.618	1.37	0.618	1.06		
Mean	0.608	1.33	0.608	1.09	0.660	0.239
CI[a]		±0.05		±0.04		±0.04
CV[b] (%)	2.48	6.49	2.48	5.67	3.91	19.82

[a]Confidence interval (CI) at 95% confidence level (determined from the *t*-distribution after checking the normality by the Shapiro-Wilk test).
[b]Coefficient of variation (CV).

regression was assumed because of the narrow windows of density values (see Table 3). A low coefficient of correlation was systematically determined, confirming the relative homogeneity of the sampled specimens within the stem.

The G_{LR}, G_{LT} and G_{RT} shear moduli determined from the Arcan test (Table 3) were compared with the *t*-test for equality of means at the 95% confidence level. It is con-

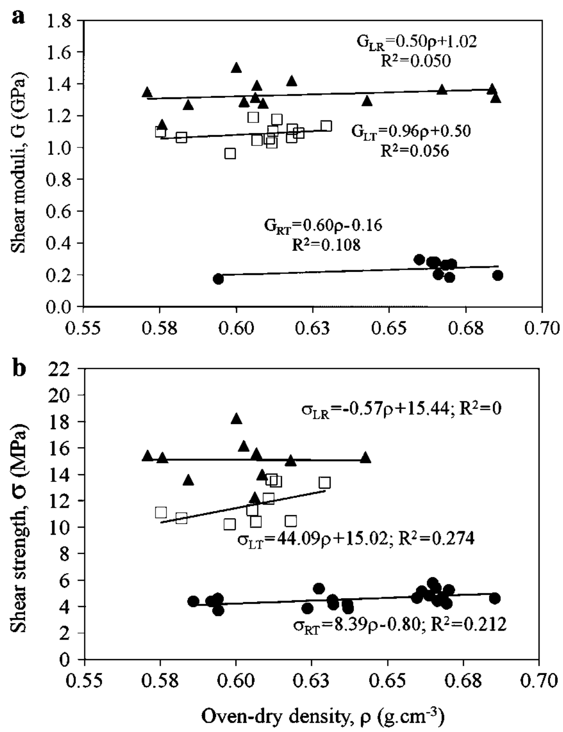

Figure 6 (a) Shear moduli-density and (b) shear strength-density relationships for the *LR*, *LT* and *RT* material planes.

cluded that their values represent different shear properties. A comparison of these results with shear moduli of *P. pinaster* reported in the literature (Xavier et al. 2004), and determined from Iosipescu and off-axis tests, is presented in Table 4. It is important to note that the Arcan specimens and the material tested on that reference, although from a different location, came from the same tree. It can be concluded that the coefficients of variation of the shear moduli, for the different planes of symmetry and determined from the complementary tests, are of the same order of magnitude; still, higher scattered results were measured in the *RT* plane from both Arcan and Iosipescu shear tests.

The G_{LR} mean value determined from the Arcan test is lower and higher than the one identified from the Iosipescu and off-axis tests, respectively, in 6% and 16%. From the *t*-test of equality of means at 95% confidence interval, it is concluded that the *LR* shear modulus determined from the Arcan and Iosipescu tests represent the same mean value ($t=1.59$); whilst the null hypothesis of equal means is rejected for this parameter between the Arcan and the off-axis results ($t=7.14$). In turn, the G_{LT} mean value identified from the Arcan test is lower than the one obtained in the Iosipescu test by 11% and is higher than the one resulted from the off-axis test by 5%. From the *t*-test of equality of means at 95% confidence interval, the shear moduli identified from the Arcan and off-axis tests represents the same mean value ($t=1.61$), whilst the values of shear moduli from the Arcan and Iosipescu tests represent different means ($t=$-3.86). Finally, G_{RT} mean value determined from the Arcan test is approximately 17% higher than the Iosipescu counterpart test. According to the *t*-test of equality of means, it is concluded that the two values are different at the 95% confidence interval, but equal at the 99% confidence interval. The differences observed among the Arcan, Iosipescu and off-axis tests for the shear moduli (Table 4) may come from the spatial variability of elastic properties within the stem. In fact, although the specimens associated with the different tests were systematically sampled in the outermost part of the stem, they were cut at different heights, which can account for some variability of the wood properties as reported by Machado and Cruz (2005).

Shear strengths

The macroscopic failure of the Arcan specimens in all planes of material symmetry is presented in Figure 7. For the *LR* and *LT* specimens, the first crack (1c) occurred at the intersection between the root and flank of one of the notches, followed by a second one (2c) on the counterpart notch (with a short interval between them), both cracks propagated parallel to the grain afterwards. These cracks create a discontinuity in the load-time curves, and no systematic observation in which notch occurred in the first crack could be reported. The *RT* specimen failed in a brittle mode; the first crack occurred near the root of a notch, propagating in an isotropic mode at about ±45° with regard to the horizontal axis of the specimen. These observations have also been confirmed by the finite element analyses (Oliveira et al. 2003), where a stress concentration effect at the region of the notch flank/root transition was identified.

For all planes of symmetry, the failure occurred in a region of a complex stress state (nearby the notch). Therefore, the shear strengths of *P. pinaster* wood could not be directly identified form the Arcan test. Nevertheless, the shear stresses at crack occurrence were deter-

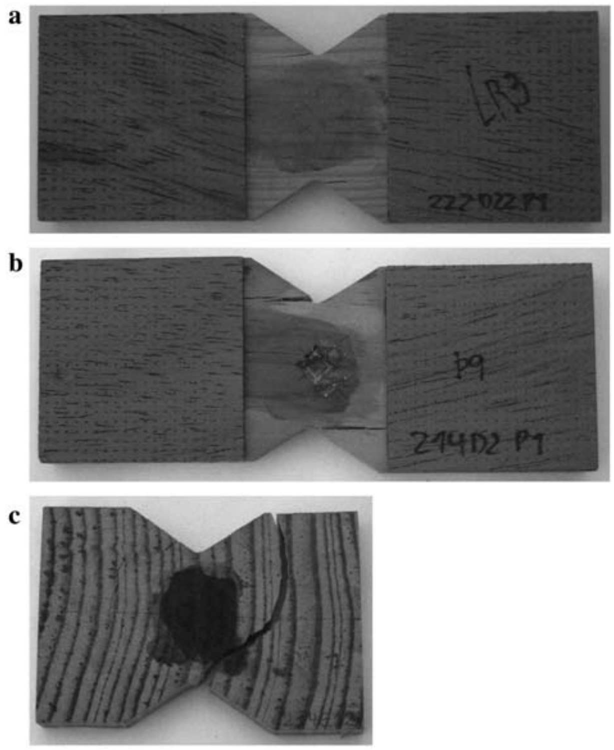

Figure 7 Typical failure of the Arcan specimen: (a) *LR*, (b) *LT* and (c) *RT* material planes.

Table 4 Comparison of the shear moduli of *Pinus pinaster* Ait. determined by the Arcan, the Iosipescu and the off-axis tests.

	G_{LR}			G_{LT}			G_{RT}	
	Arcan	Iosipescu[c]	Off-axis[c]	Arcan	Iosipescu[c]	Off-axis[c]	Arcan	Iosipescu[c]
Mean (GPa)	1.33	1.41	1.11	1.09	1.22	1.04	0.239	0.288
CI[a]	±0.05	±0.11	±0.04	±0.04	±0.07	±0.05	±0.04	±0.04
CV[b] (%)	6.5	10.3	7.0	5.7	8.5	8.1	19.8	16.2

[a]Confidence interval (CI) at 95% confidence level (determined from the *t*-distribution after checking the normality by the Shapiro-Wilk test).
[b]Coefficient of variation (CV).
[c]Xavier et al. (2004).

Table 5 First crack (1c) and ultimate (2c) average shear strengths of *Pinus pinaster* Ait. determined by the Arcan test (moisture content of approximately 11%).

Specimen	*LR* plane			*LT* plane			*RT* plane	
	ρ g•cm^{-3}	σ_{LR}^{1c} MPa	σ_{LR}^{2c} MPa	ρ g•cm^{-3}	σ_{LT}^{1c} MPa	σ_{LT}^{2c} MPa	ρ g•cm^{-3}	σ_{RT}^{1c} MPa
1	0.576	15.3	16.7	0.598	10.2	12.0	0.668	4.70
2	0.643	15.3	15.7	0.605	11.3	12.9	0.670	5.23
3	0.618	15.1	15.1	0.611	12.2	16.4	0.661	5.12
4	0.607	15.6	15.6	0.613	13.4	16.6	0.664	4.79
5	0.606	12.3	15.4	0.618	10.4	15.1	0.667	4.41
6	0.600	18.3	18.3	0.575	11.1	14.9	0.666	5.41
7	0.602	16.2	16.2	0.607	10.4	15.6	0.665	5.77
8	0.571	15.4	16.7	0.582	10.7	15.5	0.660	4.63
9	0.609	14.0	15.0	0.612	13.6	16.6	0.632	4.47
10	0.584	13.6	14.0	0.629	13.4	16.6	0.637	3.82
11							0.637	4.17
12							0.586	4.38
13							0.594	3.67
14							0.624	3.85
15							0.592	4.38
16							0.627	5.34
17							0.632	4.13
18							0.685	4.60
19							0.670	4.21
20							0.594	4.55
Mean	0.602	15.1	15.8	0.605	11.7	15.2	0.642	4.58
CI[a]		±1.15	±0.83		±0.98	±1.15		±0.263
CV[b] (%)	3.2	10.6	7.3	2.7	11.7	10.6	4.8	12.3

[a]Confidence interval (CI) at 95% confidence level (determined from the *t*-distribution after checking the normality by the Shapiro-Wilk test).
[b]Coefficient of variation (CV).

mined from Eq. (5), i.e., the average shear stress at the first and second cracks for the *LR* and *LT* specimens (σ_{LR}^{1c} and σ_{LR}^{2c}, and σ_{LT}^{1c} and σ_{LT}^{2c}, respectively) as well as the shear stress at the first crack for the *RT* specimen (σ_{RT}^{1c}). These results are summarized in Table 5. Comparing the results from the *LR* and *LT* specimens, we can conclude that the stresses at the first crack on both material planes represent different mean values, but the stresses at the second crack lead to the same mean value, according to the *t*-test for equality of means at the 95% confidence interval. Besides, these properties clearly represent different mean values when compared to results in the *RT* plane of symmetry.

As in the case of the Iosipescu test (Pierron and Vautrin 1997; Xavier et al. 2004), the type of wood failure corresponding to the maximum average shear stress is not clear and failure occurs under a combined stress state of shear and transverse stresses. In view of this observation, for both the *LR* and *LT* specimens, it is likely that the shear stresses at the first and second cracks may represent lower and upper boundaries for the shear strengths of wood (S_{LR} and S_{LT}). Moreover, because of the closeness between these stress values (especially for the *LR* specimen, Table 5), we can conclude that the Arcan test provides a reasonable estimation for the shear strengths of wood in both the *LR* and *LT* principal material planes. In the case of the *RT* specimen, a comparison with reference values for this species should be analysed in order to assess if the Arcan test can provide a reasonable estimation of the material shear strength for this plane of symmetry.

For a better interpretation of these results, a comparison with regard to the results obtained from the Iosipescu and the off-axis tests on *P. pinaster* wood provided by Xavier et al. (2004) is reported in Table 6. As it can be seen, the coefficients of variation among the Arcan, Iosipescu and off-axis tests are on the same order of magnitude. For the *LR* specimen, a similar mean value is identified among tests, which is confirmed by the *t*-test of equality of means at the 95% confidence interval ($t=0.84$ between Arcan and Iosipescu tests and $t=1.56$ between Arcan and off-axis tests). Thus, it can be concluded that the shear stresses identified from the Arcan test at the occurrence of the cracks represent an effective estimation of the S_{LR} property for *P. pinaster* wood. It has been shown that the off-axis tensile test can provide a good evaluation of the shear strength of *P. pinaster* in the *LT* plane (S_{LT}) (Xavier et al. 2004). Therefore, it can be concluded that the shear stress determined from the Arcan test at the occurrence of the second crack can provide an estimation of the S_{LT} value. In turn, for the *RT* specimen it can be concluded from the *t*-test for equality of means at the 95% confidence interval that the Arcan and Iosipescu tests lead to the same mean value. As the failure has occurred under a concentrated stress state in both tests, an independent test method is needed to verify if they can provide an accurate estimation of the shear strength of *P. pinaster* wood in the *RT* plane.

Table 6 Comparison of the shear strengths of *Pinus pinaster* Ait. determined by the Arcan, the Iosipescu and the off-axis tests.

	LR plane					*LT* plane					*RT* plane	
	Arcan		Iosipescu[c]		Off-axis[c]	Arcan		Iosipescu[c]		Off-axis[c]	Arcan	Iosipescu[c]
	σ_{LR}^{1c}	σ_{LR}^{2c}	σ_{LR}^{1c}	σ_{LR}^{1c}	S_{LR}^{d}	σ_{LT}^{1c}	σ_{LT}^{2c}	σ_{LT}^{1c}	σ_{LT}^{1c}	S_{LT}^{d}	σ_{RT}^{1c}	σ_{RT}^{1c}
Mean (GPa)	15.1	15.9	15.9	16.9	16.5	11.7	15.2	15.9	18.1	16.6	4.6	4.4
CI[a]	±1.14	±0.83	±1.86	±1.57	±1.50	±0.98	±1.15	–	±0.79	±1.00	±0.26	±0.70
CV[b] (%)	10.6	7.3	15.2	12.1	16.7	11.7	10.6	8.4	6.1	10.9	12.3	19.2

[a]Confidence intervals (CI) at 95% confidence level (determined from the *t*-distribution after checking the normality by the Shapiro-Wilk test).
[b]Coefficient of variation (CV).
[c]Xavier et al. (2004).
[d]Determined from the Tsai-Hill criterion.

The shear strength-density relationships obtained among the tested specimens are presented in Figure 6b. As it can be seen, no significant correlation was obtained in all principal material planes, which is in accordance with the sampled matched specimens.

Conclusion

In this work the application of the Arcan test for measuring the shear properties of *P. pinaster* wood was investigated in all its principal planes of symmetry (*LR*, *LT* and *RT* planes). Both shear moduli and shear strengths were identified by a suitable data reduction and a testing methodology.

Finite element analyses were performed for assessing the uniformity of the shear stress and shear strain at the gauge section of the *LR*, *LT* and *RT* specimens. A correction factor was determined taking into account these non-uniformities. For both the *LR* and the *LT* specimens, this factor was found in the order of magnitude of the scatter reported when it comes to process experimental data. On the other hand, due to the low orthotropic ratio of the *RT* specimen, no numerical correction was found necessary for the correct evaluation of the shear modulus in this plane.

For the identification of the *LR*, *LT* and *RT* shear moduli, two 0/90 rosettes were glued at ±45° back-to-back at the centre of the specimens between V-notches. An average engineering shear strain was determined afterwards taking into account possible through-to-thickness strain variations induced by the loading system. This procedure allowed a significant reduction on the coefficient of variations associated with the mean shear moduli, especially for the *LR* specimen. The Arcan test results were compared with reference values reported in the literature and determined from the Iosipescu and the off-axis tests. It was concluded that the Arcan test is suitable for the identification of the shear modulus of *P. pinaster* wood, in all its planes of symmetry.

The failure of the Arcan specimen, in all principal material planes, occurred on a concentrated stress state nearby the V-notches. Therefore, the shear strengths of wood could not be directly determined from the Arcan test. Nevertheless, by comparison of results obtained independently from the Iosipescu and the off-axis tests, a reasonable estimation of the shear strength in all planes could be evaluated from the Arcan test in all planes of material symmetry.

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