

# COMPARISON OF THE MECHANICAL PROPERTIES OF BRANCH AND STEM WOOD FOR THREE SPECIES

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**Abstract.** Branch wood could be used in new added-value products as an alternative to stem wood provided that its characteristics are known and understood. This article compares the modulus of elasticity (MOE), modulus of rupture (MOR), and compression strength of maple (*Acer* spp.) and Scots pine (*Pinus sylvestris* L.) and the compression strength of beech (*Fagus sylvatica* L.) branch wood with stem wood. The mechanical tests showed that the MOE and compression strength of maple branch wood were slightly lower than those of stem wood, maple MOR was slightly higher for branch wood, and beech compression strength was similar for branch and stem wood. However, the MOR and compression strength of Scots pine branch wood were approximately one-half of those of stem wood, whereas the MOE was approximately one-third. Branch wood had a higher density than corresponding stem wood, except for Scots pine. No correlation was observed between branch density and mechanical strength except for MOR.

**Keywords:** Branch wood, stem wood, compression parallel to the grain, bending strength, modulus of elasticity.

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## INTRODUCTION

The search for alternatives to stem wood in the manufacture of new wood-based materials represents one of the priorities of the wood industry because of decreasing raw material and an increased responsiveness to environmental pressures (Cionca et al 2006a).

Branch wood represents 25–32% of the total wood volume (Hilton 2001) and is a secondary resource with a potential for high-value applications that has been inadequately explored. Increasing the added value of branches means finding alternative uses other than as firewood or particles for wood-based panels.

An initiative to increase the degree of conversion of branch wood is part of a current national research project financed by The National Council of Scientific Research in Higher Education (Cionca et al 2006a). The project consists of manufacturing branch panels from crosscut branch slices that can be used in small articles of decorative furniture. To use branch wood as raw material in furniture, its physical and mechanical properties require an investigation in relation to the microscopic and macroscopic structure.

From the literature it can be concluded that branches have narrower annual rings (Fegel 1941; Tsoumis 1968; Bowyer et al 2003), smaller cell and lumen diameters (Fegel 1941; Brunden 1964; Bannan 1965; Tsoumis 1968; Taylor 1977; Hakkila 1989; Bowyer et al 2003), smaller cell wall thicknesses (Hakkila 1989), and smaller cell lengths (Fegel 1941; Bannan 1965; Manwiller 1974; Taylor 1977; Vurdu and Bensed 1979; Hakkila 1989) than stem wood. The length of branch wood cells increases with branch diameter and this is probably because small branches contain proportionally more juvenile wood (Hakkila 1989); the fiber length increases from pith to bark with a greater difference than for stem wood (Vurdu and Bensed 1979). Branch wood is generally characterized by a higher percentage in the volume of fibers and longitudinal parenchyma in hardwoods (Vurdu and Bensed 1980; Hakkila 1989) and by an increased number of resin canals in soft-

woods (Fegel 1941; Tsoumis 1968; Hakkila 1989; Bowyer et al 2003). Rays are more numerous (Tsoumis 1968; Bowyer et al 2003) and vessels are smaller and in greater numbers in branch wood than in stem wood (Tsoumis 1968; Vurdu and Bensed 1980). Branch wood is generally higher in density than stem wood (Fegel 1941; Kollmann and Côté 1968; Tsoumis 1968). According to some researchers, the difference between stem wood and branch wood densities appears to vary among species rather unpredictably (Manwiller 1979; Hakkila 1989). Brunden (1964) and Philips et al (1976) found branches of softwoods 5–20% lower in density than stem wood.

Although the literature contains a number of studies regarding the microscopic and macroscopic structure of branch wood compared with stem wood, there are almost no reports regarding the mechanical properties of branch wood. From a literature review on branch wood properties (Gurau et al 2006) it appears that normal branch wood 50–100 mm in diameter has similar compression strength parallel to the grain and similar shock resistance as normal stem wood but greater plasticity (Vanin 1953), whereas no studies were found for other mechanical properties.

Because reaction wood behaves quite differently from normal wood as a result of its anatomically different structure (Kucera and Philipson 1977), and its presence in softwood branches is the rule rather than the exception (Tsoumis 1968; Hakkila 1989), it decisively affects many important properties of branch wood. Generally, strength increases with increasing density, but this relationship does not apply to reaction wood (Tsoumis 1968). The modulus of elasticity and tensile strength of compression wood are lower than those of normal wood (Tsoumis 1968; Hakkila 1989), but compression parallel to the grain and bending strength is higher (Hakkila 1989). With regard to branch wood of hardwoods, in an extensive survey of tension wood on a large number of temperate and tropical species, Höster and Liese (1966) found that only 50% of the species had tension wood. Tension wood has lower compressive and bending strength than normal

wood (Tsoumis 1968; Hakkila 1989; Bowyer et al 2003). In the green condition, tension wood is particularly low in tensile strength, but when air-dried, its tensile strength is higher than that of the normal wood (Kollmann and Côté 1968).

If stem wood is an excellent material for manufacturing solid wood panels, branch wood may be used in new added-value products as an alternative to stem wood provided its mechanical properties are known and understood. Inadequate data in the literature make any comparison of branch wood with stem wood difficult unless specific mechanical tests are conducted and SEM micrographs are examined.

This article contains a comparison between the compression strength parallel to the grain, bending strength, and modulus of elasticity of branch wood and stem wood to understand the extent to which this secondary resource, wood branches, differs from stem wood.

#### MATERIALS AND METHODS

Specimens of stem wood available as sawn timber and branch wood of beech (*Fagus sylvatica* L.), maple (*Acer* spp.), and Scots pine (*Pinus sylvestris* L.) were cut for testing in compression parallel to the grain. Straight branch pieces of 500–600 mm from delimiting operations were randomly taken from a local forest warehouse; therefore, their initial distance from the base branch and their height from the ground level were unknown. The stem specimens were mature wood for maple and beech, and heartwood for Scots pine. Specimens of maple and Scots pine were cut to determine the modulus of elasticity (MOE) and modulus of rupture (MOR). The compression test specimens were sized to ISO 3787 (1976) and were 60 mm long with a cross-section of 20 × 20 mm. Five specimens were cut for each species and wood type. Specimens for MOE and MOR were 300 mm long, again with a 20 × 20-mm cross-section as recommended in BS 373 (1957) for small clear specimens. Six specimens were made for each set of test variables. The small number of specimens was caused by the reduced availability of

the material at the time, although it was acknowledged that a small sampling could give indicative rather than general results about the mechanical properties of a species.

Only the specimens of stem wood were conditioned. Because of their reduced dimensions and high initial moisture content (MC), branches tend to split easily when stored in a controlled environment (20°C and 65% RH). Therefore, they were stored until the first drying checks were detected at the cut ends. This moment was chosen to machine the branch wood specimens, which led to higher MC values at testing than in the stem wood specimens. In practice, the susceptibility to drying checks can be overcome when manufacturing branch wood panels. If green branch wood is processed into branch panels immediately and dried with the tangential direction under restraint, the product is more stable than the raw material (Cionca et al 2006b).

The actual test dimensions were measured with digital calipers (Mitutoyo Digimatic, UK) calibrated with a 25-mm ± 0-µm rod. The density of each specimen was determined before testing and a mean value calculated for each combination of species and tree location after the correction for MC. The moisture content was determined after testing by the oven-dry method and a mean value for each set of specimens was recorded. A reference specimen density was calculated for a nominal 12% MC as presented in Eq 1 in accordance with ISO 3131 (1975).

$$\rho_{12} = \rho \left[ 1 - \frac{(1 - \beta)(U - 12)}{100} \right] \quad (1)$$

where  $\rho$  = density at the MC at testing (kg/m<sup>3</sup>);  $\rho_{12}$  = density recalculated for 12% MC (kg/m<sup>3</sup>);  $U$  = the MC at testing (%); and  $\beta$  = correction coefficient depending on species.

For approximate calculations,  $\beta = 0.85 \cdot 10^{-3} \cdot \rho$  (according to ISO 3131 1975).

The overall diameter of the raw material of the branch wood specimens was approximately 60 mm for the Scots pine (age 18 yr), 90 mm for the

beech (age 65 yr) and 100–120 mm for the maple (age indeterminate). With such relatively small diameters, it was impossible to comply with the requirements of ISO 3787 (1976) and BS 373 (1957), whereby the growth rings should be parallel with one face of the specimens. The Scots pine and beech specimens contained pith more or less centrally, whereas the maple had material from near the pith on one side of the specimens. The annual ring orientation in the stem wood specimens complied with the standard requirements.

Tests were undertaken at the Forest Products Research Center in High Wycombe, UK. For the compression tests, a servohydraulic universal testing machine (Phoenix, UK) used was equipped with a  $\pm 100$ -kN load cell calibrated annually by Instron. The  $\pm 25$ -kN range of the load cell was adequate for the compression tests. The load was applied at a constant rate of displacement of 0.1 mm/min.

The MOE and MOR were determined in three-point bending according to BS 373 (1957). The load was applied at a constant rate of 6.6 mm/min. BS 373 provides results that are equivalent to other standard tests on small clear specimens.

Bending tests were carried out on a screw-driven Instron 4411 universal testing machine equipped with a  $\pm 5$ -kN load cell calibrated annually by Instron.

For both compression and bending tests, data were acquired at 25 Hz and 12-bit resolution reduced by block averaging to 5 Hz for recording to smooth data and reduce file size. Peak load was recorded from nonaveraged data.

The ultimate compressive strength was determined according to ISO 3787 (1976), whereas the MOE and MOR of each bending specimen were calculated by algorithms developed to comply with BS 373; then mean values were calculated for each combination of species and tree location, branch wood, and stem wood.

At the time of testing, the specimens had a range of moisture contents, so for comparison, all the test results were recalculated for 12% MC with

formulae contained in ISO 3787 (1976) for compression strength, ISO 3349 (1975) for MOE, and ISO 313 (1975) for MOR.

The subsequent correction formulae were used for compression strength, bending strength (Eq 2), and MOE (Eq 3). The value of  $U = 30\%$  MC was taken as the fiber saturation point (FSP). It was considered that the mechanical properties varied only for MCs up to FSP.

$$\sigma_{12} = \begin{cases} \sigma[1 + c(U - 12)] & U < 30 \\ \sigma[1 + c(30 - 12)] & U \geq 30 \end{cases} \quad (2)$$

where  $c = 0.04$  for all species according to ISO 3787 (1976) and ISO 313 (1975);  $U = \text{MC}$  during testing (%);  $\sigma_{12}$  = compression or bending strength recalculated for 12% MC; and  $\sigma$  = compression or bending strength at the test MC.

$$E_{12} = \begin{cases} \frac{E_u}{1 - [c(U - 12)]} & U < 30 \\ \frac{E_u}{1 - [c(30 - 12)]} & U \geq 30 \end{cases} \quad (3)$$

where  $c = 0.02$  for all species according to ISO 3349 (1975);  $U = \text{MC}$  during testing (%);  $E_{12}$  = MOE recalculated for 12% MC; and  $E$  = MOE at the test MC.

To better understand the behavior of branch wood and stem wood specimens subjected to mechanical testing at the microscopic level, beech, maple, and Scots pine specimens were prepared.

Small cubes of material were cut from the test specimens with a fine band saw. These cubes were boiled in flasks with refluxing condensers for approximately 24 h until saturated. Under a low-power microscope, the blocks were trimmed to expose the transverse, radial, and tangential surfaces.

Specimens were cut using a razor saw from the blocks prepared previously obtaining small cubes approximately  $3 \times 3 \times 3$  mm. Under a low-power microscope, all surfaces were trimmed with a fresh razor blade, and then the

blocks were transferred to an oven at 103°C to dry. After drying, the cubes were mounted on aluminium stubs using colloidal silver dag. After the dag had dried, the cubes were sputter-coated with gold at 10 mA for 240 s in an argon atmosphere. The cubes were examined with a Cambridge 150 Scanning Electron Microscope using secondary electron imaging. An accelerating voltage of 10 kV was used to avoid the risk of charging effects. Images at 50×, 75×, 153×, and 500× magnification of branch wood and stem wood were captured with I-Scan digital image equipment (ISS Group Manchester, UK) and compared.

## RESULTS AND DISCUSSION

### Compression Strength

The mean values obtained for branch wood (Table 1) were compared with equivalent values for stem wood reported in the literature; it was found that the mechanical properties of stem wood obtained experimentally were similar to findings in the literature. Compression strength for beech stem wood was 49.6 MPa, similar to 46.5 MPa by Filipovici (1965); for maple stem wood, 55.2 MPa falls between values obtained by Lavers (1983), 48.2 MPa, and Filipovici (1965), 56.8 MPa; and for Scots pine, 56.6 MPa was close to 53.9 MPa obtained by Filipovici (1965). Note that no reference values for branch wood were found in the literature.

Micrographs of hardwoods in Fig 1c–f show that branch wood contains a greater number of

medullary rays than stem wood, which according to Hakkila (1989), can lower compression strength parallel to the grain. As can be seen in Table 1, although the density of branch wood in beech and maple was higher than that of stem wood, the compression strength parallel to the grain was slightly lower for maple and was about the same for beech. These results support those of Vanin (1953).

All Scots pine branch wood specimens contained compression wood and most likely juvenile wood because the specimens contained pith and surrounding tissue (Fig 1i). The juvenile wood is characterized by large microfibril angles and shorter tracheid lengths than mature wood (Zobel and Sprague 1998). Perhaps as a consequence, compression strength of Scots pine branch wood was only 56% of the stem wood strength. This result is similar to findings of Pazdrowski and Splawa-Neyman (2003), who tested juvenile wood in Norway spruce and found its compression strength was lower than that of stem wood.

With regard to the branch wood specimens, maple was slightly stronger than beech but approximately 60% stronger than Scots pine.

Within a species, although the compression strength increased with an increase in density for stem wood, it had no specific trend for branch wood. As Vanin (1953) noted, branch wood appears to have a greater plasticity than stem wood. This behavior was observed during test-

Table 1. *Experimental results for compression strength parallel to grain.*

Species and wood type	Moisture content at testing (%)	Density Uncorrected (kg/m <sup>3</sup> )	Density corrected for 12% MC (kg/m <sup>3</sup> )	Compression strength uncorrected (MPa)	Compression strength corrected for 12% MC (MPa)
<b>Beech</b>					
Stem	15.4	678	669 (2.1)	43.7	49.6 (13.3)
Branch	33.8	856	805 (2.9)	28.7	49.3 (13.1)
<b>Maple</b>					
Stem	11.8	597	598 (2.2)	55.6	55.2 (8.7)
Branch	16.9	692	678 (0.8)	43.1	51.5 (11.8)
<b>Scots pine</b>					
Stem	15.3	596	586 (10.2)	50	56.6 (20.8)
Branch	20.9	518	492 (3.9)	23.4	31.8 (9.3)

Note: Coefficients of variation (%) in parentheses.  
MC = moisture content.

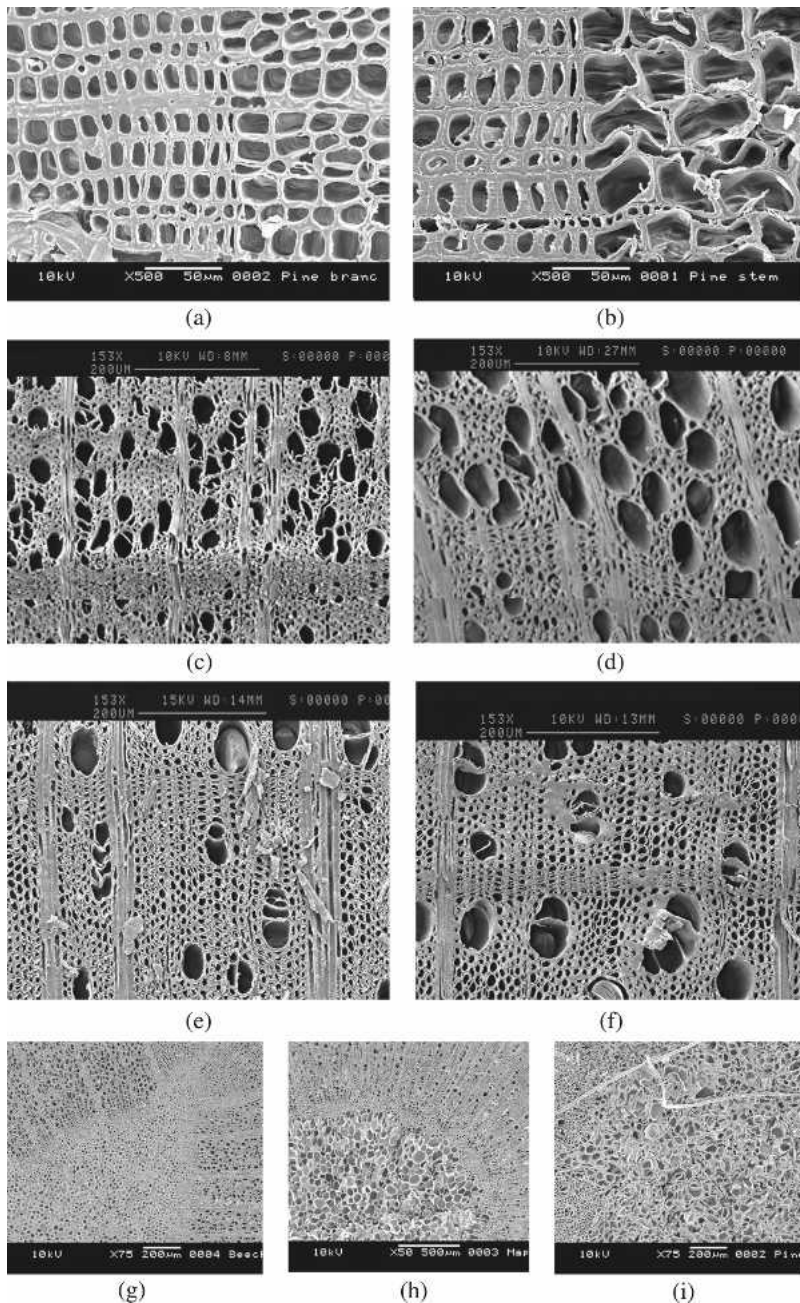


Figure 1. Transverse SEM micrographs: (a–b) Scots pine (magnification 500 $\times$ ) branch wood and stem wood, respectively; (c–d) Beech (magnification 153 $\times$ ) branch wood and stem wood, respectively; (e–f) Maple (magnification 153 $\times$ ) branch wood and stem wood, respectively; (g–i) Branch wood containing the pith and tissue around it of beech (magnification 75 $\times$ ), maple (magnification 50 $\times$ ), and Scots pine (magnification 75 $\times$ ), respectively.

ing in that branch wood specimens bent under compression rather than failing in “shearing rupture” (according to ASTM 1997) as the stem

specimens did. The trend for bending may also have been a consequence of the higher MC of the branch wood specimens.

### Static Bending Strength

The MOE of stem wood obtained experimentally (Table 2) showed similar results as the literature for Scots pine, 11.71 GPa compared with 11.76 GPa found by Filipovici (1965), whereas for maple, it was higher, 10.76 GPa compared with 9.40 GPa found by Lavers (1983).

Table 2 shows that the MOE of maple branch wood was approximately 85% of that of maple stem wood. As stated before, branch wood contains shorter fibers and a higher proportion of vessels and longitudinal parenchyma, which are characterized by thinner walls, than stem wood. These differences are likely to cause branch wood to be less stiff in bending than stem wood. In compensation, maple branch wood frequently contains tension wood, which increases tensile strength of areas subjected to tensile stresses. This may explain the more extended shear failure of maple branch wood than stem wood corresponding to a higher resistance to local tensile stresses. The type of failure for both maple branch and stem specimens was as “simple tension” as described by ASTM (1997).

In contrast, the MOE of Scots pine branch wood was only approximately 28% of the stem wood. The branch wood specimens contained compression wood on the tension side as well as juvenile wood, which caused a failure pattern characterized in ASTM (1997) as “brash failure.” This result supports the statement of Hakkila (1989) that compression wood decreases the MOE and fails brashly. The results for Scots pine branch wood appear similar to those of Pearson (1988) as cited by Larson et al (2001), who found that

the MOE of juvenile Scots pine was only 37% of that of mature wood. The higher bending strength of Scots pine stem wood may be associated with the type of failure characterized by ASTM as “splintering.”

The MOE of maple branch wood was 2.8 times greater than of Scots pine branch wood. As with compression strength, no correlation was observed between density and MOE for branch wood. This observation is similar to that of Adamopoulos et al (2007), who attributed the lower strength of juvenile wood of black locust vs mature wood to its anatomical properties rather than density.

The MOR obtained experimentally for stem specimens was very close to the values found in the literature: 106.2 MPa for maple was between the values obtained by Lavers (1983), 99 MPa, and Filipovici (1965), 109.7 MPa; Scots pine with 99 MPa was similar to 98 MPa found by Filipovici (1965).

The MOR of maple branch wood was approximately 10% higher than that of maple stem wood, which may be linked to the higher density of the branch wood (Table 2). In contrast, the MOR of Scots pine branch wood was only approximately 55% of that of Scots pine stem wood, which in this case may be associated with the higher density of the stem wood. The orientation of the test specimen, with the compression wood at the tension edge and the pith at the compression edge, may have been critical in determining the results of the test. The results seem similar to those of Pearson (1988) as cited by Larson et al (2001), who found that the MOR for

Table 2. *Experimental results for bending strength (MOR) and modulus of elasticity (MOE).*

Species and wood type	Moisture content at testing (%)	Density uncorrected (kg/m <sup>3</sup> )	Density corrected for 12% MC (kg/m <sup>3</sup> )	MOR uncorrected (MPa)	MOR corrected for 12% MC (MPa)	MOE uncorrected (GPa)	MOE corrected for 12% MC (GPa)
<b>Maple</b>							
Stem	10	614	620 (1.6)	115.5	106.2 (11.5)	11.20	10.76 (4.9)
Branch	16.6	713	700 (3.2)	99.3	117.5 (9.9)	8.41	9.27 (8.4)
<b>Scots pine</b>							
Stem	14.2	594	588 (7.8)	91.1	99 (16.3)	11.20	11.71 (21.6)
Branch	37.5	566	492 (13.5)	32.4	55.8 (12.8)	2.12	3.32 (16.9)

Note: Coefficients of variation (%) in parentheses.  
MC = moisture content.

Scots pine juvenile wood was 52% of that of mature wood. The MOR of maple branch wood was twice that of Scots pine and for both maple branch and stem wood was directly linked with specimen density.

There was greater plasticity in bending of branch wood than stem wood for both species, as measured by the maximum deflection. The maximum deflection of maple branch wood was 1.86 times that of stem wood, whereas for Scots pine, it was 2.76 times higher. It is not clear to what extent this is the result of differences between branch and stem wood rather than resulting from the higher MC of the branch wood.

### **Microscopic Appearance of Branch and Stem Wood**

Micrographs of transverse and longitudinal sections showed that all cell diameters, wall thicknesses, and lumen diameters of fibers and vessels (hardwoods) and tracheids (Scots pine) were smaller in branch wood than in stem wood. This is in agreement with findings in the literature presented previously. Vessels and medullary rays are more numerous in branch wood than in stem wood of maple and beech. Figures 1a–f are comparative images of branch and stem wood for Scots pine, beech, and maple.

The density of the branch wood of maple and beech was higher than that of the stem wood (Tables 1 and 2), which appears to be in agreement with Fegél (1941) and Kollmann and Côté (1968). This is probably from the smaller cell lumina in branch wood than stem wood. However, all branch specimens contained pith (Fig 1g–i). For Scots pine, the branch wood density was substantially lower than the stem wood density.

Branches normally contain juvenile wood around the pith. In softwoods, the juvenile wood has different physical properties than mature wood, but the differences are less pronounced in hardwoods (Zobel and Sprague 1998; Bao et al 2001). The lowest density wood in Scots pine is produced near the pith of the tree, where the

growth rings are usually wide with relatively small proportions of latewood, whereas in broad-leaved trees, the highest density wood is usually produced near the pith (Kollmann and Côté 1968). Orsler et al (1972) found the density of juvenile wood significantly lower in Scots pine than that of its mature wood. It should be noted that the proportion of juvenile wood in branches depends on the age of the tree and of the branches. Zobel and Sprague (1998) found that 15-yr-old loblolly pines have approximately 85% of their volume in juvenile wood, whereas 40-yr-old trees have only 19%. Because the age of the tested Scots pine branches was approximately 18 yr, its proportion of juvenile wood may have been important and thereby decreased branch density.

### **CONCLUSIONS**

Because branch wood is a secondary resource under investigation as an alternative to stem wood, some mechanical properties were tested—compression parallel to the grain, MOE, and MOR—and compared with those of stem wood.

The MOE and compression strength of maple branch wood were slightly lower than those of the stem wood, maple MOR was slightly higher for branch wood, and beech compression strength was similar for branch and stem wood. However, the MOR and compression strength of Scots pine branch wood were approximately one-half those of stem wood, whereas the MOE was approximately one-third.

Maple branch wood had similar compression strength as beech branch wood, but compared with Scots pine, branch wood was 60% stronger in compression, had double the MOR, and almost triple the MOE.

The poor performance in mechanical tests of Scots pine branch wood compared with maple and beech may be attributed to the presence in Scots pine of compression and juvenile wood.

Branch wood had a higher density than corresponding stem wood, except for Scots pine. No



correlation was observed between branch density and mechanical strengths except for MOR, which increased with density.

For all species and tests, branch wood exhibited greater plasticity in its behavior than stem wood, but this may be attributed, at least in part, to the higher MC of the branch wood.

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