The Shear Strength of Calabrian Pine (*Pinus brutia* Ten.) Bonded with Polyurethane and Polyvinyl Acetate Adhesives

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ABSTRACT: In this study, the change in shear strength on radial and tangential surfaces of Calabrian Pine (*Pinus brutia* Ten.) wood having different roughness values as the result of sawing with a circular ripsaw, planing and sanding, and bonded with polyurethane (PU) and polyvinyl acetate (PVAc) adhesives at the pressure levels of 3, 6, and 9 kgf/cm^2, was studied. Each of the 360 specimens prepared to determine the effect of the variables on bond performance were subjected to shear test in an universal test machine in accordance with the ASTM D 905–98 standards. The values obtained were analyzed statistically and the results were interpreted. The highest shear strength (11.83 N/mm^2) for plane of cut was obtained on the tangential surface after sanding and applying PVAc adhesive with a pressing pressure of 9 kgf/cm^2. The lowest shear strength (6.01 N/mm^2) was obtained in the joinings made on the planed surfaces by using PU adhesive and a pressing pressure of 3 kgf/cm^2. The highest shear strength (9.10 N/mm^2) on the radial surface was obtained after sanding and applying PVAc adhesive and pressing with a pressure of 6 kgf/cm^2. The lowest shear strength (3.76 N/mm^2) was obtained in the specimens whose surfaces were sanded and glued with PU adhesive with a pressing pressure of 3 kgf/cm^2. In general, in the radial surfaces, just like in the tangential surfaces, the specimens bonded with PVAc exhibited a higher shear strength compared with those glued with PU. According to these results, it is definitely necessary to sand the surfaces prior to the bonding process to have a higher shear strength. The bonding process should be made on the tangential surfaces with higher pressures. The PVAc adhesive should be preferred instead of the PU adhesive. © 2006 Wiley Periodicals, Inc. J Appl Polym Sci 99: 3050–3061, 2006

Key words: adhesives; shear strength; wood; roughness

INTRODUCTION

Adhesives are still the most used constructive bonding elements along with mechanical fitting elements in the manufacture of finished products, such as furniture and furnishings, gift items, musical instruments, sea vessels, etc., as well as in the production of intermediate products, such as particle board, fiberboard, plywood, etc., in which wood is used as a raw material. In wood-based products, the general performance of the bonded product changes according to the adhesive composition, wood property, wood preparation, application of adhesive, wood geometry, and product service, besides the potential adhesion forces. The results of some studies made on this subject are given below.

Adhesive and coating properties on four tropical woods were examined in tests according to the Japanese Agricultural Standards (JAS) and the Japanese Industrial Standards (JIS). Adhesive properties of bonds of urea resin (UF), polyvinyl acetate emulsion (PVAc), aqueous polymer solution–isocyanate resin (API), and resorcinol–formaldehyde resin (RF) were evaluated by shear strength tests under dry and wet conditions. The strengths under dry conditions had the same dependencies upon the specific gravities of the woods, whereas the strengths under wet conditions had small values for specimens bonded with PVAc and API, which are not greatly waterproof.[1]

The sensitivity to geometrical imperfections of various test methods for wood–adhesive bonds was investigated using nonlinear finite element analysis. The results show that the prediction of bond line strength is highly dependent on both the specimen type used and adhesive properties, such as strength, fracture energy, and the shape of the stress–slip behavior of the adhesive layer. Another finding is that the sensitivity of the test methods to geometrical imperfections and erroneous load application is also highly dependent on the specimen and adhesive types.[2]

Among the three-ply plywoods produced by using peeled veneers of Oriental beech (*Fagus orientalis* Lipsky), Gaboon mahogany (*Aucoumea klaineana*), and hybrid Poplar (*Populus euramericana*) and urea formaldehyde (UF) adhesive, the highest values of shear strength, bending strength, and elasticity

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modulus in bending were obtained for beech plywood.[3]

Four commercial PU adhesives, along with a RF adhesive to represent a standard of performance, were subjected to a series of industry-accepted tests that assess varying levels of bond strength and durability. The polyurethanes did not differ significantly from each other in their performance in the binding of yellow birch and Douglas fir. As a group, however, their dry shear strengths showed that they were significantly stronger than the resorcinol. Dry wood failures with the polyurethanes were high and did not differ significantly from resorcinol. After three water-saturating procedures, wet shear strengths of polyurethanes and resorcinol were statistically comparable.[4]

Resistances of four types of adhesives (sader, bostik, ebycoll, ponal adhesives) selected on the Cameroonian market were researched and the results obtained were compared with each other. Sader adhesive is more resistant than bostik adhesive, which is more resistant than ebycoll adhesive. The ponal adhesive is in the last position. Bostik adhesive has a higher standard deviation. This can be attributed to its low viscosity.[5]

The lap shear strength of the adhesive solutions of chlorinated natural rubber (CNR) and phenol formaldehyde (PF) resins are considerably higher compared with the commercially sold adhesives.[6]

The shear strengths of Apitong (*Dipterocarpus* spp.) and Caribbean pine (*Pinus caribaea* morelet), which were purified of their excessive extractives, which affect their adhesive characteristics, and were bonded with aqua vinyl polymer isocyanide (API), RF, and PVAc adhesives, were studied. The wettability of the Caribbean pine was greater compared with the Apitong, despite the fact that it contained more resin. Although solvent extractions made of hexane and ethanol–benzene for 8 h do not affect the wettability, they can improve the adhesive characteristic. It was determined that the specimens subjected to a high temperature of 125°C for 4 min had an increase in their bond strengths when they are glued with API, RF, PVAc, and UF adhesives.[7]

In wood-to-wood joinings, prevulcanization of the natural rubber latex-based adhesives by mixing them with different amounts of ammonium caseinate, carboxymethylcellulose, baked starch, and PF resin increases the resistance of these adhesives to hot and cold water to a significant extent compared with commercial adhesives.[8]

The marine adhesives are formaldehyde-free and environmentally friendly. However, the marine adhesives are not readily available. It was investigated whether a polymer, poly (4-vinylphenol) (PVP), containing the phenolic hydroxyl groups, but no peptide linkages, could be used as a wood adhesive. The shear strength of wood composites bonded with an aqueous suspension of PVP could reach up to 3 MPa. Addition of 1.6-hexanediamine or diethylene-triamine to the aqueous suspension of PVP resulted in a significant increase of the shear strength. When the molar ratio of the phenolic hydroxyl group in PVP and1.6-hexanediamine was 3:1, the shear strength could be twice as high as when the aqueous suspension alone is used.[9]

Polyester polyols for use in the preparation of polyurethane (PU) adhesives were synthesized from potato starch and natural oils by a transesterification reaction. These polyester polyols were combined with an aromatic adduct based on toluene 2.4-diisocyanate to form a PU adhesive. Both the polyols and the PU adhesives were characterized by means of Fourier Transform Infrared (FTIR) spectroscopy. The PU adhesive derived from natural products was found superior to the commercially available adhesive.[10]

Increasing the ratio of urea in UF adhesives used in the poplar plywoods decreases the shear strength and increases the bending strength and modulus of elasticity. Increasing the pressing pressure and pressing period increases the value of the specified strength characteristics.[11]

Using a new modified shear test set-up, the longitudinal shear strength and the shear modulus of solid wood were determined, and the resulting shear strength was compared with the results of widely used block shear test. The two wood species studied—Norway spruce and European larch—showed a clear increase of shear properties with increasing density.[12]

Some mechanical properties (compression, static bending, impact bending, and shear strengths) of eastern beech wood (*Fagus orientalis* Lipsky) were researched and compared with those of other beeches. The results showed that the mean compression strength was 60.6 N/mm^2, the mean static bending strength was 120.4 N/mm^2, the mean impact-bending strength was 0.085 Nm/mm^2, and the mean shear strength was 9.9 N/mm^2. The relations of strengths with density were determined using regression analysis, and were compared with other values available in the literature. As a result of this comparison, it was shown that Andirin beech wood has similar mechanical properties to the other beech woods.[13]

Using a new method to determine the longitudinal shear modulus (G) and shear strength (τ) of solid wood in a single test, the observed shear properties of normal (NW) and compression wood (CW) of larch samples were related to their microstructure, *i.e.*, density, microfibril angle (MFA), and lignin content. To estimate the effective G of the solid cell wall, a semiempirical model, which calculates G on the basis of porosity by extrapolation from experimental data, was used. For comparison, the effective G was derived from an analytical model, which considers the cell wall as a unidirectional laminate consisting of fiber and matrix material. Both models and mechanical test results demonstrated that effects of variability in cell wall ultrastructure on G are minor compared with the effects of porosity and density. A multivariate regression model combining G and density showed that a good estimate of τ could be achieved using these input data.[14]

An investigation of the effect of knots on the parallel to grain shear strength of wood was conducted using shear block specimens. All specimens were Douglas fir and the tests were conducted according to ASTM D 143. Statistical analysis of the data showed no significant difference in the mean shear strength of clear and knotted specimens.[15]

Three tropical hardwoods, ishpingo (*Amburana cearensis* A.C. Smith), pumaquiro (*Aspidosperma macrocarpon* Mart.), and tulpay (*Clarisia racemosa* Ruiz and Pav.), were studied to determine the effects of wood density and interlocked grain on the shear strength parallel to the grain. The maximum angular deviation (MAD) and the interlocked grain index (IG) were used to evaluate interlocked grain. Wood density positively affected the apparent shear strength of the wood. The relationships were stronger for actual shear strength compared with nominal shear strength. For all species studied, the interlocked grain negatively affected actual shear strength. The relationships between nominal shear strength and interlocked grain parameters were positive for ishpingo and tulpay, but negative for pumaquiro. Finally, the ASTM D 143 block shear test method should be adapted for woods with heavily interlocked grain.[16]

The effect of wood extractive content on adhesive adhesion and surface wettability was evaluated. Specimens of pine heartwood (*Pinus silvestris*) stored at different times after surface planing, were assembled with water-resistant PVAc adhesive. The results showed that when the strength of the bonds was determined, the percentage adhesion failure increased with increasing extractive content for specimens exposed to the water-boiling test; but no such correlation was found in tests without water boiling. The correlation between adhesive bond strength and extractive content was poor. Surface storage time had no significant effect on the adhesion parameters. Surface wettability measurements revealed a complex relationship between extractive content and surface storage time.[17]

Tepa (*Laureliopsis philippiana* Looser) is a valuable Chilean temperate hardwood lumber species. In anticipation of projected lumber shortages in the United States, a request has been made to the Animal and Plant Health Inspection Service (APHIS) to permit importation of tepa logs. The only known major pathogen-related defect of tepa is a discoloration of the heartwood known as butterfly stain. This stain, which extends through the length of the bole, appears in cross section as a series of partially overlapping orange-brown arcs, each limited by a black zone line. The stained wood versus unstained wood for possible differences in mechanical strength, mineral content, pH, moisture content (MC), and density were examined. Compression ($n = 148$) and static bending ($n = 139$) tests demonstrated that samples from stain-affected trees were significantly weaker than samples from unaffected trees, regardless of whether the sample contained stained wood. There were no differences in shear strength ($n = 119$).[18]

The strength of larch compression wood specimens in longitudinal shear in the radial plane was determined and compared with normal wood. Fracture surfaces were examined with a scanning electron microscope. Compression wood showed higher shear strength than did normal wood. The difference persisted after correction of the strength values for density. Scanning electron microscopy (SEM) revealed clear differences in the pattern of failure in normal wood compared with compression wood.[19]

Analysis of lumber surface properties affirms that neither surface roughness nor dynamic contact angle (DCA) parameters are suited as easy-to-interpret indicators for the quality of 1 K PU bonds. Priming of the wood surface before gluing efficiently improves wet strength of 1 K PU.[20]

In the joining of two wood materials with adhesive, withdrawal strength of the joining varies according to the type of wood, plane of cut, and the type of adhesive. In constructions of Scotch pine (*Pinus sylvestris* L.), Oriental beech wood (*Fagus orientalis* L.), oak (*Quercus borealis* L.), and cedar (*Cedrus libani*), it was set forth that the highest shear strength is on the 45° tangential–radial surface joinings in the beech constructions with Klebit 303 adhesive.[21]

The mixing of some adhesive types with each other in different proportions produces different bond performance values. Among the joinings made in samples of Scotch pine (*Pinus sylvestris* L.) and Oriental beech wood (*Fagus orientalis* L.) with the adhesives obtained with the mixing of PVAc, UF, melamine-formaldehyde (MF), and FF, the highest bonding strength was obtained in the beech specimens joined with a mixture of UF plus 50% MF adhesive.[22]

Mechanical properties of composites are a direct function of the interface bonding between strengthening fiber and the matrix. Single wood–polyethylene interfaced samples were prepared by introducing extruded polyethylene from a twin extruder to bond to the rip surface of a rod-shaped wood specimen. Sodium hydroxide and sulfuric acid were used as surface modifiers for wood. The bond-modifying properties of three silane coupling agents were investigated. The coupling agents used were 98% vinyltrimethoxysilane, 97% 3-(trimethoxysilyl) propylmethacrylate and 96% 3-glycidoxypropyltrimethoxy silane. Direct measurement of the interfacial bond strength was carried out using an Instron tensile test machine. Individually, the acidic modifier showed adverse effects on the interface. Sodium hydroxide improved the interface bonding and enhanced the bond strength by a factor of 1.3–1.5. All of the coupling agents individually increased the interface bonding; vinyltrimethoxysilane ($H_2C{=}CHSi(OCH_3)_3$) had the greatest effect. Also, surface modifiers and coupling agents applied together showed a synergistic effect, which contributed to an improved polymer–woodstock interface bond.[23]

Two types of liquefied wood/epoxy resins with the ratio of liquefied wood to epoxy compounds (L/E ratio) of either 1/0.5 or 1/1 were synthesized. Furthermore, the viscoelastic properties were obtained from the dynamic mechanical measurements of the cured resins and measured their adhesive bond properties as tensile shear strength. The results from dynamic mechanical measurements indicated that the resins with an L/E ratio of 1/0.5 could be cured at 90°C, while the resins with an L/E ratio of 1/1 were cured at 150°C. The resins cured with triethylene tetramine (TETA) at 150°C or 90°C had almost the same level of the normal adhesive shear strength as that of the commercial epoxy resin. The high level of adhesive shear strength of the resin cured at 150°C was maintained after the glued specimens were soaked in water at 60°C, while the shear strength of the resins cured at 90°C was reduced either by soaking in water at 60°C or by cyclic boiling test.[24]

The strength properties of 35-year-old Taiwan incense-cedar wood were studied to investigate the effects of pruning, tree height, and distance from the pith. No significant pruning effect on the bending strength of the wood was detected. Pruning, however, increased the compression and shear strength of the wood. The strength properties, except for shear strength, decreased with increasing tree height and with increasing distance from the pith.[25]

Measuring the shear strength of both the glue line and the solid wood with the same test specimen offers the advantages that the comparison is direct and the influence of wood variability is minimized. New specimen geometry was developed for this purpose and the test is run with two successive loading steps. Finite element modeling showed that the stress distribution is not significantly influencing the results, whereas the compressive prestress on the wood adherents results in a slightly lower resistance, probably mainly caused by micro-cracks that are already present or occur during the first loading step and propagate during the second.[26]

The interaction of wood (*Pinus sylvestris*) with commercial PVAc adhesive, polymethylmethacrylate (PMMA), and a more hydrophilic acrylate were studied with a dynamic mechanical thermal analyzer (DMTA) operating in tensile mode in the tangential direction of wood. The DMTA results were correlated with SEM fractography studies of adhesion between polymers and wood on a cell wall level. The hypothesis put forward is that a good adhesion on the cell wall level results in a decrease in the glass transition temperature (T_g) measured with DMTA. A decrease in T_g for the hydrophilic acrylate was shown when it was impregnated in wood. The decrease of T_g was correlated with good adhesion to wood on the cell wall level. For PVAc and PMMA, no decrease in T_g was measured when bonded or impregnated in wood. The SEM study also showed that the adhesion on a cell wall level was poor.[27]

An increase in temperature of the environment decreases the bond strength of wood joinings with PVAc and UF adhesives.[28]

An experimental study was carried out to determine the bonding strength of PVAc-based adhesives, *i.e.*, Klebit 303 (K_{303}), Kleiberit 305.0 ($K_{305.0}$), and Super Lackleim 308 (SL_{308}) for some impregnated wood materials used in the woodworking industries. For this purpose, Oriental beech (*Fagus orientalis* Lipsky), Uludag fir (*Abies bormulleriana* mattf.), and Scotch pine (*Pinus sylvestris* Lipsky) woods were impregnated with Tanalith-CBC (T-CBC) and Immersol-WR 2000 (I-WR 2000) by the dipping and vacuum methods. The shear strength test was conducted on the connection surface of samples joined with four different adhesives. The test results showed that the highest shear strength (11.84 N/mm^2) was obtained for the wood materials of Oriental beech treated with T-CBC with K_{303} by using the dipping method. The lowest shear strength (3.1 N/mm^2) was obtained for Scotch pine treated with T-CBC with $K_{305.0}$ by using the vacuum method.[29]

Samples of Oriental beech (*Fagus orientalis* Lipsky), oak (*Quercus petraea* liebl.), Scotch pine (*Pinus sylvestris* Lipsky) and Taurus cedar (*Cedrus libani* A. Rich), which were treated with Immersol-aqua (I-A) with the short, medium, and long-term dipping methods, were bonded with K_{303}, $K_{305.0}$, SL_{308}, and PU adhesives on sanded or unsanded samples and the shear strengths were measured. The highest shear strength was obtained in unsanded specimens of Oriental beech in which I-A was applied with the short-period dipping method and that were bonded with K_{303}. The lowest shear strength was obtained in unsanded specimens of Oriental beech in which I-A was applied with the long-period dipping method and that were bonded with K_{303}. The highest shear strength was obtained in sanded specimens in which I-A was applied with the short-period dipping method and that were bonded with PU. The lowest shear strength was obtained in the sanded specimens in which I-A was applied with the long-period dipping method and that were bonded with $S\text{-}L_{308}$.[30]

According to the results obtained from the study aimed at the bending strength, modulus of elasticity, and shear strength in different climatic environments of laminated lumber produced by using UF and FF adhesives with melamine additives, the melamine additive to the adhesives caused an increase in the shear strength.[31]

The shear strengths of specimens of Oriental beech (*Fagus orientalis* Lipsky), Scotch pine (*Pinus sylvestris* Lipsky), and Uludağ fir (*Abies Bormulleriana* mattf.) on which T-CBC and I-WR 2000 substances were applied with the dipping and vacuum methods and that were bonded with the PVAc-based K_{303}, $K_{305.0}$, and SL_{308} adhesives, were measured. The highest shear strength was obtained in the Oriental beech specimens with the application of T-CBC with the dipping method and by gluing with K_{303}. The lowest shear strength was obtained in the Scotch pine specimens with the application of T-CBC with the vacuum method and by bonding with $K_{305.0}$ glue.[29]

In this study, it was aimed to determine the change in shear strength in the radial and tangential surfaces of Calabrian pine wood, which has different roughness values as the result of three wood surfacing techniques, and bonded with different types of adhesives and by applying different levels of pressure. These surfacing techniques are sawing with a circular ripsaw, planning, and sanding, which are used the most in the production of all kinds of wood products.

Experimental

Materials

Wood material

The Calabrian pine trees (*Pinus brutia* Ten.) from which the specimens to be used in the study were obtained were supplied from the regions under the supervision of the Forestry Operations Directorates of Pos, Kahramanmaraş, Yayladağ and Akdere in the south of Turkey by felling and bucking them according to the ISO 4471[32] standards. Care was taken in felling that the tree was normal and strong from the aspect of its trunk and crown formation, that the color was normal, there was no cross grain on the trunk, and that it had not been subjected to insect and fungal attacks. The logs obtained in this manner were brought to the research location. From these logs, the stocks (lumber) of specimens were cut in the rough measurements in a manner in which the annual rings would come with a maximum perpendicularity to the surface, and by also taking into account the dimensions of the specimen and the tolerances that would emerge with drying. This lumber was subjected to technical drying until it reached an 8% moisture content value and it was stored in a closed environment after drying.

A total of 20 specimens were prepared for determining the specific gravity of the Calabrian pine used in the study. The specific gravity values were examined in conformance with ISO 3131[33] and it was determined to be 0.56 g/cm^3.

Adhesives

PVAc and PU adhesives were used and the bonding performance of these types of adhesives on the different planes of cut and on the different surface roughness values was determined. Since PVAc adhesive is used in the assembly of wood products used in interiors and PU adhesive is used in the assembly of wood products mostly in exteriors and humid environments, these types of adhesive were preferred in the study. The adhesives were applied onto the surfaces as they were purchased and the recommendations of the manufacturing company were complied with in their application.

The specific gravity of the PVAc adhesive is 1.05 g/cm^3, its fluidity is 12–18 PaS (at 20°C) and its assembly time is 8 ± 1 min. The specific gravity of the PU adhesive is 1.2 g/cm^3 and its assembly time is 15–40 min.

Machines

The planing, ripsawing, and sanding processes were applied on the surfaces of the specimens to obtain different roughness values. As the final surfacing techniques, planing in the thickness planer, sawing in the circular ripsaw machine, and sanding in the wide belt sanding machine were made. During the processing of the pieces in these machines, the rate of feeding was kept constant at 10 m/min.

A 100-ton hydraulic laboratory press with a 450 × 450 mm^2 plate surface dimension, of which the temperature and pressure can be adjusted, was used in the pressing of the specimens according to the cutting directions.

The Mitutoyo Surfest-402 equipment was used in the measurement of the surface roughness values by the Contact Stylus Tracing Method, and a 4-ton universal test machine was used in the determination of shear strength.

Preparation of the specimens

The plane of cut, surfacing technique, type of adhesive, and pressing pressure were planned as the main variables in the preparation of the specimens. It was envisaged to prepare a total of 360 each specimens ($2 \times 3 \times 2 \times 3 \times 10 = 360$) in Calabrian pine with two planes of cut (tangential and radial), with three different techniques of surfacing (sawing, planing and sanding), two different types of adhesives (PVAc and

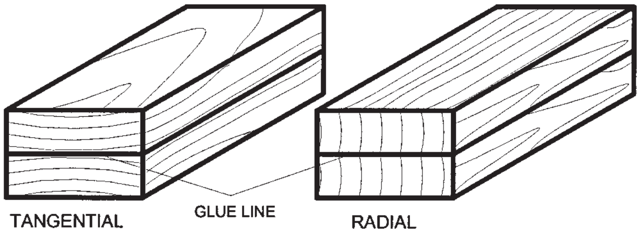

Figure 1 The pairing and coating adhesive to the stocks.

PU), and three different pressure levels (3, 6, and 9 kgf/cm^2) and 10 repeats of each test to determine the effect of shear strength.

Since the moisture content of wood is influential on the roughness, stocks were kept in a climatization room at a temperature of (20 ± 2)°C and a relative humidity of (65 ± 3)% until they reached an unchanging weight (until reaching a rate of 12% moisture content). After this stage, the stocks were insulated to prevent them from losing moisture and were kept waiting for the surfacing.

The stocks, within suitable processes, were subjected to sawing with the 40-tooth circular ripsaw, planing with the 3-blade thickness planer, and sanding with the 60-grit belt sander by taking into consideration the tangential–radial surfaces and the thickness of the specimens to obtain different roughness values to determine the effect of different surface roughness values on bond performance. The technique of surfacing was specified with symbols on the back and end sides of the stocks. The roughness measurements according to the technique of surfacing were made in conformation with the ISO 4288[34] principles. The needle of the surface roughness measurement instrument, with the values of 0.5 mm/s. speed, 2.5 mm cut off length limit (λc), 12.5 mm sampling length, and a sensitivity of ±0.01 μm, was moved perpendicular to the grain of stocks prepared and the Ra value of each pieces was determined and recorded.

The stocks, whose roughnesses were measured, were paired as identical parts in a manner suitable to the bonding of tangential–tangential and radial–radial surfaces by taking into consideration the different surfacing techniques (Fig. 1). The PVAc and PU adhesives were coated separately on the surfaces (200 g/m^2) in conformance with the recommendation of the manufacturing company. The specimen blocks were obtained by the pieces being put one on top of the other whose surface is coated with adhesive and put into the press at different pressures of 3, 6, and 9 kgf/cm^2 and being pressed for a period of 1 h each (Fig. 1). In pressing, a 50°C pressing temperature was used for the specimens with PVAc adhesive and an 80°C pressing temperature was used for the specimens with PU adhesive in accordance with the recommendation of the manufacturing company.

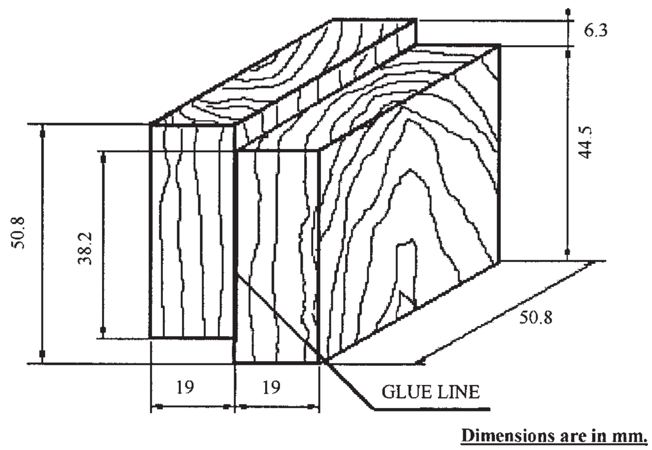

Figure 2 Shear test specimen (ASTM D905–98).

The specimen blocks, which were pressed, were cut in the dimension of 50 × 51 mm^2 in the envisaged number at least 48 h later. These pieces were transformed into test specimens by forming rabbets at their ends to place into the test machine in conformance with ASTM D905–98[35] (Fig. 2).

The specimens prepared were once again put into the climatization room at a temperature of (20 ± 2)°C and a relative humidity of (65 ± 3)% to homogenize their moisture and to bring them to the air dry moisture content. After this point, the specimens were insulated to prevent a loss of moisture and were kept for the tests.

Method

Each of the 360 specimens was subjected to the shear test in a 10-ton universal test machine in conformance with the ASTM D 905–98 standards. The specimens were connected to the machine with a special apparatus for testing according to the standards and a load was applied to the specimens in accordance with the model given in Figure 3. The loading speed of the machine during the experiment was adjusted to 12.7 mm/min.

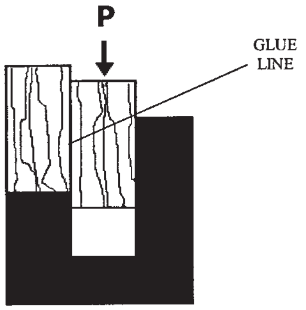

Figure 3 Shear strength test model in the universal test machine

The load at the moment of separation (breaking off) of the parts from each other was read from the dial and recorded. The values obtained were put in the formula given below and the shear strength of each piece was determined.

$$\sigma_{\mathrm{M}} = \frac{P_{\max}}{A}$$

where

σ_M : Maximum shear strength (N/mm^2)
$P_{\max}$: Maximum load at breaking point (N)
A: Bond surface area (mm^2)

Evaluation of the data

The data obtained with the testing of each of the 360 specimens according to different variables were statistically analyzed. The multivariance analysis was applied for testing whether or not the type of surfacing, the plane of cut, the type of adhesive, and the pressing pressure were effective on the shear strength of Calabrian pine. At the end of this analysis, if the significance (P) value obtained was less than ±5%, then the variable was effective on the shear strength, otherwise, it was accepted to be ineffective. The SPSS package program was used for this analysis.

Since the variances were not homogeneous at $P < 0.05$ according to the Levene test, the Tamhane 2 test was applied in the comparison of the averages. The shear strength values of the variables were compared through the homogeneity groups formed according to the Tamhane 2 test and the results were interpreted.

RESULTS AND DISCUSSION

The shear strength values obtained for the plane of cut, surfacing technique, the type of adhesive used, and the pressure values applied in the pressing at the end of the tests made are given in Table I.

The bar diagram formed for comparing the magnitudes of the shear strength values obtained according to the test variables are given in Figure 4.

As it can be seen from the figure, the highest shear strength (11.83 N/mm^2) was obtained on the tangential surface after sanding by coating it with PVAc adhesive and with a pressure of 9 kgf/cm^2. The lowest shear strength (6.01 N/mm^2) was obtained in the joining made on the tangential surface after planing by coating it with PU adhesive and with a pressing pressure of 3 kgf/cm^2. At the same time, this is the surfacing technique, which gives the lowest roughness value. In other words, as the roughness decreases on the tangential surfaces, the shear strength also decreases. Another general observation is that in general, as the pressure increases, the shear strength also increases.

The highest shear strength (9.10 N/mm^2) was obtained on the radial surface after sanding and by coating it with PVAc adhesive and after applying a pressure of 6 kgf/cm^2. The lowest shear strength (3.76 N/mm^2) was obtained on the sanded surfaces of the specimens coated with PU adhesive and pressed with a pressure of 3 kgf/cm^2. In general, on the radial surfaces, just like on the tangential surfaces, the specimens bonded with PVAc had higher shear strengths compared with those bonded with PU.

According to the surfacing technique, higher shear strength values are obtained with the bonding of the tangential surfaces. When the roughness values occurring in these two surfaces connected to the surfacing techniques are taken into consideration, the roughness values in the tangential surfaces are relatively lower in general. It is observed that with a decrease in the roughness value, the shear strength increases.

The values obtained from the analysis of variance made for determining whether or not the test variables are effective on the shear strength, alone or in a group, connected to the values obtained, are given in Table II.

According to the analysis of variance results given in Table II, all of the variables (Plane of cut, surfacing tecnique, type of adhesive, pressing pressure) were effective on the shear strength, alone or as a group, excluding the dual interaction of type of adhesive × pressing pressure and the triad interaction of plane of cut × type of adhesive × pressing pressure. At the same time, they are also effective on the surface roughness ($P < 0.05$).

The Tamhane 2 test was made to determine whether or not there was a difference among the shear strength values obtained according to the test variables and if there was a difference, and to determine among which variables there was a difference. The homogeneity groups (HG) were determined with this test and the homogeneity groups obtained are given in Table III.

According to the data shown in Table III, higher shear strength values were obtained in the tangential surfaces and at the same time, this surface also had less roughness. The increase in adhesion as the roughness decreases could have been influential in the increase of shear strength in the tangential surfaces. According to this result, if a higher shear strength were sought, then it would be appropriate to join the tangential surfaces.

There is no significant difference between the shear strength values resulting in the joining of surfaces obtained with the circular ripsaw cut and the sanding. These two variables are within the same homogeneity group. The strength obtained with the bonding of the surfaces after planing is lowerer than that obtained using the other surfacing technique. According to this,

TABLE I
Shear Strength Values According to Plane of Cut, Surfacing Technique, Adhesive Type, Pressure, and Roughness Values

				Mean ¯(X)		Standard deviation (S)	
Plane of cut	Surfacing type	Adhesive	Pressing pressure (kgf/cm^2)	Shear strength (N/mm^2)	Roughness (μm)	Shear strength (N/mm^2)	Roughness (μm)
Tangential	Sawing with circular ripsaw	PVAc	3	8.59	6.64	0.24	1.16
			6	8.95		0.45	
			9	9.65		0.50	
		PU	3	6.02		0.53	
			6	8.21		0.28	
			9	7.46		0.38	
	Planning	PVAc	3	7.54	4.48	0.50	0.70
			6	7.73		0.41	
			9	7.91		0.56	
		PU	3	6.15		0.47	
			6	6.94		0.61	
			9	6.97		0.66	
	Sanding	PVAc	3	8.90	5.32	1.38	0.41
			6	11.60		0.73	
			9	11.83		0.48	
		PU	3	6.79		0.84	
			6	6.89		1.02	
			9	9.22		0.87	
Radial	Sawing with circular ripsaw	PVAc	3	7.92	6.77	0.30	1.25
			6	8.46		0.70	
			9	8.45		0.59	
		PU	3	6.45		0.47	
			6	6.60		0.66	
			9	6.73		0.89	
	Planing	PVAc	3	7.26	5.55	0.35	0.84
			6	8.62		0.36	
			9	8.61		0.47	
		PU	3	6.35		0.53	
			6	6.82		0.55	
			9	7.53		0.33	
	Sanding	PVAc	3	8.63	5.74	0.63	0.85
			6	9.10		0.34	
			9	9.01		0.29	
		PU	3	3.76		0.29	
			6	4.46		0.47	
			9	4.51		0.23	

related to the surfacing technique, as the roughness increases, the shear strength increases. It is thought that this result stems from bringing face to face a large number of micro hills and cavities, which emerge with the sander grains or the saw teeth and which interlock with each other at the moment of bonding.

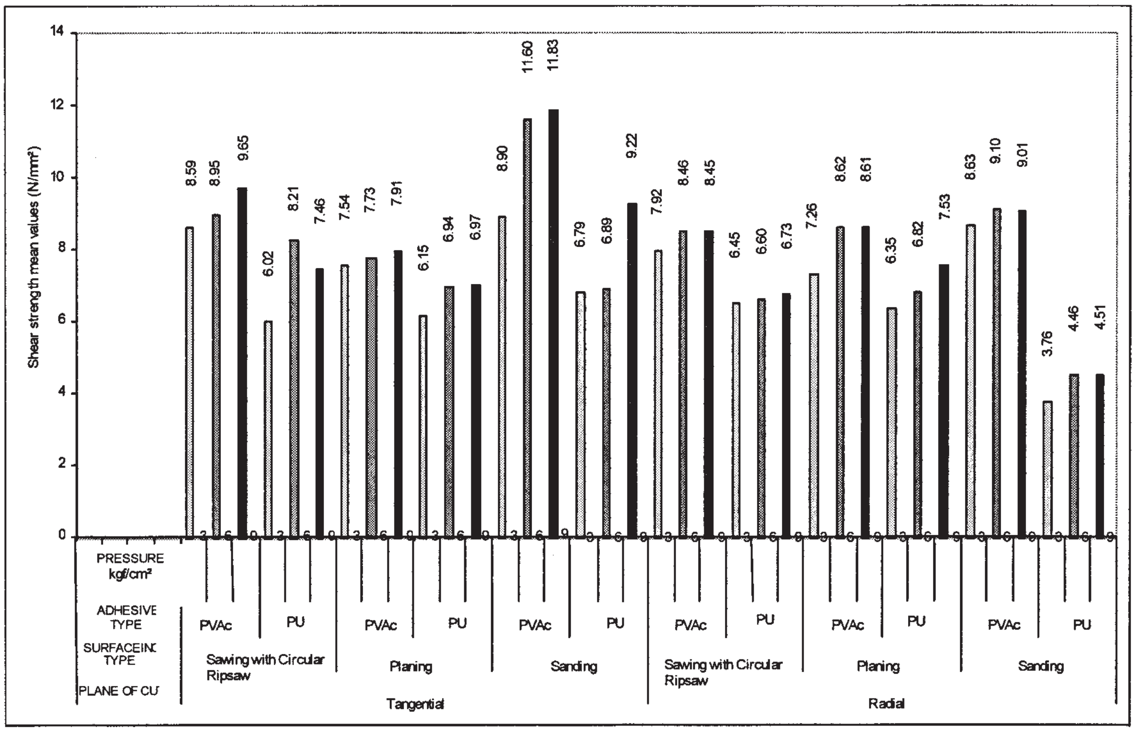

Figure 4 Shear strength values according to plane of cut, surfacing technique, adhesive type, and pressing pressure.

TABLE II
Analysis of Variance of Variables at Different Interaction Degrees

Source	Degrees of freedom		Sum of squares		Mean square		F		Significance ($P < 0.05$)	
	Shear strength (N/mm^2)	Roughness (μm)	Shear strength (N/mm^2)	Roughness (μm)	Shear strength (N/mm^2)	Roughness (μm)	Shear strength (N/mm^2)	Roughness (μm)	Shear strength (N/mm^2)	Roughness (μm)
Plane of cut (A)	1	1	90.91	26.35	90.91	26.35	263.87	31.63	0.00[a]	0,000[a]
Surfacing technique (B)	2	2	18.48	180.08	9.24	90.04	26.82	108.06	0.00[a]	0,000[a]
A × B	2	2	134.63	8.29	67.31	6.91	195.37	8.29	0.00[a]	0,000[a]
Adhesive (C)	1		465.00		465.00		1349.60		0.00[a]	
A × C	1		6.43		6.43		18.67		0.00[a]	
B × C	2		126.06		63.03		182.93		0.00[a]	
A × B × C	2		11.65		5.82		16.90		0.00[a]	
Pressing pressure (D)	2		81.93		40.96		118.89		0.00[a]	
A × D	2		8.89		4.44		12.90		0.00[a]	
B × D	4		8.12		2.03		5.89		0.00[a]	
C × D	2		1.05		0.54		1.53		0.22 (n.s.)	
A × B × D	4		21.51		5.38		15.61		0.00[a]	
A × C × D	2		0.31		0.16		0.46		0.64 (n.s.)	
B × C × D	4		11.27		2.82		8.17		0.00[a]	
A × B × C × D	4		19.45		4.86		14.12		0.00[a]	
Error	324	354	111.63	294.96	0.35	0.83	–	–	–	–
Total	360	360	22367.42	12405.06	–	–	–	–	–	–

[a] significant.
n.s., not significant.

TABLE III
Homogeneity Groups (HG) According to Plane of Cut, Surfacing Technique, Adhesive, and Pressure

Variables	Shear strength mean values (N/mm^2)		Surface roughness mean values (Ra) (μm)	
Plane of cut	$\bar{X}$	HG	$\bar{X}$	HG
Tangential	8.19	A	5.48	A
Radial	7.18	B	6.02	B
LSD	0.2720		0.1892	
Surfacing technique				
Sawing with circular ripsaw	7.79	A	6.70	C
Planing	7.37	B	5.01	A
Sanding	7.89	A	5.53	B
LSD	0.1216		0.2317	
Adhesive				
PVAc	8.82	A		
PU	6.55	B		
LSD	0.1490			
Pressure (kgf/cm^2)				
3	7.03	C		
6	7.86	B		
9	8.16	A		
LSD	0.1490			

There is a significant difference between the shear strength values obtained in the PVAc and PU adhesives used in the bonding of the specimens. The PVAc adhesive produces higher shear strength values compared with the PU adhesive. PVAc penetrates deeper and makes a better bond formation compared with PU and the fact that its capability of penetration is higher and that it produces a more flexible bond could be influential in the increase of shear strength.

The differences among the shear strength values obtained according to the three different pressing pressures were also significant. As it can be seen from the table, the shear strength values also increase as the pressure increases. Higher shear strengths (8.16 N/mm^2) are obtained with a pressing pressure of 9 kgf/cm^2 compared with the pressing pressures of 3 and 6 kgf/cm^2.

When the homogeneity groups are examined for the type of adhesive used in the bonding and the pressures applied are examined, the shear strength values obtained according to the adhesive type and pressing pressure are significant. A higher shear strength value (8.82 N/mm^2) is obtained with the PVAc adhesive compared with the PU adhesive. A higher shear strength value (8.16 N/mm^2) is obtained with the 9 kgf/cm^2 pressing pressure compared with the 3 and 6 kgf/cm^2 pressing pressures. The fact that high pressure levels provide for a formation of a better bond by increasing the pumping of adhesive to the cavities and increase the adhesion could be influential in this higher shear strength. According to this, it would be useful to increase the pressing pressure up to a value that would not harm the wood to increase the shear strength in joinings.

The shear strengths and roughness values obtained with the comparisons made connected to the dual interactions related to the test variables are given in Table IV.

As it can be observed from an analysis of the table, the highest shear strength value (9.21 N/mm^2) obtained was for the plane of cut × the surfacing technique dual interaction with the bonding of the tangential surfaces, which had been sanded. The lowest shear strength value (6.58 N/mm^2) was obtained with the radial surfaces, which had been sanded.

The highest shear strength value (9.189 N/mm^2) in the plane of cut x type of adhesive dual interaction was obtained on the tangential surfaces with the PVAc adhesive. The lowest shear strength value (5.19 N/mm^2) was obtained on the radial surfaces with PU adhesive.

The highest shear strength value (8.84 N/mm^2) in the plane of cut x pressing pressure dual interaction was obtained on the tangential surfaces with a pressing pressure of 9 kgf/cm^2. The lowest shear strength value (6.73 N/mm^2) was obtained on the radial surfaces with a pressing pressure of 3 kgf/cm^2.

When the surfacing technique x type of adhesive dual interaction are examined, the highest shear strength (9.85 N/mm^2) was obtained on the sanded surfaces on which the PVAc adhesive was coated. The lowest shear strength (5.94 N/mm^2) was obtained on the sanded surfaces on which the PU adhesive was coated.

The largest shear strength (8.64 N/mm^2) in the surfacing technique and pressing pressure dual interaction was obtained on the sanded surfaces with a pressing pressure of 9 kgf/cm^2. The lowest shear strength (6.83 N/mm^2) was obtained on the planed surfaces with a pressing pressure of 3 kgf/cm^2.

The largest shear strength (9.24 N/mm^2) in the type of adhesive and pressing pressure dual interaction was obtained with the PVAc and a pressing pressure of 9 kgf/cm^2. The lowest shear strength (5.92 N/mm^2) was obtained with the PU and a pressing pressure of 3 kgf/cm^2.

In conclusion, it would be appropriate to take the following into consideration. The surfaces, which are the subject of bonding, should be tangential surfaces to increase the shear strength in the wood structural elements under the influence of shear strength. Prior to bonding, the surfaces, which are obtained with circular ripsaws or planing, should definitely be sanded. In bonding, by also taking into consideration the strength characteristics of the material, a higher pressing pressure should be applied in a manner that would not create structural deterioration. PVAc adhesive should be used in place of PU adhesive.

TABLE IV
The Shear Strengths and Roughness Values Obtained According to the Dual Interactions Among the Variables ($\alpha = 0.05$)

Source	Shear strength Mean value (N/mm^2)	Surface roughness mean value (Ra) (μm)
Plane of cut × Surfacing technique (LSD: 0.1490) shear strength; (LSD : 0.3277) surface roughness		
Tangential + Sawing with circular ripsaw	8.15	6.64
Tangential + Planing	7.21	4.48
Tangential + Sanding	9.21	5.32
Radial + Sawing with circular ripsaw	7.44	6.77
Radial + Planing	7.53	5.55
Radial + Sanding	6.58	5.74
Plane of cut × Adhesive type (LSD: 0.1216)		
Tangential + PVAc	9.19	
Tangential + PU	7.18	
Radial + PVAc	8.45	
Radial + PU	5.19	
Plane of cut × Pressing pressure (LSD: 0.1490)		
Tangential + 3 kgf/cm^2	7.33	
Tangential + 6 kgf/cm^2	8.39	
Tangential + 9 kgf/cm^2	8.84	
Radial + 3 kgf/cm^2	6.73	
Radial + 6 kgf/cm^2	7.34	
Radial + 9 kgf/cm^2	7.47	
Surfacing technique × Adhesive type (LSD: 0.1720)		
Sawing with circular ripsaw + PVAc	8.67	
Sawing with circular ripsaw + PU	6.91	
Planing + PVAc	7.94	
Planing + PU	6.79	
Sanding + PVAc	9.85	
Sanding + PU	5.94	
Surfacing technique × Pressing pressure (LSD: 0.2107)		
Sawing with circular ripsaw + 3 kgf/cm^2	7.24	
Sawing with circular ripsaw + 6 kgf/cm^2	8.05	
Sawing with circular ripsaw + 9 kgf/cm^2	8.07	
Planing + 3 kgf/cm^2	6.83	
Planing + 6 kgf/cm^2	7.53	
Planing + 9 kgf/cm^2	7.75	
Sanding + 3 kgf/cm^2	7.02	
Sanding + 6 kgf/cm^2	8.01	
Sanding + 9 kgf/cm^2	8.64	
Adhesive type × Pressing pressure (LSD: 0.3649)		
PVAc + 3 kgf/cm^2	8.14	
PVAc + 6 kgf/cm^2	9.07	
PVAc + 9 kgf/cm^2	9.24	
PU + 3 kgf/cm^2	5.92	
PU + 6 kgf/cm^2	6.65	
PU + 9 kgf/cm^2	7.07	

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