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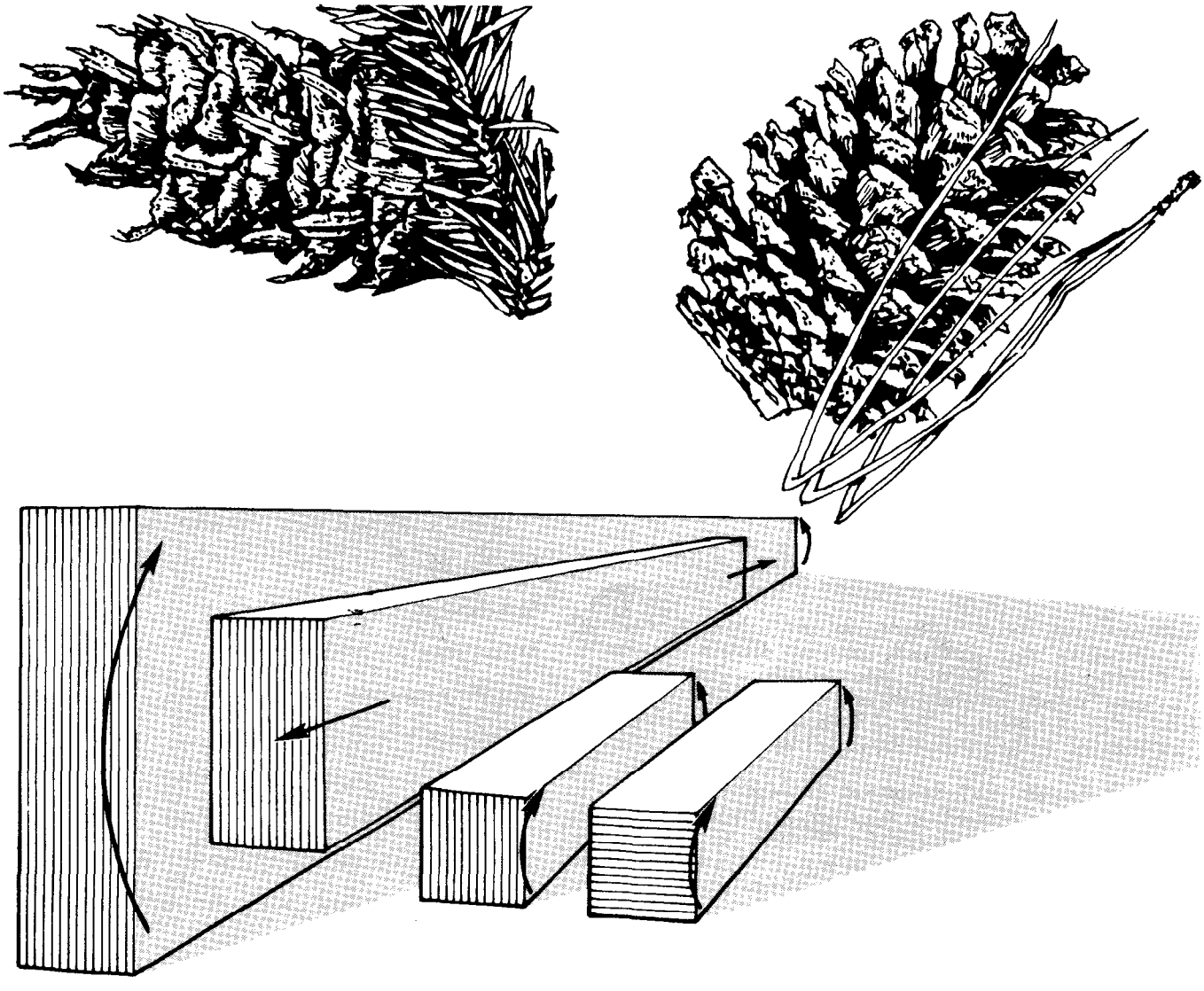
Effect of Various Proportions of Juvenile Wood on Laminated Veneer Lumber

David E. Kretschmann
Russell C. Moody
Roy F. Pellerin
B. Alan Bendtsen
James M. Cahill
Robert H. McAlister
Donald W. Sharp



Abstract

To satisfy the increased demand for forest products while addressing environmental concerns, much of the future timber supply will be from managed plantations of rapidly grown trees. These trees will be harvested in short-rotation cycles and will contain large quantities of juvenile wood. This report discusses the influence that Douglas-fir and Southern Pine juvenile wood has on veneer grading and its implications on structural performance of laminated veneer lumber (LVL). Veneer blocks cut from fast-grown Douglas-fir and Southern Pine lumber were examined and divided into three zones based on age: mature, transition, and juvenile. Veneer peeled from these zones was tracked through the peeling, drying, and grading process. The LVL made of various proportions of juvenile and mature veneer was tested in flatwise bending, edgewise bending, and tension. Results of this study suggest that two forms of nondestructive grading techniques are capable of placing juvenile material in a low-grade classification. Also, during veneer preparation, the low strength of juvenile wood veneer in both species led to a significant increase in breakage during handling when compared to normal veneer losses. The LVL manufactured in this study showed a predictable decrease in strength and stiffness with increased juvenile wood content. The ratio of juvenile to mature material in the same nondestructive grade for Southern Pine and Douglas-fir was approximately 0.8 for strength and stiffness. This study demonstrates that an LVL-type product with structural integrity using significant quantities of juvenile wood veneer is possible but will result in products with design values lower than those of mature wood. The amount of juvenile wood acceptable to manufacturers will depend on the economic consideration of each manufacturer.

Keywords: Juvenile wood, laminated veneer lumber, Douglas-fir, Southern Pine, proportions, stiffness, tension, bending

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Research Highlights

To satisfy the increased demand for forest products while addressing environmental concerns, much of the future timber supply will be from young-growth trees from managed plantations. These trees will be harvested in short-rotation cycles and will contain large quantities of juvenile wood. This report discusses the influence of Douglas-fir and Southern Pine juvenile wood on veneer grading and its implications on structural performance of laminated veneer lumber (LVL).

The objectives of this study were to determine the influence of varying the proportion of juvenile wood on mechanical properties, examine the effectiveness of nondestructively sorting juvenile veneer, compare the warp characteristics of proposed LVL lamination schemes, and conduct a preliminary economic analysis of increasing juvenile wood content in LVL.

The Douglas-fir veneer source represents a lower bound on the quality of the veneer sources that are anticipated in the future, and the Southern Pine veneer material represents the typical quality expected in fast-grown Southern Pine veneer supplies. Veneer blocks cut from fast-growing Douglas-fir and Southern Pine were examined and divided based on age into three zones: mature, transition, and juvenile. Veneer peeled from these zones was tracked through the peeling, drying, and grading process. The LVL made of various proportions of juvenile and mature veneer was manufactured and tested in 2 by 2 flatwise bending, 2 by 2 edgewise bending, 2 by 4 tension, and 2 by 8 edgewise bending.

The results of this study indicate the following:

- It is possible to manufacture an LVL type product with structural integrity using significant quantities of juvenile wood veneer, but design values would be lower than those currently in use.
- LVL stiffness properties for Douglas-fir and Southern Pine reacted similarly to the inclusion of juvenile material. However, strength results for Douglas-fir were much more affected by the inclusion of juvenile material than was Southern Pine.
- A significant difference exists between material manufactured with mature or juvenile material having the same nondestructive grade.
- The two techniques of nondestructive grading used in this study are capable of indicating the low quality of veneer sheets and placing them into low grades. However, these techniques are unable to differentiate between low-grade mature and juvenile material.
- No difference in warping characteristics existed between the different layups investigated.
- The amount of juvenile wood acceptable to manufacturers will be heavily influenced by the manufacturer's production costs and performance requirements. Compared to mature wood, the falldown rate of veneer containing juvenile wood nearly doubled.

As a result of this study, areas for improvement in the manufacturing process of LVL are suggested. An improved method is needed to sort the juvenile wood material prior to processing. Also, improved methods to dry and handle juvenile wood veneer are necessary to reduce the large falldown expected. If the high amount of resin, pitch, and tar found in this study are typical of Southern Pine juvenile wood, improved manufacturing techniques to handle anticipated difficulties will have to be developed. Finally, accurate estimates are needed of how much young-growth material will enter the market place.

Terminology

Billet Large sheet of material either 2 or 4 ft (0.6 or 1.22 m) wide composed of a number of parallel laminated plies of veneer sheets

- 1mE Billet Billets made entirely of 1mE tight band veneer
- 2m Billet Billets made entirely of 2m veneer
- 2j Billet Billets made entirely of 2j veneer
- D Billet Billets with exterior plies of 1mE tight band mature veneer and various proportions of low-grade core veneer (2j or 2m)
  - D25j D Billets with 25% low-grade juvenile wood core veneer
  - D50j D Billets with 50% low-grade juvenile wood core veneer
  - D50m D Billets with 50% low-grade mature wood core veneer
  - D57j D Billets with 57% low-grade juvenile wood core veneer
  - D57m D Billets with 57% low-grade mature wood core veneer
  - D75j D Billets with 75% low-grade juvenile wood core veneer

Block Short subsection of a log that is conditioned and placed in a lathe for peeling into veneer

Blow Heat delamination

Butt Block Block from the bottom or butt of the tree

CFD Cumulative frequency distribution

Falldown Veneer that does not make it through the manufacturing process

Fb Allowable bending strength

Log-run Logs as they arrive at the mill yard

LVL Laminated veneer lumber, material made by parallel lamination of veneers into thicknesses common to solid sawn lumber

M C Moisture content

MOE Modulus of elasticity

MOR Modulus of rupture

NDE Nondestructive evaluation

R Remanufactured specimens made from 1mE exterior and 2j core veneer

- R25j Remanufactured specimens with 25% 2j core veneer
- R50j Remanufactured specimens with 50% 2j core veneer
- R75j Remanufactured specimens with 75% 2j core veneer

Top Block Any block above the butt block

UPT Ultrasonic propagation time

UTS Ultimate tensile stress

VGS Veneer grading system

2 by 2 Test specimens having a cross section of 1.5 by 1.5 in. (38 by 38 mm); also referred to as small bending specimens

2 by 4 Test specimens having a cross section of 1.5 by 3.5 in. (38 by 89 mm); also referred to as tension specimens

2 by 8 Test specimens having a cross section of 1.5 by 7.5 in. (38 by 191 mm); also referred to as large bending specimens

1m Mature veneer sheets that are greater than the preselected grading cut-off

2m Mature veneer sheets that are less than the preselected grading cut-off

1mE Material selected from the subset of 1 m veneer that is estimated to have a stiffness of 2.0×10^6 lb/in^2 $\pm$ 0.2×10^6 lb/in^2; also referred to as tight band material

1t Transition veneer sheets that are greater than the preselected grading cut off

2t Transition veneer sheets that are smaller than the preselected grading cut off

1j Juvenile veneer sheets that are greater than the preselected grading cut off

2j Juvenile veneer sheets that are less than the preselected grading cut off

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David E. Kretschmann, Research General Engineer
Russell C. Moody, Supervisory Research General Engineer
Forest Products Laboratory, Madison, Wisconsin

Roy F. Pellerin, Professor
Washington State University, Pullman, Washington

B. Alan Bendtsen, Supervisory Forest Products Technologist (retired)
Forest Products Laboratory, Madison, Wisconsin

James M. Cahill, Research Forester
USDA Forest Service, Pacific Northwest Station, Portland, Oregon

Robert H. McAlister, Research Forester
USDA Forest Service, Southeastern Station, Athens, Georgia

Donald W. Sharp, System Performance Engineer
Trus Joist/MacMillan Corp., Boise, Idaho

Introduction

Laminated veneer lumber (LVL) is a high-performance product that was developed in response to a need for increased strength and stiffness, good dimensional stability, and low variability in highly engineered structural components (Forest Products Laboratory 1987). To ensure the high-performance characteristics of LVL, some manufacturers use nondestructive evaluation (NDE) grading techniques to sort low-stiffness veneer from LVL stock. As the forest products industry moves toward a rapidly grown, young wood resource, it is suspected that the amount of veneer rejected by NDE grading techniques will increase because of the predominance of juvenile wood. A thorough understanding of the properties and problems associated with manufacturing juvenile wood is needed, so that processing procedures can be modified to utilize this resource without sacrificing high-performance characteristics. The objectives of this study were the following:

a. Determine the influence of varying the proportion of juvenile wood on the mechanical properties of an LVL product.

b. Examine the effectiveness of nondestructively sorting juvenile veneer.

c. Compare the warp characteristics of proposed LVL lamination schemes.

d. Conduct a preliminary analysis on the cost of increasing juvenile wood in LVL products compared to the cost of current LVL and solid-sawn lumber products.

Background

The low strength and stiffness values of juvenile wood are a concern in North America and overseas. Summaries of the initial work on the properties of juvenile wood are found in Bendtsen (1978, 1986). Since Bendtsen's research, a significant amount of literature has been added on the effect of juvenile wood on clear wood and dimension lumber. However, the same type of research on LVL has been limited.

Clear Wood

Work by Boone and Chudnoff (1972) and Bower and others (1976) on plantation Caribbean pine drew attention to the properties of plantation material. Both works reported that clear wood plantation material had less than 50% of expected specific gravity, bending strength, and stiffness for virgin timber of the same species. At the same time, research by Pearson and Gilmore (1971) on clear wood of loblolly pine clearly demonstrated that the problem was juvenile wood, not plantation wood. Their research found juvenile wood to have substantially lower values of mechanical properties than did mature wood. This accounts for the subordinate properties of plantation wood when compared to that of old-growth timber.

Intricate work by Bendtsen and Senft (1986) demonstrated that properties for loblolly pine and eastern cottonwood are important to solid wood utilization. These woods are subpar in the first-formed annual ring, improve dramatically each year in the early juvenile wood zone, and improve more gradually during the latter years. Early juvenile wood (juvenile wood closest to the pith) is distinctly of poorer quality than later juvenile wood. Properties that influence mechanical behavior include fibril angle, cell length, and specific gravity-the latter a composite of the percentage of late wood, cell wall thickness, and lumen diameter. Bendtsen and Senft (1986) results suggest that the ratios of juvenile wood to mature wood for strength and stiffness range from 0.59 to 0.78 and 0.47 to 0.62, respectively. The excessively high micro-fibril angle in juvenile wood causes excessive longitudinal shrinkage that may be more than 10 times that of mature wood. Compression wood and spiral grain, both more prevalent in juvenile wood than in mature wood, also contribute to excessive longitudinal shrinkage.

Factors that affect transition to mature wood were also investigated. For Southern Pine, the length of juvenile growth in years was shown to be dependent on geographic location (Clark and Saucier 1989). The length of juvenility was also shown to differ from species to species. For example, Southern Pine can have a range of juvenility from 6 to 14 years (Bendtsen and Senft 1986, Clark and Saucier 1989). Red pine is reported to have a juvenile wood transition from 14 to 17 years (Smith and others 1991). Douglas-fir is considered to have a gradual transition that ends after 18 to 23 years (Di Lucca 1989, Megraw 1985).

Solid-Sawn Lumber

The potential problem of low mechanical property values in juvenile wood structural lumber was perhaps first observed by Koch (1966) while involved in research to develop straight studs from Southern Pine veneer cores. He found that most of these studs had lower bending strength and stiffness than was expected for Southern Pine studs in general. Additional evidence of property reduction of lumber as a result of juvenile wood was suggested by Moody (1970) when evaluating finger joints in Southern Pine lumber, No. 1 or Better. Moody noted that the strength and stiffness of control specimens with pith-associated materials were respectively 30% and 10% less than that of material not containing pith.

Since these first indications of juvenile wood effects, much international work has been done on how juvenile wood properties compare to mature wood properties for full-size lumber. In the United States, several studies evaluated the influence of juvenile wood on the mechanical properties of Douglas-fir and Southern Pine dimension lumber (Bendtsen and others 1988, Biblis 1990, Fahey and others 1991, Kretschmann and Bendtsen 1992, MacPeak and others 1990, Pearson 1984). In New Zealand, work by Bier and Collins (1984) and Tsehaye and others (1991) looked at Radiata pine. In Canada, Douglas-fir was studied by Barrett and Kellogg (1989).

These studies indicate that lumber cut from the juvenile wood zone of logs has the potential to be significantly less in strength and stiffness than does lumber from the mature wood zone; the magnitude of reductions varies by species. For example, ratios of mature to juvenile wood material for Douglas-fir modulus of rupture (MOR), ultimate tensile stress (UTS), and modulus of elasticity (MOE) range from 0.62 to 0.97, 0.62 to 0.97, and 0.45 to 0.75, respectively, and ratios for Southern Pine MOR, UTS, and MOE range from 0.54 to 0.74, 0.51 to 0.77, and 0.45 to 0.59, respectively. The magnitude of reductions in strength or stiffness also seems to vary by and within species. For example, juvenility seems to have a greater influence on Southern Pine than on Douglas-fir. For Douglas-fir, the MOE ratio of all-mature to all-juvenile material is less influenced by juvenile wood than is MOR. For Southern Pine, the magnitude of the reduction in the ratio of juvenile to mature material is similar for strength and stiffness (Bendtsen and others 1988, Kretschmann and Bendtsen 1992).

Laminated-Veneer Lumber

In the literature by Biblis and Mercado (1991), Braun and Moody (1977), Jung (1982), Moody (1972), Stump and others (1981), and Youngquist and others (1984), no effort was made to identify the differences between juvenile and mature material. However, one study investigated the difference between juvenile and mature bending and compression strength of LVL made from

larch (Jo and others 1981). This study indicated that specimens of 100% juvenile wood had a ratio of juvenile to mature wood compression strength of 0.9 and bending strength of 0.7.

In summary, intricate studies of clear wood have produced a thorough understanding of the physical property changes that occur as a result of juvenile wood. Several studies completed on solid-sawn lumber have provided a good understanding of how juvenile wood affects the mechanical properties of solid-sawn lumber. However, the information available on the effect of juvenile wood in reconstituted wood products is minimal.

Experimental Methods

This study investigated the effects of mature and juvenile wood on LVL made of Douglas-fir and a mixture of slash and loblolly pine. The study involved the cooperation of several institutions for study plan development, material selection and preparation, manufacture of LVL billets, and evaluation.

Material Selection and Preparation

Log Procurement and Identification

Through the cooperation of the USDA Forest Service and the forest products industry, a careful selection process was used to ensure that the logs to be peeled were from rapidly grown trees. The logs were obtained from the inventory of cooperating veneer mills. As previously described, the transition from juvenile wood to mature wood can vary from geographic location and species. We decided that the ages that would best represent the beginning and end of the transition to mature material would be 12 and 18 years for Douglas-fir and 8 and 12 years for Southern Pine (Fig. 1).

The Douglas-fir sample blocks were selected from logs cut from one 53-year-old stand located in the coastal mountains of Oregon with a site index (50 year) of 134 (King 1966). Stocking throughout the stand history was light. Trees had characteristics often associated with open-grown trees-large persistent limbs varying in size from 1 to 2-1/2 in. diameter and wide, coarse annual growth rings. (See Table 1 for metric conversion.) Logs were selected log-run until we had a sufficient number to generate the volume of juvenile wood required to make the LVL billets. Diameter measurements were taken on both ends of 338 blocks. Average diameters at 12 and 18 years were 8.4 and 11.8 in., respectively. The growth rate of this material averaged 2.9 rings per inch. We emphasize that logs were sampled from one, relatively fast-grown stand and do not necessarily represent the average quality of the Douglas-fir young-growth resource in the Pacific

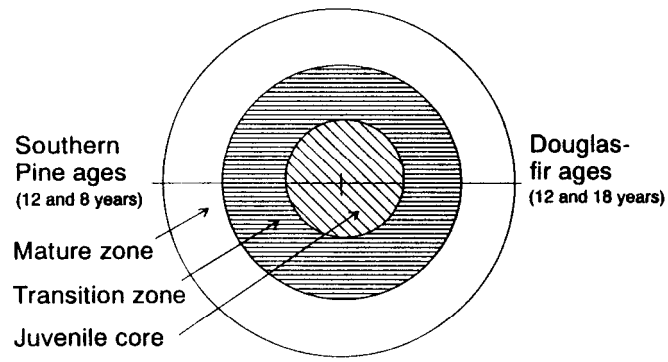

Figure 1–Zones of material *tracked in veneer.*

Table 1—SI conversion factors

English unit	Conversion factor	SI unit
foot (ft)	0.3048	meter (m)
inch (in.)	25.4	millimeter (mm)
pound per square inch (lb/in^2) (stress)	6,895	Pascal (Pa)
pound-force (lbf)	4.448	newton (N)
degree Fahrenheit (°F)	$t_{°C} = \frac{t_{°F} - 32}{1.8}$	Celsius (C)

Northwest. In general, we felt that the Douglas-fir logs used would best be characterized as low-quality material and expected to represent a lower bound of quality. The blocks were conditioned using typical industry schedules.

The Southern Pine material consisted of 416 blocks of a mixture of slash and loblolly pine selected from yard inventory of a plywood plant in Cedar Springs, Georgia. The material was from 20- to 30-year-old trees. Logs were selected at the debarker from log-run and cut into blocks. We selected enough material to make one charge of the plant's conditioning facilities. Fast-grown, cylindrical, even-growth-rate logs were selected. The growth rate of this material averaged 2.8 rings per inch. The mixture of blocks was approximately two top for each butt block. The blocks selected were conditioned in a steam vat using a typical industry schedule.

Veneer Peeling, Drying, and Handling

The veneer sheets were divided into three categories based on the annual growth rings: an outer mature zone, a transition zone, and a juvenile core (Fig. 1). The positions at which the bolts had 8 and 12 annual rings in the south and 12 and 18 annual rings in the

west were used as cut-off points to separate the veneer into the mentioned categories.

The Douglas-fir material was processed at a veneer mill in Independence, Oregon. Mill equipment allowed each veneer ribbon to be painted to differentiate between mature, transition, and juvenile core as each block was being peeled. This was accomplished by using the rings marked at the end of each bolt. The mature zone, transition zone, and juvenile core categories were marked using portable equipment on the top surface of the veneer with dye as it was peeled off the bolt. The dye markings were triggered by a person located near the veneer lathe who was in a position to observe the end of the veneer bolt as it was peeled. When the knife passed through the ring marked on the bolt, the appropriate dye was triggered. Of the 338 blocks selected, we peeled 182 8-ft blocks, from which approximately 1,440 sheets of juvenile, 1,100 sheets of transition, and 1,800 sheets of mature 1/10-in. veneer were produced. The 182 blocks were peeled to the smallest possible core (approximately 5 in.) to maximize the juvenile wood yield and include as much early juvenile wood as possible. Note that the lathe speed had to be reduced by one-third to peel the Douglas-fir juvenile wood to a veneer thickness of 1/10 in.

After peeling, the veneer was shipped to an LVL plant in Junction City, Oregon, for drying. The Douglas-fir juvenile wood appeared to dry quicker than did the mature veneer. To compensate for this, the veneer dryers were run at a low-temperature, high-speed redry schedule while processing the juvenile veneer.

The Southern Pine veneer was peeled in a normal process to 1/8 in., with no reported adjustments for the juvenile wood. The 416 blocks were peeled to the smallest possible core (3.5 in.) to maximize the juvenile wood yield and include as much early juvenile wood as possible. Prior to conditioning and peeling the veneer, diameters at 8 years were measured on 50 bolts in the yard to obtain an estimated average juvenile wood core diameter of 6 in. The average outside diameter for the bolts was 12 in.

Because of available equipment at the Southern Pine mill, the marking of the veneer was initiated when the bolt diameter reached 6 in. A single-dye spraying unit was located one and one-half veneer sheets from the lathe knife. When marked, the veneer traveled through an in-line dryer. Drying was completed using a typical drying schedule with no adjustments for juvenile wood. After emerging from the dryer, the veneer ribbon came past the clipper and was cut into sheets. Each sheet was numbered sequentially using dye as it emerged from the clipper. The material without dye was considered to be mature veneer. The first two veneer sheets having a dye mark were considered transition material, and the remaining sheets were judged to be juvenile core material. The veneer collected was shipped dry to an LVL plant in Natchitoches, Louisiana.

Grading of Mature and Juvenile Veneer

Veneer sheets were sorted and graded into two categories (high and low) using nondestructive mechanical techniques. The grade distribution for the various zones of veneer from this particular source of material was not known prior to the grading process. An exploratory grading run of the veneer sheets from the veneer mill for each area established an estimated distribution of the NDE parameter for juvenile and mature wood sheets. To investigate the effectiveness of current grading techniques on juvenile wood material, we set up an NDE grading parameter cut-off point that would allow low-grade mature wood in the overlapping region between the juvenile and mature wood distributions. The remaining veneer sheets from the veneer mill source were graded based on this cut-off point.

The grading process resulted in seven grade classifications of the veneer sheets: 1m, 1mE, 2m, 1t, 2t, 1j, and 2j (Fig. 2). The subset of grade 1m veneer, designated grade 1mE, came from a tight band with an estimated MOE of 2.0×10^6 lb/in^2 ±5%. The tight band of MOE was meant to eliminate the high and low tails of mature material from the mature zone distribution. Low-strength core material and some high-strength mature zone material could be dominated by the high-strength material, thus making the effect of the juvenile wood material unclear. Therefore, the value of 2.0×10^6 lb/in^2 was selected because it represented a common stiffness that is produced by LVL manufacturers.

Grading Effectiveness

The Douglas-fir veneer was graded on an ultrasonic veneer grader. After running a test batch of trial veneer, an ultrasonic propagation time (UPT) of 550 μs was selected as the grading cut-off point. The juvenile material consistently had a longer UPT (implying low grade) than did the mature material (Fig. 3). We also observed that juvenile veneer produced four times as many grading signal failures than did the mature veneer. These observations suggest that the threshold levels for the grading signals should be further investigated as a means of more effectively grading juvenile material. A random sample indicated that the relative density of Douglas-fir juvenile veneer was approximately 20% less than that of normal Douglas-fir veneer.

The Southern Pine veneer was graded by a proprietary veneer grading system (VGS) that incorporated UPT

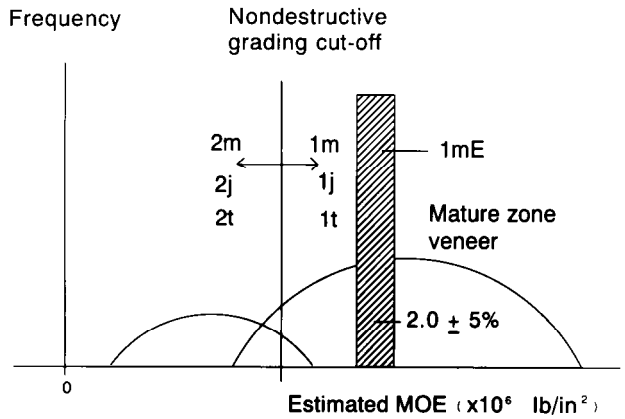

Figure 2–Grade designations for nondestructive evaluation techniques to sort veneer.

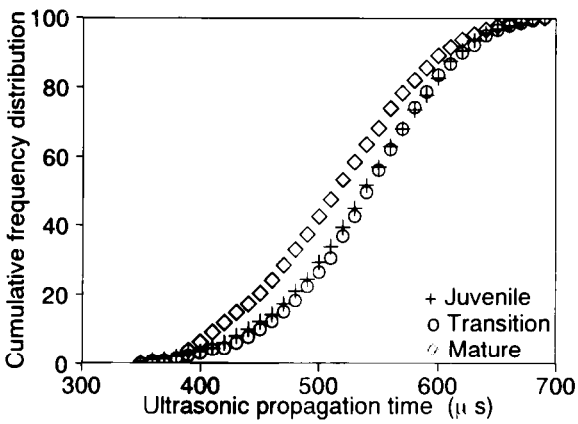

Figure 3–Grading results for Douglas-fir veneer using an ultrasonic pulse technique.

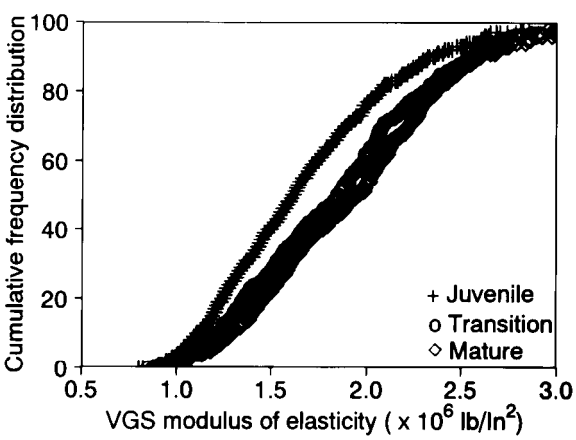

Figure 4–Grading results for Southern Pine veneer using the VGS.

and a density measurement into a grading model. After running the trial grading run of the juvenile and mature veneer, the cut-off point was selected to be a VGS grade of 1.8×10^6 lb/in^2. Again, a clear difference in the grading machine distributions was noted between the grading results of the juvenile veneer and the mature veneer (Fig. 4) with the transitional veneer falling between. The VGS predicted an average MOE of about 1.67, 1.85, and 1.93×10^6 lb/in^2 for the juvenile, transition, and mature veneer, respectively. The juvenile veneer was 16% less than the normal 2.0×10^6 lb/in^2 for the plant. The relative density of Southern Pine was determined by the VGS to be about 5% less than that of a typical mill supply of veneer.

The nondestructive techniques applied in the western and the southern United States have the capability of placing juvenile material in a low grade with low stiffness values. The VGS machine, using both UPT and density as predictors, was successful in assigning grades to the processed veneer. The ultrasonic veneer grading machine, having a high frequency of signal failures on juvenile material, also suggests that this machine may be used as an indicator of low-quality juvenile material.

The juvenile wood veneer in both species had a significant increase in breakage during handling compared to that of normal mill veneer. In fact, the drying and grading falldown was nearly double that of the mill's normal veneer run.

Manufacture of LVL Billets

Manufacturing for both species was in accordance with normal procedures of the LVL manufacturer for the 1.5-m-thick billets produced. A continuous hot press produced the LVL from multiple plies using 8-ft-long veneer sheets with 2-in. overlapping veneer joints and an exterior-type (phenol formaldehyde) adhesive spread on one side. The glue was applied at a spread rate of 40 to 45 lb/ft^2 on Southern Pine and 30 to 35 lb/ft^2 on Douglas-fir.

Layup

Three grades of veneer sheets were used to manufacture the billets: tight band 1mE, low-grade mature 2m, and low-grade juvenile 2j. Four types of billets were manufactured from the three grades (1mE, 2m, 2j, and D). The first type of billets (1mE) was made of 1mE mature wood veneer from only the peeled veneer mill source that had been sorted into a tight range of MOE (2.0×10^6 lb/in^2 ± 5%). The second type of billets (2m) was made from grade 2m mature zone veneer. The third type of billets (2j) was made from 2j grade juvenile core veneer. The fourth type of billets (D) was

made from a mixture of 1mE grade veneer for external plies and juvenile 2j grade or 2m mature grade veneer as core (Figs. 5a,b). When the mature wood from the veneer mill source was exhausted, veneer that had been sorted into the same tight range of MOE from plant stock was used to fill in the manufacture of the required number of billets. The plant stock used to fill was at most 30% of the 1mE material used.

Because of material and equipment restrictions, the method of LVL manufacture differs in the western and southern United States. The manufacturing techniques require two billet lay-up schemes and billets sizes.

Billets of Douglas-fir were defined to be 2 ft wide, 12 ft long, and 1.5 in. thick. The billets were manufactured from 16 2-ft-wide by 8-ft-long by 1/10-in.-thick veneers oriented parallel to the lengths of the billets in a continuous hot press (Fig. 5a). A total of 118 12-ft billets were manufactured: 19 each of class 1mE and class 2j billets, 16 of class 2m, and 16 each of four types of class D (D25j, D50j, D50m, or D75j, i.e., 25%, 50%, and 75% low-grade core).

Billets of Southern Pine were defined to be 4 ft wide, 12 ft long, and 1.5 in. thick. The billets were manufactured from 14 1/8-in. veneers oriented parallel to the lengths of the billets in a continuous hot press (Fig. 5b). A total of 32 billets were manufactured in the South: 6 class 1mE and class 2m, 8 class 2j, and 6 each of two types of class D (D57j and D57m, i.e., 57% low-grade core).

Concerns

No difficulty was encountered in the manufacturing of the Douglas-fir billets. The material handled and behaved similarly to typical Douglas-fir veneer supplies. However, a significant number of the Southern Pine billets containing juvenile veneer were damaged by heat delaminations or blows. The high frequency of blows was attributed to primarily a high pitch content and elevated moisture content in the juvenile wood veneer. Posey and Robinson (1969) observed an increase in extractive content near the pith, depending on the age of the tree. The result was that a considerable number of potential specimens had to be discarded because of blows to the center portion of the billets.

Specimen Preparation

Appendix A gives the scheme for the specimen preparation and remanufacture. The 12-ft billets (118 Douglas-fir and 32 Southern Pine) were ripped into 12-ft-long strips of specified widths at the LVL plants. The strips of material were shipped to the testing laboratory at Washington State University.

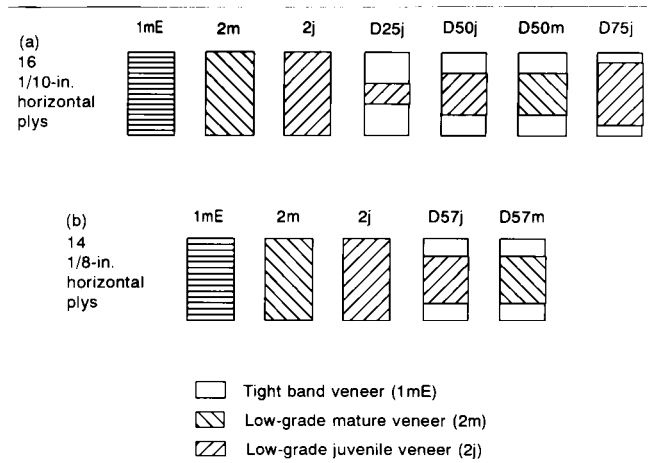

Figure 5–Layups for LVL billets produced with (a) Douglas-fir and (b) Southern Pine.

Prior to testing, all strips from the manufacturing plants were conditioned to equilibrium in a climate controlled room under 65% relative humidity and 75°F (approximately 12% equilibrium moisture content). After conditioning, the strips were cut to produce matched 1.5- by 1.5- by 30-in. (2 by 2) edgewise and flatwise small bending specimens, 1.5- by 3.5- by 96-in. (2 by 4) tension specimens, and 1.5- by 7.4- by 144-in. (2 by 8) edgewise large bending specimens from each billet. This was done according to a cutting pattern that would maximize the variability between specimens that were cut from the same billet while using all the material produced.

The remaining specimens were 2 by 8 bending specimens made of one 2j core strip glued between two mature 1mE strips, referred to as remanufactured specimens (R) (Fig. 6). The Douglas-fir strips designated for remanufacture were glued together to form one of the three types of 2 by 8 bending specimens: R25j, R50j, or R75j (25%, 50%, and 75% 2j core). The core and exterior veneer sheets were oriented vertically. The Southern Pine specimens had a considerable amount of material that had to be discarded as a result of delamination blows in the center of the billets. This resulted in an inadequate number of specimens for the initial test matrix. Therefore, we used the strips cut for remanufacture to supplement the remaining test material.

Evaluation

Test results were to be obtained for moisture content, specific gravity, tensile and bending strength, and stiffness for the various specimens produced from the four types of billets. The following tests were conducted in accordance with ASTM D 2395 and D 4761 (1991):

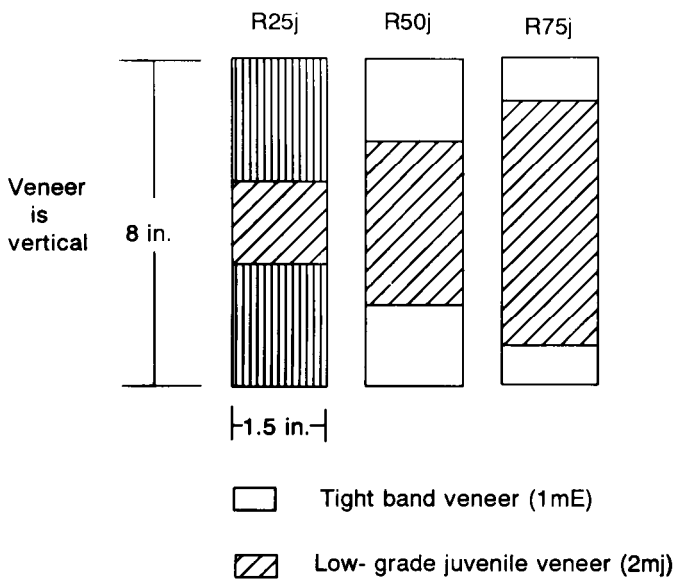

Figure 6–Remanufactured 2 by 8 specimen layup, veneer sheets running vertical.

a. Edgewise and flatwise flexure of 2 by 2 LVL with third-point loading over a span to depth ratio of 17:1. For all bending specimens, the information was measured, recorded, or calculated for billet type, cross-section dimension, modulus of rupture (MOR), modulus of elasticity (MOE), moisture content (MC) at time of test, and failure code.

b. Tension of 2 by 4 LVL with an approximate span of 48 in. For tension tests, information was measured, recorded, or calculated for billet type, cross-section dimension, ultimate tensile stress (UTS), MOE, MC at time of test, and failure mode.

c. Edgewise flexure of 2 by 8 LVL with third-point loading over a span to depth ratio of 17:1. The same information gathered for the small bending tests was gathered for the large bending tests. Prior to testing, information was also gathered on warp (twist, bowing, or crook).

d. Specific gravity for each 1.5-in. strip of the billet was obtained from the 1.5- by 3.5- by 18-in. sections. Specific gravity was determined for ovendry weight and ovendry volume.

Economic Analysis

A baseline of typical strength and stiffness material was manufactured and labeled 1mE. Two categories were established for analysis: veneer costs and other costs. Other economic factors included forest taxes, inventory, electricity, and labor. The baseline strength and stiffness data and production costs were used to estimate the relative value of juvenile veneer to the current veneer supply. The remaining test results for the various low-grade core combinations were used to estimate the amount of additional material that would be needed to produce a product capable of the same load-carrying or deflection capacity. The deflection and load-carrying capacity for each cross-section was estimated by using simple beam theory. This analysis allows for a preliminary look at the value that should be associated with juvenile veneer.

Results and Discussion

The mean test results for moisture content, specific gravity, strength, and stiffness for the various combinations of the three grades of veneer are listed in Tables 2 and 3. A detailed summary of the test results is provided in Appendix B. The cumulative frequency distribution (CFD) values of strength and stiffness are given in Appendix C. In the following discussion, where differences are reported, the transition material was expected to fall somewhere between the extremes of juvenile and mature wood.

Moisture Content and Specific Gravity

For both Douglas-fir and Southern Pine, specimens were very close to the target 12% MC (Tables 2, 3). The levels ranged from 10.1% to 14.6% MC with the exception of the 2 by 4 tension specimens containing 50% juvenile wood. Equipment failure caused 10 specimens to have an unexpected and undetected exposure to moisture, resulting in moisture levels greater than 15% for those specimens. The results are reported with and without the 10 specimens.

The density difference between the juvenile veneer and typical veneer supply is reflected in the specific gravity results for both Douglas-fir and Southern Pine. As low-grade core material increased, specific gravity values decreased. The density of the low-grade mature and the low-grade juvenile materials also showed a detectable difference. The Southern Pine material appeared to have a much closer match between low-grade mature and low-grade juvenile veneer density levels than did the Douglas-fir. The ratio of the low-grade juvenile to the low-grade mature materials for Douglas-fir was 0.87, and the ratio for Southern Pine was 0.94.

Strength and Stiffness Variability

The coefficient of variation (COV) averaged 13.5% (range 6.2% to 26.5%) for strength and 10% (range 3.6% to 22.1%) for stiffness. As the percentage of low-grade core material increased, the variability increased

Table 2—Douglas-fir test results[a]

Test	Identification	Sample size[a]	Moisture content Mean (%)	Moisture content Coefficient of variation (%)	Specific gravity Mean	Specific gravity Coefficient of variation (%)	Strength Mean (lb/in^2)	Strength Coefficient of variation (%)	Modulus of elasticity Mean ($\times 10^6$ lb/in^2)	Modulus of elasticity Coefficient of variation (%)
2 by 2[a] edgewise bending	1mE	60	12.1	2.7	0.52	5.4	9,850	7.6	1.86	11.2
	D25j	64	11.9	4.0	0.52	5.2	9,290	9.4	1.78	9.5
	D50j	64	12.3	2.9	0.48	5.2	7,170	11.7	1.56	6.7
	D50m	64	11.8	2.9	0.51	5.4	8,340	9.9	1.74	6.1
	D75j	64	12.5	2.0	0.46	5.2	6,690	12.6	1.43	7.9
	2j	60	11.9	2.2	0.45	6.2	5,500	16.0	1.30	10.1
	2m	64	11.9	3.6	0.50	5.3	6,450	22.6	1.59	11.2
2 by 2[a] flatwise bending	1mE	60	12.1	2.7	0.52	5.4	8,930	11.7	1.98	12.7
	D25j	64	11.9	4.0	0.52	5.2	9,270	13.2	1.89	10.0
	D50j	64	12.3	2.9	0.48	5.2	8,190	13.6	1.88	8.5
	D50m	64	11.8	2.9	0.51	5.4	8,700	11.5	1.79	7.8
	D75j	64	12.5	2.0	0.46	5.2	7,540	11.3	1.61	8.1
	2j	60	11.9	2.2	0.45	6.2	4,900	21.5	1.30	14.4
	2m	64	11.9	3.6	0.50	5.3	5,720	24.3	1.60	15.6
2 by 4 tension	1mE	60	11.9	3.5	0.52	5.4	7,100	11.5	1.87	6.9
	D25j	64	11.6	3.8	0.52	5.2	6,540	12.3	1.76	5.8
	D50j	64	13.0	12.5	0.48	5.2	5,270	11.6	1.58	5.0
	D50j	54[b]	12.4	7.0	0.48	5.2	5,170	11.5	1.59	5.0
	D50m	64	11.9	3.8	0.51	5.4	5,780	9.9	1.68	4.8
	D75j	64	12.1	2.9	0.46	5.2	4,320	10.7	1.44	6.5
	2j	60	12.2	3.0	0.45	6.2	3,020	11.8	1.24	6.1
	2m	64	11.5	3.0	0.50	5.3	3,920	10.6	1.57	5.5
2 by 8 edgewise bending	1mE	15	11.4	2.2	0.52	5.4	8,490	6.2	1.90	4.3
	D25j	16	11.3	4.6	0.52	5.2	8,030	12.7	1.84	7.3
	D50j	16	11.6	3.1	0.48	5.2	6,430	14.1	1.67	5.7
	D50m	16	11.0	3.0	0.51	5.4	7,070	8.9	1.72	5.1
	D75j	16	12.2	3.5	0.46	5.2	5,360	14.5	1.48	7.2
	2j	15	11.4	2.9	0.45	6.2	3,610	9.4	1.17	8.7
	2m	16	11.5	4.5	0.50	5.3	5,260	12.1	1.58	4.9
2 by 8 remanufacture	R25j	8	11.5	1.9	0.52	5.2	8,070	8.2	2.00	3.6
	R50j	8	11.7	5.4	0.48	5.2	7,940	11.2	1.95	4.6
	R75j	8	11.3	2.5	0.46	5.2	6,760	8.7	1.73	6.1

[a] In some instances for the 2 by 2 specimen, sample size for MOE was smaller by one or two specimens because of difficulties with measuring deflection.

[b] 2 by 4 results with specimens having greater than 15% moisture content were not included.

Table 3—Southern Pine test results[a]

Test	Identification	Sample size[a]	Moisture content: Mean (%)	Moisture content: Coefficient of variation (%)	Specific gravity: Mean	Specific gravity: Coefficient of variation (%)	Strength: Sample size	Strength: Mean (lb/in^2)	Strength: Coefficient of variation (%)	Modulus of elasticity: Mean ($\times 10^6$ lb/in^2)	Modulus of elasticity: Coefficient of variation (%)
2 by 2[a] edgewise bending	1mE	51	12.0	3.3	0.63	3.2	64	10,190	13.4	1.98	13.6
	D57j	31	11.9	3.7	0.60	5.3	46	8,120	19.3	1.57	14.8
	D57m	48	11.7	3.6	0.62	4.9	58	9,220	14.1	1.73	14.2
	2j	36	11.7	3.6	0.59	6.2	54	7,530	16.9	1.34	14.2
	2m	50	11.9	3.1	0.59	4.9	50	9,210	12.5	1.74	14.4
2 by 2[a] flatwise bending	1mE	51	12.0	3.3	0.63	3.2	64	9,650	14.6	1.89	14.5
	D57j	31	11.9	3.7	0.60	5.3	46	7,850	26.5	1.49	22.1
	D57m	48	11.7	3.6	0.62	4.9	58	9,020	17.4	1.79	12.2
	2j	36	11.7	3.6	0.59	6.2	54	6,940	25.2	1.27	17.6
	2m	50	11.9	3.1	0.59	4.9	49	8,580	20.0	1.70	16.8
2 by 4 tension	1mE	50	11.8	5.7	0.63	3.2	50	7,430	16.8	1.97	9.6
	D57j	23	11.9	5.6	0.60	5.3	23	6,440	15.0	1.69	11.0
	D57m	54	11.8	6.2	0.62	4.9	54	6,910	15.1	1.76	7.5
	2j	35	11.6	6.8	0.59	6.2	35	5,210	14.0	1.39	11.8
	2m	45	11.8	4.6	0.59	4.9	45	6,400	17.3	1.67	13.1
2 by 8 edgewise bending	1mE	8	11.9	3.6	0.63	3.2	8	9,060	5.9	1.73	5.8
	D57m	8	11.9	2.9	0.62	4.9	8	7,810	12.4	1.53	11.6
	2j	5	13.1	10.8	0.59	6.2	5	6,660	6.4	1.26	4.0
	2m	9	11.9	1.0	0.59	4.9	9	7,750	13.3	1.72	7.9

[a] Sample size for moisture content was less than sample size for strength and MOE because of introduction of additional samples from remanufactured specimens.

(Tables 2, 3). In most cases, the stiffness results were also less variable than were the strength results. The edgewise bending results were less variable than were the flatwise bending results; the large bending results were less variable than were the small bending results; the Douglas-fir results were less variable than were the Southern Pine results. Variability within billets was also examined, and little difference was detected for a given billet type in Douglas-fir. However, a noticeable difference did exist between material at the center of the billet and the edge material in Southern Pine, with the edge being slightly stronger and stiffer than the center. This was partially caused by manufacturing difficulties encountered with the Southern Pine veneer.

Low-Grade Core Content

To investigate the effect of increasing low-grade core content, the mean values in Tables 2 and 3 were normalized by taking the mean of each test result and dividing it by the tight band all-mature-test mean value. The 90% confidence interval for the ratios was calculated using an approach based on the DELTA method (a Taylor series approximation, Mood and others 1976) and a normal approximation. The effects of increasing proportions of low-grade material on the normalized mean values of strength and stiffness and the 90% confidence intervals for all test results are illustrated with respective theoretical predictions in Figures 7 to 11. For the edgewise bending and tension specimens, a linear rule of mixtures approach was used for the theoretical approximations. For the flatwise bending and remanufactured 2 by 8 bending specimens, a transformed section approximation based on an apparent moment of inertia resulted in a cubic equation as the theoretical basis.

Strength and Juvenile Wood

Douglas-fir normalized test results and confidence intervals are shown in Figure 7. In all cases, the mature wood strength test data closely matched the theoretically predicted curve. The flatwise juvenile wood test results also closely followed the theoretically predicted

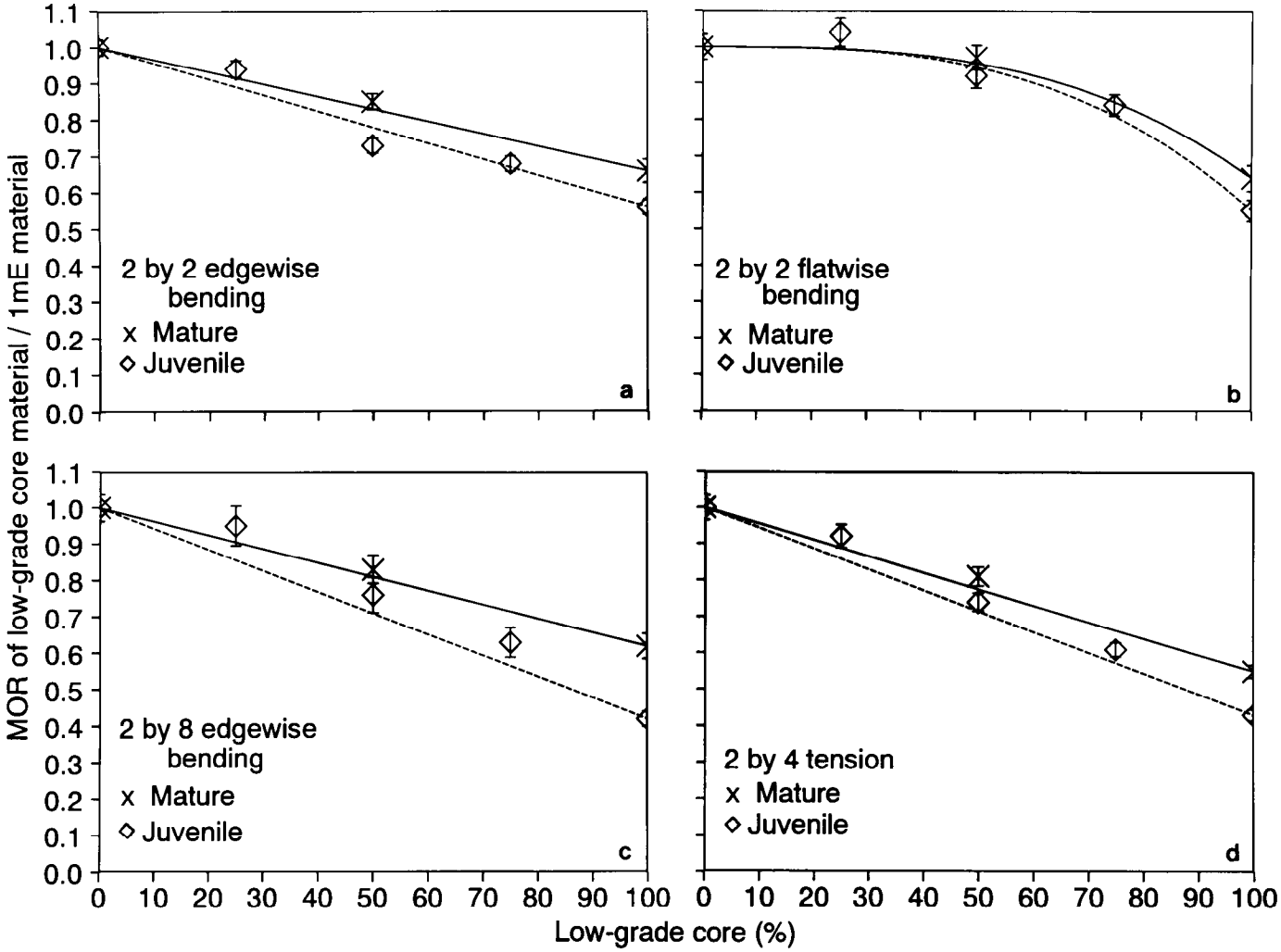

Figure 7–Normalized mean values for Douglas-fir 2 by 2 edgewise and flatwise bending, 2 by 8 edgewise bending, and 2 by 4 tension strength results compared to percentage of low-grade core content. Solid and dashed lines represent theoretically predicted results for mature and juvenile core material, respectively

cubic curve. However, the juvenile wood results for all test modes indicated that the inclusion of 25% low-grade juvenile material had little effect on the normalized strength. The 25% low-grade juvenile material was within the 90% confidence interval of the all-mature material. When the juvenile wood content reached 50%, the edgewise bending and tension results were significantly different from that of the all-mature ratio.

The normalized strength results for the Southern Pine material are shown in Figure 8. As discussed previously, the Southern Pine material was much more variable than was the Douglas-fir. The inclusion of 57% low-grade core material seemed to significantly reduce the edgewise bending strength of the test material. For the bending tests, both flatwise and edgewise, little distinction appeared between material with the 57% low-grade core material and the 100% low-grade core material, with the normalized ratio falling within each other's 90% confidence interval. However, the tension test results closely followed the theoretically predicted reductions in strength.

Modulus of Elasticity and Juvenile Wood

In the Douglas-fir material, the small bending and tension normalized test results for juvenile wood followed the theoretically predicted curves (Fig. 9). For the mature 2 by 8 edgewise bending test material, the theoretically predicted curve was within the confidence intervals of the normalized ratio. The juvenile 2 by 8 material was less sensitive to increases in juvenile wood content than was predicted.

The Southern Pine normalized stiffness results are shown in Figure 10. The inclusion of low-grade core

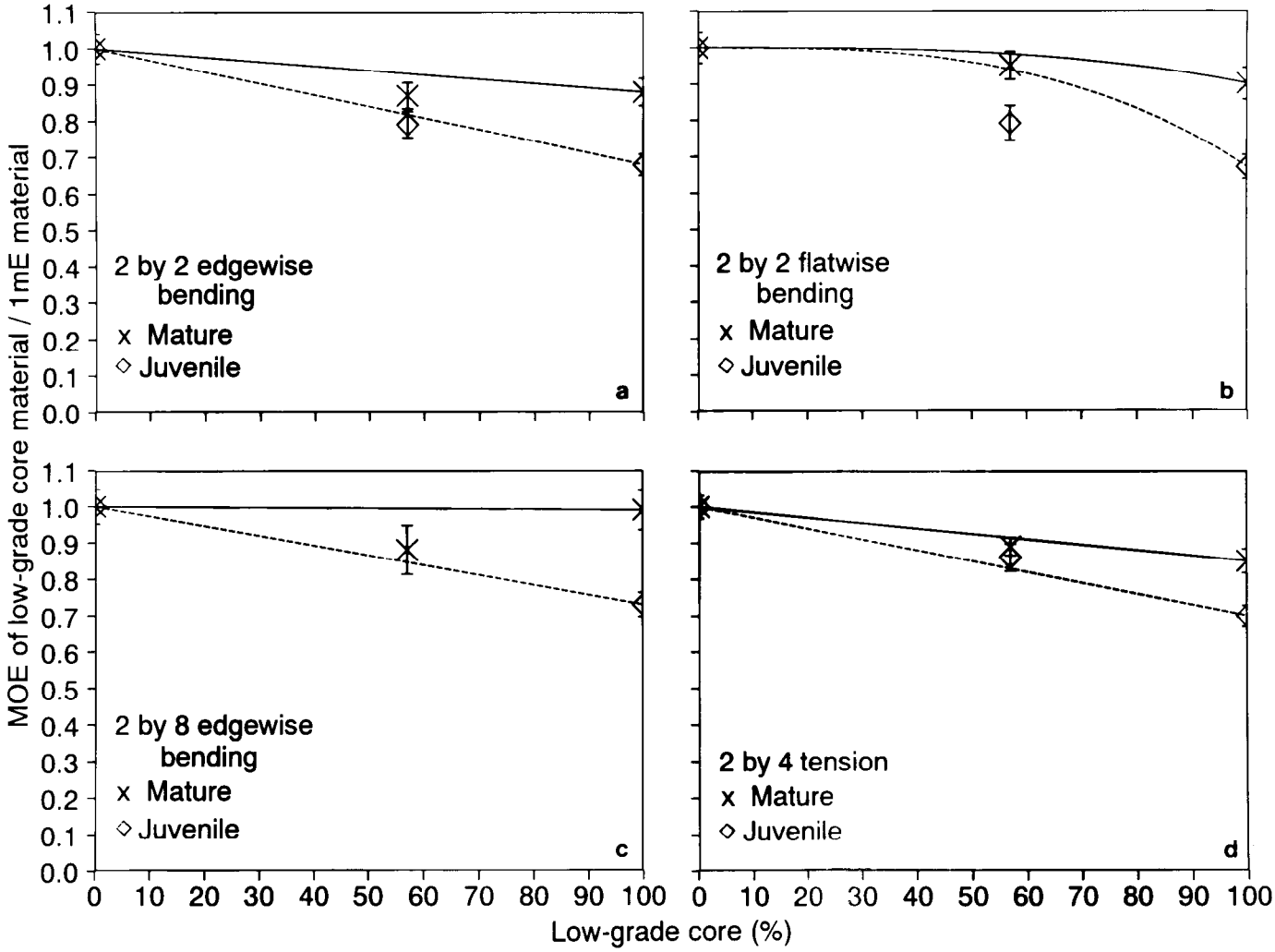

Figure 8–Normalized mean values *for Southern Pine 2 by 2 edgewise and flatwise bending, 2 by 8 edgewise bending, and 2 by 4 tension strength test results compared to percentage of low-grade core content. Solid and dashed lines represent theoretically predicted results for mature and juvenile core material, respectively.*

material seemed to dominate the resulting stiffness. For all tests, the inclusion of 57% and more of the juvenile wood core material caused a significant decrease in stiffness. As was the case with the strength results, the results of including the 57% low-grade core material were not significantly different than the test results for all low-grade core material. In all test modes, the tension stiffness results came closest to the expected theoretical curves.

Similarities and Differences

The test results summarized in Tables 2 and 3 indicate that (1mE) tight band material for the two species was similar, having almost equal strength and stiffness. However, the low-grade core material in the Douglas-fir was 27% weaker than that in the Southern Pine. The ratio of the all-low-grade juvenile material (2m) strength to the tight band mature strength for Douglas-fir averaged about 0.50 compared to about 0.75 for the strength of Southern Pine. In contrast, the effect of low-grade core content on stiffness was quite similar between the two species. The ratios of low-grade juvenile wood core material (2j) to the tight band mature material (1mE) for stiffness were almost the same and averaged 0.68. Another major difference between the two species occurred in the manufacturing process. The Douglas-fir material caused fewer problems during the manufacturing process and resulted in a less variable product than did the Southern Pine material.

Mature and Juvenile Low-Grade Material

For the combinations where comparisons could be made, strength and stiffness of the mature low-grade material (2m) were consistently greater by an average

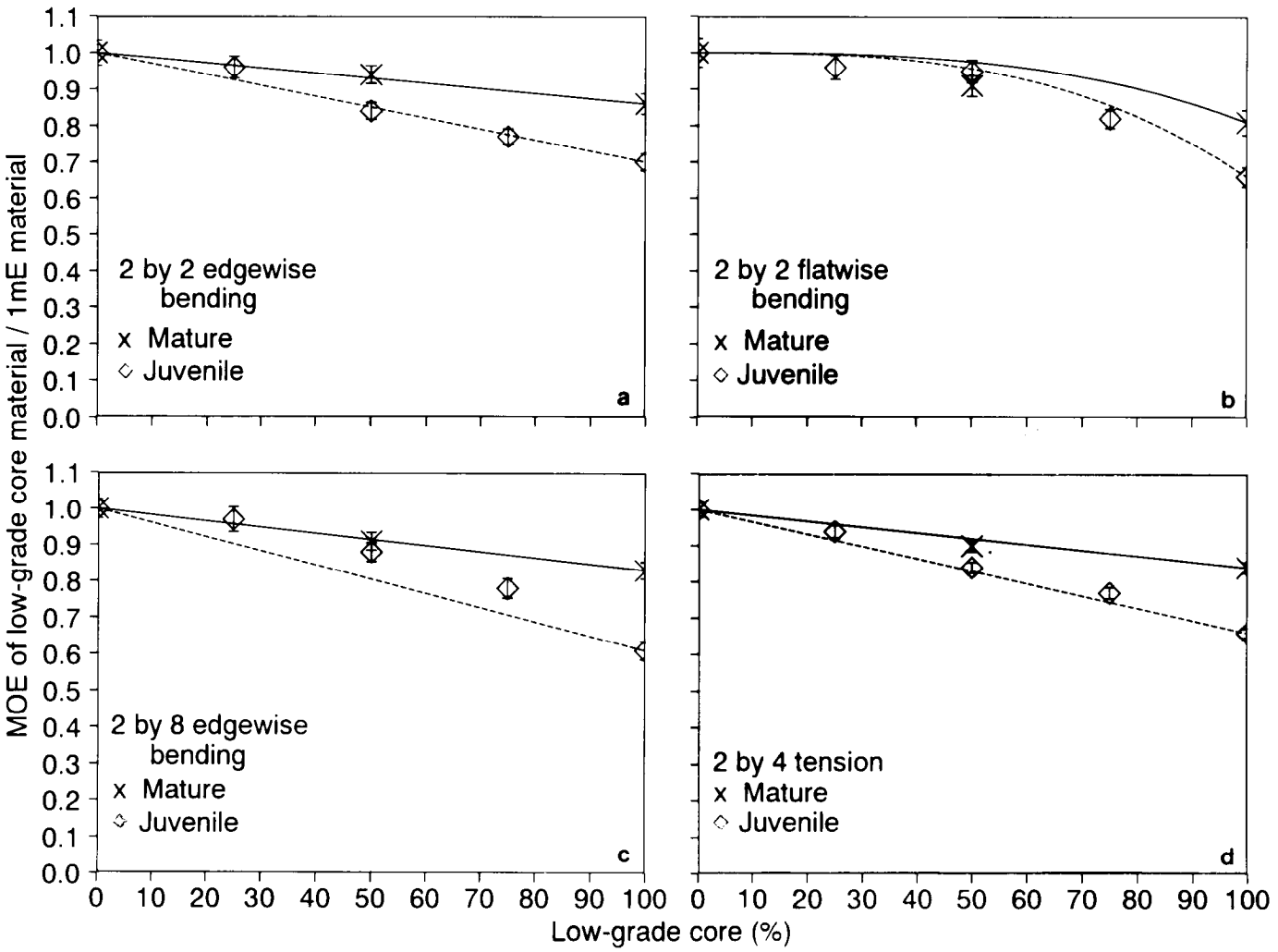

Figure 9–Normalized mean values for Douglas-fir 2 by 2 edgewise and flatwise bending, 2 by 8 edgewise bending, and 2 by 4 tension stiffness results compared to percentage of low-grade core content. Solid and dashed lines represent theoretically predicted results for mature and juvenile core material, respectively.

of 22% than were the strength and stiffness of the juvenile low-grade material (2j) (Tables 2, 3). The strength and stiffness values for the juvenile low-grade material, with the exception of the Douglas-fir 2 by 2 flatwise bending 50% (2j) stiffness results, were less than the strength and stiffness values for the mature low-grade core. The average ratio of all-juvenile low-grade core material (2j) to all-mature low-grade core material (2m) for both species was consistent at about 0.8 for strength and stiffness.

Flatwise and Edgewise Bending

In the Douglas-fir, the flatwise bending strength values of specimens, made up of one grade of material, were about 11% less on average than were the edgewise specimen values. However, the MOE values were generally the same for flatwise and edgewise specimens. As expected from theory, an increase in low-grade core content had little effect on the Douglas-fir flatwise material test results until 50% of the low-grade core content was exceeded; then the strength and stiffness decreased dramatically. We also noted in the Douglas-fir edgewise specimens that the inclusion of 25% juvenile wood core material had little effect on strength and stiffness (Table 2).

In the Southern Pine material, the flatwise MOR values were consistently 5% less than were the edgewise MOR values, with all the various combinations of material. In most cases, the edgewise MOE values for the Southern Pine material were also slightly greater than were the flatwise MOE values. However, there was far less agreement with theory. Strength was only slightly reduced as a result of including 57% of the low-grade core in the flatwise and edgewise specimens.

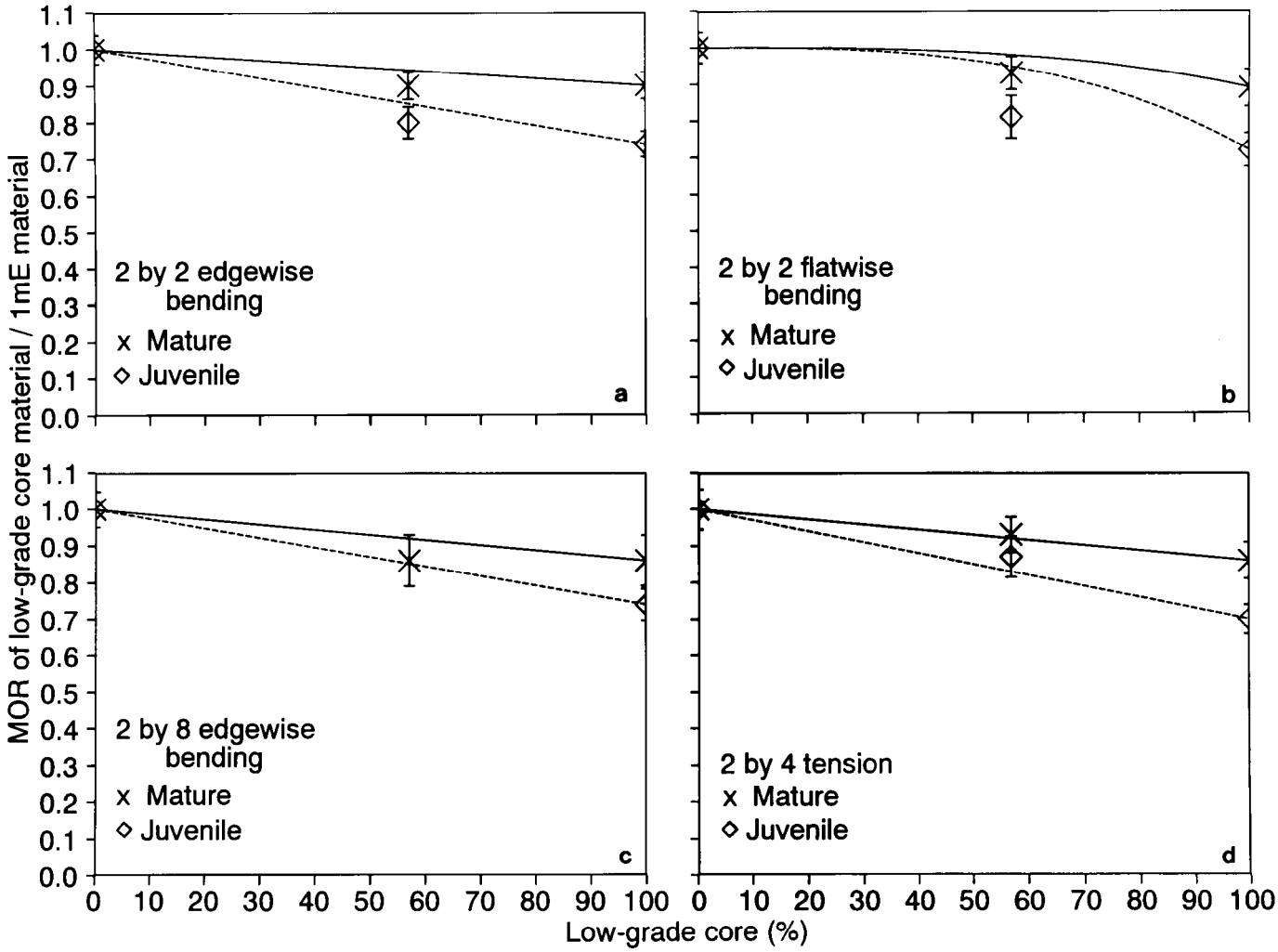

Figure 10–Normalized mean values for Southern Pine 2 by 2 edgewise and flatwise bending, 2 by 8 edgewise bending, and 2 by 4 tension stiffness results compared to percentage of low-grade core content. Solid and dashed lines represent theoretically predicted results for mature and juvenile core material. respectively

Tensile Properties and Juvenile Wood

Juvenile wood affected tensile strength and stiffness differently. A definite species difference was noticed between the ratios of all juvenile wood (2j) and the all tight band material (0.55 and 0.7 for Douglas-fir and Southern Pine, respectively, Tables 2, 3). Although juvenile wood had a similar effect on the ratio of stiffness for the two groups (both approximately 0.7), the effect of increased low-grade core content on the normalized mean values for UTS and tensile MOE for both species related closest to theory. All tension test results closely followed the predicted results from a rule of mixtures. A -25% increase in low-grade core material resulted in a proportionate reduction in expected strength and stiffness.

Size Effect

The ratio of large to small mean MOR values was consistent for Douglas-fir and Southern Pine and averaged 0.84, with the exception of 100% juvenile wood for the Douglas-fir material (Tables 2, 3). The all-juvenile Douglas-fir material had a ratio of 0.66. Also, the data showed that the MOE values for Douglas-fir increased slightly with specimen size. For the Southern Pine material, MOE was affected little, with a slight tendency for the 2 by 8 specimens to be lower in MOE than the 2 by 2 specimens. The overall average ratio for large to small specimen mean MOE values for Douglas-fir and Southern Pine was 0.98. The large specimens consistently had lower variability than did the 2 by 2 specimens.

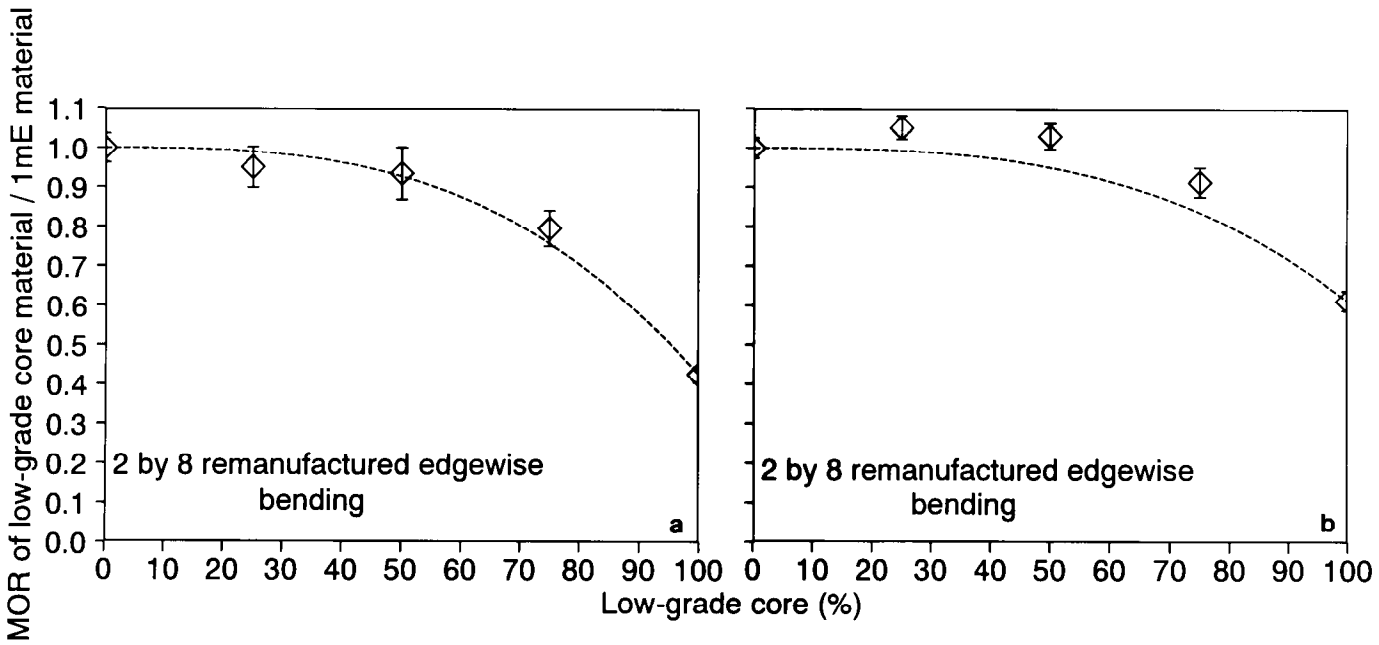

Figure 11–Normalized mean values for Douglas-fir 2 by 8 remanufactured bending, strength, and stiffness results compared to percentage of low-grade core content. Dashed lines represent theoretically predicted results for juvenile core material.

Sharp and Suddarth (1991) showed that generally for composite lumber, volume effects can be reasonably predicted with the weak-link theory. In their approach, they demonstrated that volume effects are sensitive to strength variability. As variability increases, the volume effect also increases. When the thickness and span to depth ratio of the beams are held constant, the theoretical bending volume (K_b) can be expressed in terms of depth (d) alone:

$$Kb = (d1/d2)^{2/B}$$

where

K_b is the volume adjustment factor,

d_1 depth of initial volume,

d_2 depth of final volume, and

B the shape parameter exponent.

This work was not designed to determine a shape parameter for LVL. However, our results of 0.84 appear reasonable when compared to 0.836 for the past historical shape parameter used on clear wood based on an exponent of 1/9 (Bohannan 1966) or the current adjustment used for the LVL product Micro-lam of 0.803 based on an exponent of 0.136 (Council of American Building Officials 1990). Because the general trend is to increase COV with increasing proportions of juvenile wood, it is likely that volume effect will be more pronounced in the juvenile material. The all Douglas-fir results (Table 2) supported this concept and the Southern Pine results (Table 3) did not, but the sample size was small for the Southern Pine large bending specimens.

Remanufactured Edgewise Bending Specimens

Results of the bending tests on the remanufactured specimens, which were produced only for the Douglas-fir, are shown in Figure 11. The MOR results of the remanufactured billets followed the expected theoretically predicted curve well. However, the MOE results appeared to be offset upward by 5% from the theoretically predicted results. No procedural explanation was found for this offset.

Failure Codes and Warp Characteristics

The majority of tests failed in tension within the wood between the load heads (see Appendix D). All edgewise bending test specimens failed between or at the load heads, with the majority failing within the wood and not at the overlapping veneer joint. The flatwise bending test failure characteristics were noticeably different than those of the edgewise bending tests. Shear failures and failures outside the load heads occurred only in the flatwise bending tests. Joints were critical in the tension tests. The largest number of joint failures occurred in the tension test specimens.

Measurements for warp were taken on all 2 by 8 edgewise bending specimens to investigate the effect an increased proportion of juvenile wood would have on LVL material. No warpage was detected for the various proportions of low-grade core material, whether it was mature or juvenile. A different result may have occurred if mature and juvenile low-grade core material had been mixed within a billet instead of concentrated symmetrically in the core.

Value Effect

The 1mE material produced was chosen to represent the typical strength and stiffness of material produced by LVL manufacturers. The test result obtained from the inclusion of juvenile wood material allows for a preliminary look at what the economic impact of increased juvenile wood would have on production of LVL. Several combinations of veneer and other costs, at various mixtures of juvenile and mature materials, using the strength and stiffness results from Tables 2 and 3, are found in Appendix E, Table El.

We assumed that the customer would be willing to pay a unit price regardless of the juvenile content as long as the LVL product satisfied current performance requirements. The amount of increased volume needed to compensate for the low-quality juvenile material was determined by expanding the width or depth of the original test specimens to produce members of the same load-carrying or deflection capacity as the 1mE material for the same test mode. The calculation procedure used to establish values is discussed in Appendix E. Table El allows a manufacturer with an understanding of fixed cost to estimate the value of the juvenile veneer for a given mixture and determine at what point it is inadvisable to add further juvenile material.

For example, a producer knows that veneer costs are 60% of total costs. The Douglas-fir 2 by 2 edgewise bending data suggest that if one expects to span the same distance, having the same depth, carrying the same load, with a 50% juvenile core, then the volume of the member must be increased by 17% to produce the expected strength. Other costs are assumed to remain constant and directly proportional to the volume processed. An additional falldown rate of 20% in low-grade juvenile veneer during manufacture was assumed in these calculations. The data in this study suggest that a producer can obtain juvenile wood veneer at a cost per unit of 0.25 relative to the current price of 0.60 per unit of mature veneer. Thus, veneer costs of the juvenile wood supply must be 58% less than the current veneer costs to break even.

If the same 2 by 2 edgewise specimen is needed to deflect a similar amount as the current manufactured material, a 6% increase in volume is needed, resulting in a relative juvenile veneer cost per unit of 0.41, compared to the 0.6 currently paid. This would suggest that to maintain a similar deflection the veneer costs of the juvenile wood supply must be 32% less than the current supply to break even.

If other costs dominate the unit cost, the increased juvenile wood material required to meet performance conditions can also cause the relative value of the juvenile veneer to become negative, as demonstrated by the 2 by 4 tension results. This indicates that at a certain ratio of veneer costs to other costs, it would be impossible to maintain current performance strength and stiffness levels with an influx of low strength and stiffness core material.

Conclusions

The results of this study give insight into the effect that anticipated future wood resources will have on LVL manufacturing practices. Including more juvenile material in the veneer supply is a situation that can be handled with current technology, but the technology has much room for improvement. In this study, both veneer sources represented rapidly grown material. The Douglas-fir veneer source represents a lower bound on the quality of the veneer sources that are anticipated. The Southern Pine veneer material represents the typical quality expected in rapidly grown Southern Pine veneer supplies. The results of this study indicate the following:

- It is possible to manufacture an LVL type product with structural integrity using significant quantities of juvenile wood veneer, but design values would be less than those currently in use. However, our Douglas-fir tests indicate that including 25% proportions of juvenile wood in the core of LVL has little effect on the overall strength and stiffness of the LVL.
- LVL stiffness for Douglas-fir and Southern Pine react similarly to inclusion of juvenile material. However, the strength of Douglas-fir is affected more by the inclusion of juvenile material than is that of Southern Pine.
- A significant difference exists between material manufactured with mature or juvenile material having the same nondestructive grade. For both Southern Pine and Douglas-fir, the ratio of juvenile to mature material with the same nondestructive grade is approximately 0.8 for strength and stiffness.
- The two techniques of nondestructive grading used in this study are capable of indicating the low quality of veneer sheets and placing them into low grades. These techniques, however, are unable to

differentiate between low-grade mature and juvenile material.

- For the material we examined, no detectable differences were noted in the warp characteristics of the test material with increasing juvenile wood content.
- The addition of juvenile wood has a significant effect on the costs of manufacturing LVL capable of maintaining current performance. Unless the rapidly grown resource can be harvested at a low cost, increased member sizes will have an adverse impact on the economics of the LVL industry. During veneer preparation, the low strength of the juvenile wood veneer and high number of checks in both species led to a significant increase in breakage during handling when compared to normal veneer losses. The falldown rate nearly doubled. The amount of juvenile wood acceptable to manufacturers will be heavily influenced by production costs.

Future Considerations

This study suggests a number of areas for improvement in the manufacturing process of LVL. The low strength of the juvenile wood veneer in both species led to significant increases in breakage during handling compared to normal veneer. The effect of this would be an increase in cost, the magnitude depending on the proportion of juvenile wood used and the relative cost of the veneer in the finished product. Better ways of drying and handling juvenile veneer are necessary to reduce the large falldown expected. To improve handling, a better method is needed to detect juvenile wood material prior to processing. If the high resin content observed in this study is typical of Southern Pine juvenile wood, improved manufacturing techniques to handle anticipated difficulties will have to be developed. Finally, accurate estimates are needed of how much rapidly grown material will enter the market place.

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Appendix A-Specimen Preparation

Appendix A details the billet and strip cut-up procedure used in manufacturing the test specimens. The billets were cut into strips and labeled with an identification code at the LVL manufacturing plant. The strips were then transported to the laboratory facility and conditioned prior to being cut up for specimens.

Cutting Strips

A total of 118 2-ft by 1.5-in. by 12-ft Douglas fir and 32 4-ft by 1.5-in. by 12-ft Southern Pine billets were manufactured at the LVL plants. The 12-ft-long billets were ripped into strips of specified widths according to the patterns shown in Figures Al. For Douglas-fir, each of the 110 billets (15 each of class 1mE and 2j; 16 each of 2m, D25j, D50j, D50m, and D75j) were cut into five 144-in.-long strips that were 3.5, 3.5, 7.4, 3.5, and 3.5 in. wide. Each of the eight remaining class 1mE and 2j billets (four each of class 1mE and 2j) were cut into six strips that were 2, 3.75, 5.5, 2, 3.75, and 5.5 in. wide. These strips were reassembled in various combinations to produce 1.5- by 7.25- by 144-in. remanufactured R specimens using an adhesive.

For Southern Pine, each of the first 28 billets (4 of class 1mE; 6 each of class 2m, 2j, D57j, and, D57m) were cut into 11 strips that were 3.5, 3.5, 7.4, 3.5, 3.5, 3.5, 3.5, 7.4, 3.5, 3.5, and 3.5 in. wide, respectively. Each of the four remaining class 1mE and 2j billets (two each) were cut to be remanufactured to produce the R specimens. They were cut into 12 strips that were 2, 3.75, 5.5, 2, 3.75, 5.5, 2, 3.75, 5.5, 2, 3.75, and 5.5 in. wide (Fig. A2).

For both species, the completed strips were sent to Washington State University's Wood Engineering Laboratories for specimen preparation and testing.

Specimen Cut-Up Procedure

Prior to cutting the specimens, all strips from the manufacturing plants were conditioned to equilibrium in a climate-controlled room under 65% relative humidity and 75°F (approximately 12% equilibrium moisture content). Afterwards, the strips were cut to produce matched edgewise and flatwise 1.5- by 1.5- by 30-m. bending (2 by 2), 1.5- by 3.5- by 96-m. tension (2 by 4), and 1.5- by 7.4- 144-in. (2 by 8) edgewise bending specimens from each billet according to a cutting pattern meant to maximize the variability between specimens that are cut from the same billet while using all the material produced.

The Douglas-fir strips cut (Fig. A2) were remanufactured by gluing one 2j core strip between two mature 1mE strips. The material was glued so that the veneer sheets were oriented vertically. Three mixtures of 2j core were manufactured (25%, 50%, and 75%). In the Southern Pine material, a considerable amount of material was discarded as a result of delamination blows in the center of the billets. This resulted in an inadequate number of specimens for the initial test matrix. Therefore, we used the strips cut up for remanufacture (Fig. A2) to supplement the remaining dedicated test material. The Southern Pine remanufactured strips were cut in a pattern similar to the material shown in Figure Al.

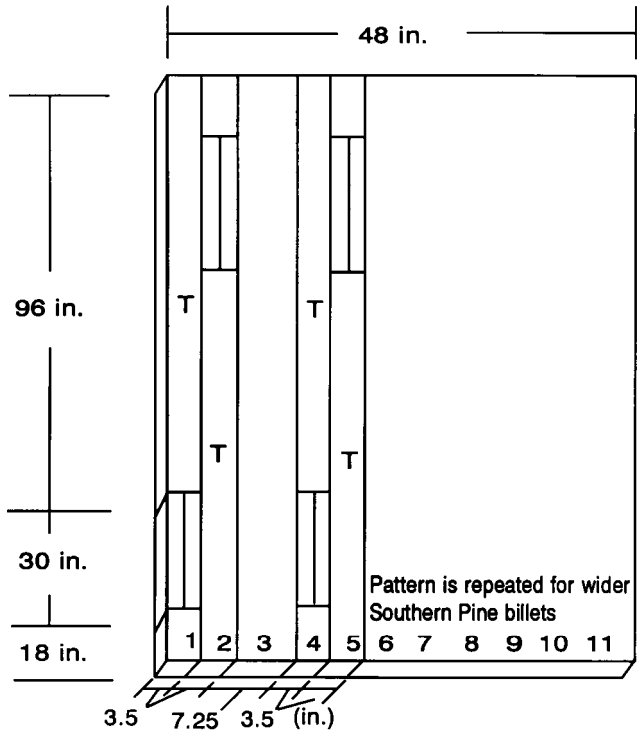

Figure Al-Cutting patterns for type 1mE, 2m, 2j. and D billets.

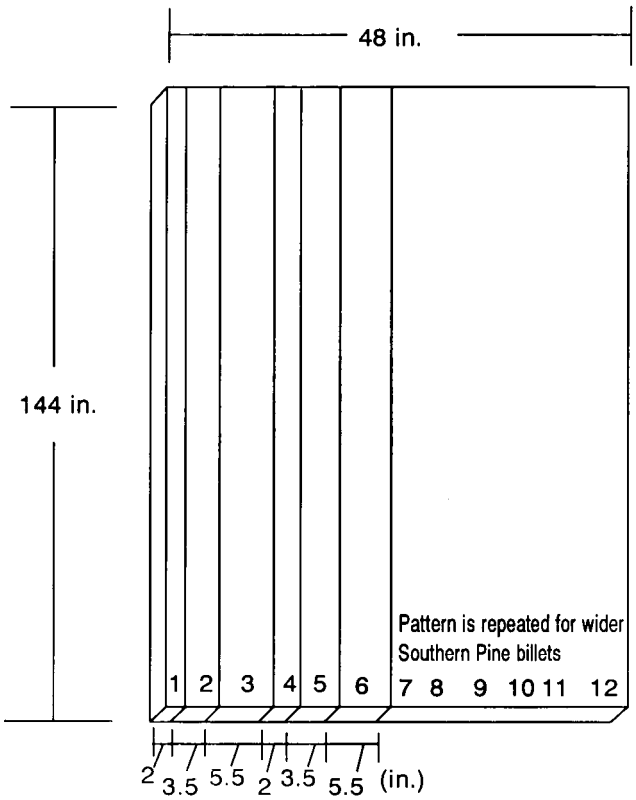

Figure A2–Cutting patterns for remanufactured R specimens.

Appendix B-Data Summary Tables

Appendix B contains results of the moisture content, specific gravity, strength, and stiffness tests for the combinations of various grades of veneer. For each species, size, and low-grade core content combination, the sample size, mean, standard deviation, coefficient of variation, minimum, 5th percentile, 25th percentile, median, 75th percentile, and maximum values for specific gravity and moisture content are given (Table B1). The same distributional information is also given for strength and modulus of elasticity test results in Tables B2 and B3, respectively.

Table B1—Distributional data for specific gravity and moisture content

Test	Identi-fication	Low-grade core (%)	Sample size	Average (lb/in^2)	Coefficient of variftion	Percentile distribution: Mini-mum	5	25	50	75	Maxi-mum
Douglas-fir											
2 by 2 moisture content, %	1mE	0	60	12.1	2.7	11.2	11.5	12.0	12.2	12.3	12.7
	D25j	Juvenile 25	64	11.9	4.0	10.8	11.1	11.6	12.0	12.3	13.0
	D50j	Juvenile 50	64	12.3	2.9	11.4	11.7	12.1	12.4	12.6	13.1
	D50m	Mature 50	64	11.8	2.9	11.0	11.2	11.5	11.8	12.1	12.4
	D75j	Juvenile 75	64	12.5	2.0	11.6	12.0	12.3	12.5	12.6	13.1
	2j	Juvenile 100	60	11.9	2.2	11.5	11.5	11.7	11.9	12.1	12.6
	2m	Mature 100	64	11.9	3.6	9.9	11.3	11.7	11.8	12.1	12.8
2 by 4 moisture content, %	1mE	0	60	11.9	3.5	11.0	11.3	11.6	11.9	12.2	13.2
	D25j	Juvenile 25	64	11.6	3.8	10.8	10.9	11.3	11.7	12.0	12.5
	D50j	Juvenile 50	64	13.0	12.5	10.8	11.3	11.9	12.4	13.9	17.7
	D50j	Juvenile[a] 50	54	12.4	7.0	10.8	11.3	11.8	12.3	12.6	14.5
	D50m	Mature 50	64	11.9	3.8	10.9	11.0	11.6	11.8	12.2	12.8
	D75j	Juvenile 75	64	12.1	2.9	11.0	11.4	11.8	12.1	12.2	13.1
	2j	Juvenile 100	60	12.2	3.0	11.1	11.3	12.1	12.2	12.4	13.0
	2m	Mature 100	64	11.5	3.0	10.9	11.2	11.4	11.7	11.7	12.6
2 by 8 moisture content, %	1mE	0	15	11.4	2.2	11.0	—	11.2	11.3	11.5	11.9
	D25j	Juvenile 25	16	11.3	4.6	10.6	—	10.9	11.2	11.7	12.3
	D50j	Juvenile 50	16	11.6	3.1	10.9	—	11.4	11.6	12.0	12.2
	D50m	Mature 50	16	11.0	3.0	10.4	—	10.7	11.0	11.2	11.7
	D75j	Juvenile 75	16	12.2	3.5	11.6	—	11.8	12.1	12.5	13.0
	2j	Juvenile 100	15	11.4	2.9	10.8	—	11.2	11.4	11.6	12.0
	2m	Mature 100	16	11.5	4.5	10.8	—	11.2	11.4	12.0	12.4
2 by 8 remanu-factured moisture content, %	R25j	Juvenile 25	8	11.5	1.9	11.2	—	11.3	11.5	11.6	11.9
	R50j	Juvenile 50	8	11.7	5.4	11.0	—	11.1	11.4	12.3	12.6
	R75j	Juvenile 75	8	11.3	2.5	10.9	—	11.0	11.3	11.6	11.7
2 by 2 specific gravity	1mE	0	60	0.517	5.4	0.45	0.47	0.50	0.51	0.53	0.61
	D25j	Juvenile 25	64	0.516	5.2	0.47	0.47	0.50	0.52	0.54	0.60
	D50j	Juvenile 50	64	0.483	5.2	0.43	0.43	0.47	0.48	0.50	0.57
	D50m	Mature 50	64	0.509	5.4	0.46	0.47	0.49	0.51	0.53	0.57
	D75j	Juvenile 75	64	0.464	5.2	0.42	0.42	0.45	0.46	0.48	0.51
	2j	Juvenile 100	60	0.449	6.2	0.39	0.41	0.43	0.45	0.47	0.52
	2m	Mature 100	64	0.497	5.3	0.44	0.46	0.48	0.50	0.52	0.56
Southern Pine											
2 by 2 moisture content, %	1mE	0	51	12.0	3.3	11.3	11.5	11.7	12.0	12.3	13.1
	D57j	Juvenile 57	31	11.9	3.7	11.3	11.3	11.5	12.0	12.3	13.0
	D57m	Mature 57	48	11.7	3.6	10.9	11.0	11.5	11.7	12.0	12.8
	2j	Juvenile 100	36	11.7	3.6	11.1	11.1	11.4	11.6	12.1	12.8
	2m	Mature 100	50	11.9	3.1	11.2	11.3	11.7	11.9	12.1	12.7
2 by 4 moisture content, %	1mE	0	50	11.8	5.7	10.5	10.7	11.3	11.7	12.2	13.7
	D57j	Juvenile 57	23	11.9	5.6	10.8	10.8	11.3	11.9	12.4	13.2
	D57m	Mature 57	54	11.8	6.2	10.2	10.7	11.3	11.6	12.2	14.5
	2j	Juvenile 100	35	11.6	6.8	10.1	10.4	11.0	11.5	12.1	13.8
	2m	Mature 100	45	11.8	4.6	10.2	11.0	11.4	11.8	12.2	13.1
2 by 8 moisture content, %	1mE	0	8	11.9	3.6	11.5	—	11.5	12.0	12.2	12.8
	D57m	Mature 57	8	11.9	2.9	11.4	—	11.5	11.9	12.2	12.3
	2j	Juvenile 100	5	13.1	10.8	11.4	—	11.6	13.5	14.4	14.6
	2m	Mature 100	9	11.9	1.0	11.8	—	11.8	11.9	12.0	12.1
2 by 2 specific gravity	1mE	0	51 -	0.63	3.2	0.59	0.60	0.62	0.63	0.65	0.67
	D57j	Juvenile 57	31	0.60	5.3	0.53	0.54	0.57	0.60	0.62	0.66
	D57m	Mature 57	48	0.62	4.9	0.55	0.58	0.60	0.62	0.64	0.70
	2j	Juvenile 100	36	0.59	6.2	0.51	0.53	0.57	0.60	0.62	0.67
	2m	Mature 100	50	0.59	4.9	0.52	0.54	0.57	0.59	0.61	0.66

[a] 2 by 4 tension test results with specimens having greater than 15% moisture content were dropped.

Table B2—Distributional data on bending and tensile strength properties

Test	Identification	Low-grade core (%)	Sample size	Average (lb/in^2)	Coefficient of variation	Percentile distribution: Minimum	5	25	50	75	Maximum
Douglas-fir											
2 by 2 edgewise MOR	1mE	0	60	9,853	7.6	8,110	8,412	9,303	9,990	10,340	11,390
	D25j	Juvenile 25	64	9,293	9.4	7,180	7,918	8,705	9,255	9,788	11,280
	D50j	Juvenile 50	64	7,167	11.7	4,040	5,538	6,805	7,210	7,638	8,900
	D50m	Mature 50	64	8,344	9.9	6,640	6,830	7,663	8,555	8,928	10,080
	D75j	Juvenile 75	64	6,688	12.6	4,260	5,265	6,220	6,715	7,300	8,530
	2j	Juvenile 100	60	5,502	16.0	3,320	4,060	4,853	5,525	6,193	7,310
	2m	Mature 100	64	6,454	22.6	3,140	5,495	5,495	6,470	7,633	9,080
2 by 2 flatwise MOR	1mE	0	60	8,926	11.7	6,540	7,043	8,262	8,965	9,805	10,830
	D25j	Juvenile 25	64	9,267	13.2	5,040	7,128	8,440	9,075	10,160	11,560
	D5Oj	Juvenile 50	64	8,190	13.6	5,160	6,085	7,490	8,120	8,888	10,500
	D50m	Mature 50	64	8,699	11.5	6,730	7,055	7,810	8,780	9,385	10,650
	D75j	Juvenile 75	64	7,538	11.3	5,740	5,920	6,905	7,670	8,035	9,600
	2j	Juvenile 100	60	4,899	21.5	2,600	3,111	4,068	4,790	5,650	7,320
	2m	Mature 100	64	5,716	24.3	1,810	3,132	4,868	5,760	6,890	7,860
2 by 4 UTS	1mE	0	60	7,105	11.5	5,150	5,930	6,492	7,045	7,580	9,100
	D25j	Juvenile 25	64	6,543	12.3	4,630	5,295	6,028	6,565	6,995	8,330
	D50j	Juvenile 50	64	5,266	11.6	3,300	4,042	4,925	5,360	5,748	6,420
	D50j	Juvenile[a] 50	54	5,172	11.5	3,300	3,935	4,855	5,255	5,620	6,210
	D50m	Mature 50	64	5,785	9.9	4,530	4,678	5,412	5,775	6,200	7,040
	D75j	Juvenile 75	64	4,319	10.7	3,270	3,480	3,995	4,370	4,710	5,030
	2j	Juvenile 100	60	3,024	11.8	2,360	2,434	2,745	3,020	3,260	3,960
	2m	Mature 100	64	3,921	10.6	2,900	3,145	3,652	3,965	4,210	4,670
2 by 8 edgewise MOR	1mE	0	15	8,489	6.2	7,530	—	8,070	8,410	8,950	9,450
	D25j	Juvenile 25	16	8,029	12.7	6,940	—	7,318	7,750	8,435	11,100
	D50j	Juvenile 50	16	6,428	14.1	5,100	—	5,833	6,340	6,930	9,020
	D50m	Mature 50	16	7,074	8.9	6,180	—	6,578	7,095	7,355	8,500
	D75j	Juvenile 75	16	5,358	14.5	3,830	—	4,855	5,575	5,868	6,450
	2j	Juvenile 100	15	3,607	9.4	2,870	—	3,320	3,650	3,750	4,170
	2m	Mature 100	16	5,265	12.1	4,110	—	4,720	5,190	5,865	6,160
2 by 8 remanufactured MOR	R25j	Juvenile 25	8	8,074	8.2	7,290	—	7,518	8,010	8,452	9,300
	R50j	Juvenile 50	8	7,939	11.2	7,100	—	7,605	7,630	8,118	10,000
	R75j	Juvenile 75	8	6,755	8.7	5,670	—	6,325	6,920	7,275	7,310
Southern Pine											
2 by 2 edgewise MOR	1mE	0	64	10,191	13.4	6,450	7,618	9,498	10,220	11,118	12,560
	D57j	Juvenile 57	46	8,119	19.3	4,440	4,924	7,292	8,115	9,208	11,510
	D57m	Mature 57	58	9,218	14.1	5,140	6,665	8,310	9,580	10,220	11,280
	2j	Juvenile 100	54	7,527	16.9	3,760	5,070	7,068	7,630	8,360	10,080
	2m	Mature 100	50	9,206	12.5	5,740	6,580	8,510	9,310	10,005	11,260
2 by 2 flatwise MOR	1mE	0	64	9,646	14.6	5,580	7,018	8,695	9,880	10,765	12,610
	D57j	Juvenile 57	46	7,852	26.5	2,850	3,846	6,418	7,710	9,165	12,970
	D57m	Mature 57	58	9,019	17.4	4,860	6,073	7,870	9,080	10,078	11,840
	2j	Juvenile	54	6,943	25.2	2,870	3,310	5,940	7,325	8,292	9,890
	2m	Mature 100	49	8,584	20.0	5,070	5,400	7,690	8,530	9,950	13,100
2 by 4 UTS	1mE	0	50	7,426	16.8	5,280	5,494	6,460	7,245	8,482	10,500
	D57j	Juvenile 57	23	6,440	15.0	4,660	4,688	5,610	6,480	6,980	8,370
	D57m	Mature 57	54	6,907	15.1	5,190	5,455	6,080	6,835	7,450	9,370
	2j	Juvenile 100	35	5,206	14.0	3,930	4,082	4,570	5,230	5,780	6,880
	2m	Mature 100	45	6,395	17.3	4,250	4,532	5,500	6,220	7,115	9,360
2 by 8 edgewise MOR	1mE	0	8	9,062	5.9	8,270	—	8,425	9,285	9,415	9,690
	D57m	Mature 57	8	7,814	12.4	6,680	—	6,872	7,595	8,855	9,270
	2j	Juvenile 100	5	6,664	6.4	5,940	—	6,340	6,780	6,930	7,060
	2m	Mature 100	9	7,751	13.3	6,370	—	6,795	7,640	8,530	9,510

[a] 2 by 4 tension test results with specimens having greater than 15% moisture content were dropped.

Table B3—Distributional data for modulus of elasticity

Test	Identification	Low-grade core (%)	Sample size	Average (× 10^6 lb/in^2)	Coefficient of variation	Percentile distribution: Minimum	5	25	50	75	Maximum
Douglas-fir											
2 by 2 edgewise MOE	1mE	0	59	1.857	11.2	1.356	1.592	1.709	1.827	1.961	2.528
	D25j	Juvenile 25	64	1.781	9.5	1.315	1.537	1.673	1.757	1.869	2.257
	D50j	Juvenile 50	64	1.558	6.7	1.314	1.380	1.480	1.564	1.629	1.880
	D50m	Mature 50	64	1.742	6.1	1.498	1.529	1.682	1.752	1.811	1.989
	D75j	Juvenile 75	64	1.428	7.9	1.209	1.225	1.364	1.428	1.481	1.836
	2j	Juvenile 100	60	1.302	10.1	1.042	1.108	1.210	1.292	1.386	1.663
	2m	Mature 100	64	1.589	11.2	1.195	1.326	1.473	1.561	1.689	2.311
2 by 2 flatwise MOE	1mE	0	58	1.975	12.7	1.627	1.649	1.827	1.916	2.001	2.726
	D25j	Juvenile 25	64	1.891	10.0	1.449	1.574	1.767	1.872	2.022	2.396
	D50j	Juvenile 50	63	1.882	8.5	1.549	1.625	1.750	1.904	2.003	2.261
	D50m	Mature 50	63	1.791	7.8	1.449	1.552	1.687	1.815	1.884	2.129
	D75j	Juvenile 75	64	1.612	8.1	1.324	1.416	1.502	1.628	1.694	2.004
	2j	Juvenile 100	60	1.299	14.4	0.855	1.029	1.148	1.294	1.435	1.791
	2m	Mature 100	64	1.601	15.6	1.202	1.219	1.435	1.572	1.761	2.388
2 by 4 tensile MOE	1mE	0	60	1.870	6.9	1.659	1.676	1.766	1.852	1.929	2.193
	D25j	Juvenile 25	64	1.757	5.8	1.519	1.589	1.671	1.752	1.839	1.950
	D50j	Juvenile 50	64	1.580	5.0	1.389	1.417	1.530	1.581	1.636	1.752
	D50j	Juvenile[a] 50	54	1.587	5.0	1.389	1.431	1.530	1.586	1.641	1.752
	D50m	Mature 50	64	1.675	4.8	1.511	1.520	1.625	1.692	1.737	1.878
	D75j	Juvenile 75	64	1.440	6.5	1.255	1.326	1.366	1.433	1.490	1.781
	2j	Juvenile 100	60	1.239	6.1	1.045	1.143	1.197	1.239	1.270	1.572
	2m	Mature 100	64	1.574	5.5	1.421	1.430	1.509	1.574	1.625	1.822
2 by 8 edgewise MOE	1mE	0	15	1.896	4.3	1.770	—	1.813	1.909	1.961	2.029
	D25j	Juvenile 25	16	1.837	7.3	1.681	—	1.735	1.838	1.881	2.218
	D50j	Juvenile 50	16	1.667	5.7	1.498	—	1.632	1.649	1.694	1.935
	D50m	Mature 50	16	1.725	5.1	1.485	—	1.699	1.730	1.780	1.850
	D75j	Juvenile 75	16	1.482	7.2	1.322	—	1.386	1.496	1.580	1.670
	2j	Juvenile 100	15	1.165	8.7	0.994	—	1.130	1.148	1.166	1.469
	2m	Mature 100	16	1.580	4.9	1.444	—	1.527	1.587	1.636	1.697
2 by 8 remanufactured MOE	R25j	Juvenile 25	8	1.994	3.6	1.938	—	1.950	1.958	2.054	2.136
	R503	Juvenile 50	8	1.954	4.6	1.827	—	1.891	1.932	2.039	2.091
	R75j	Juvenile 75	8	1.732	6.1	1.644	—	1.662	1.716	1.784	1.887
Southern Pine											
2 by 2 edgewise MOE	1mE	0	64	1.980 9	13.6	1.324	1.520	1.809	1.977	2.121	2.792
	D57j	Juvenile 57	46	1.566 2	14.8	0.930	1.183	1.414	1.578	1.728	2.051
	D57m	Mature 57	58	1.726 5	14.2	1.151	1.585	1.585	1.724	1.822	2.407
	2j	Juvenile 100	54	1.342 1	14.2	0.926	0.992	1.228	1.345	1.480	1.794
	2m	Mature 100	50	1.743 1	14.4	1.183	1.569	1.569	1.752	1.919	2.289
2 by 2 flatwise MOE	1mE	0	64	1.886	14.5	1.080	1.715	1.715	1.930	2.048	2.506
	D57j	Juvenile 57	46	1.488	22.1	0.889	0.972	1.256	1.420	1.678	2.354
	D57m	Mature 57	58	1.794	12.2	1.316	1.484	1.637	1.776	1.978	2.306
	2j	Juvenile 100	54	1.267	17.6	0.815	0.918	1.117	1.242	1.401	1.786
	2m	Mature 100	49	1.698	16.8	0.955	1.170	1.528	1.683	1.838	2.687
2 by 4 tensile MOE	1mE	0	50	1.973	9.6	1.492	1.586	1.890	2.013	2.102	2.321
	D57j	Juvenile 57	23	1.692	11.0	1.336	1.338	1.514	1.728	1.827	1.987
	D57m	Mature 57	54	1.763	7.5	1.464	1.535	1.678	1.760	1.869	2.074
	2j	Juvenile 100	35	1.388	11.8	1.154	1.156	1.279	1.326	1.543	1.762
	2m	Mature 100	45	1.673	13.1	1.152	1.212	1.536	1.697	1.825	2.148
2 by 8 edgewise MOE	1mE	0	8	1.733	5.8	1.543	—	1.647	1.769	1.804	1.840
	D57m	Mature 57	8	1.529	11.6	1.215	—	1.402	1.554	1.680	1.743
	2j	Juvenile 100	5	1.264	4.0	1.220	—	1.225	1.250	1.310	1.350
	2m	Mature 100	9	1.719	7.9	1.522	—	1.570	1.776	1.841	1.850

[a] 2 by 4 tension test results with specimens having greater than 15% moisture content were dropped.

Appendix C-Cumulative Frequency Distributions

Appendix C provides comparison plots of cumulative frequency distributions for strength and stiffness test results for the four different tests (flatwise and edgewise 2 by 2 bending, 2 by 4 tension, and 2 by 8 edgewise bending) conducted on each species. Figure C1 shows the strength results for various combinations of low-grade core materials for the Douglas-fir bending and tension tests. Figure C2 shows the Southern Pine strength results for the bending and tension tests on low-grade core material combinations. The MOE cumulative frequency results for Douglas-fir are shown in Figure C3. Figure C4 shows the Southern Pine MOE results for the various test sizes and combinations of low-grade core material.

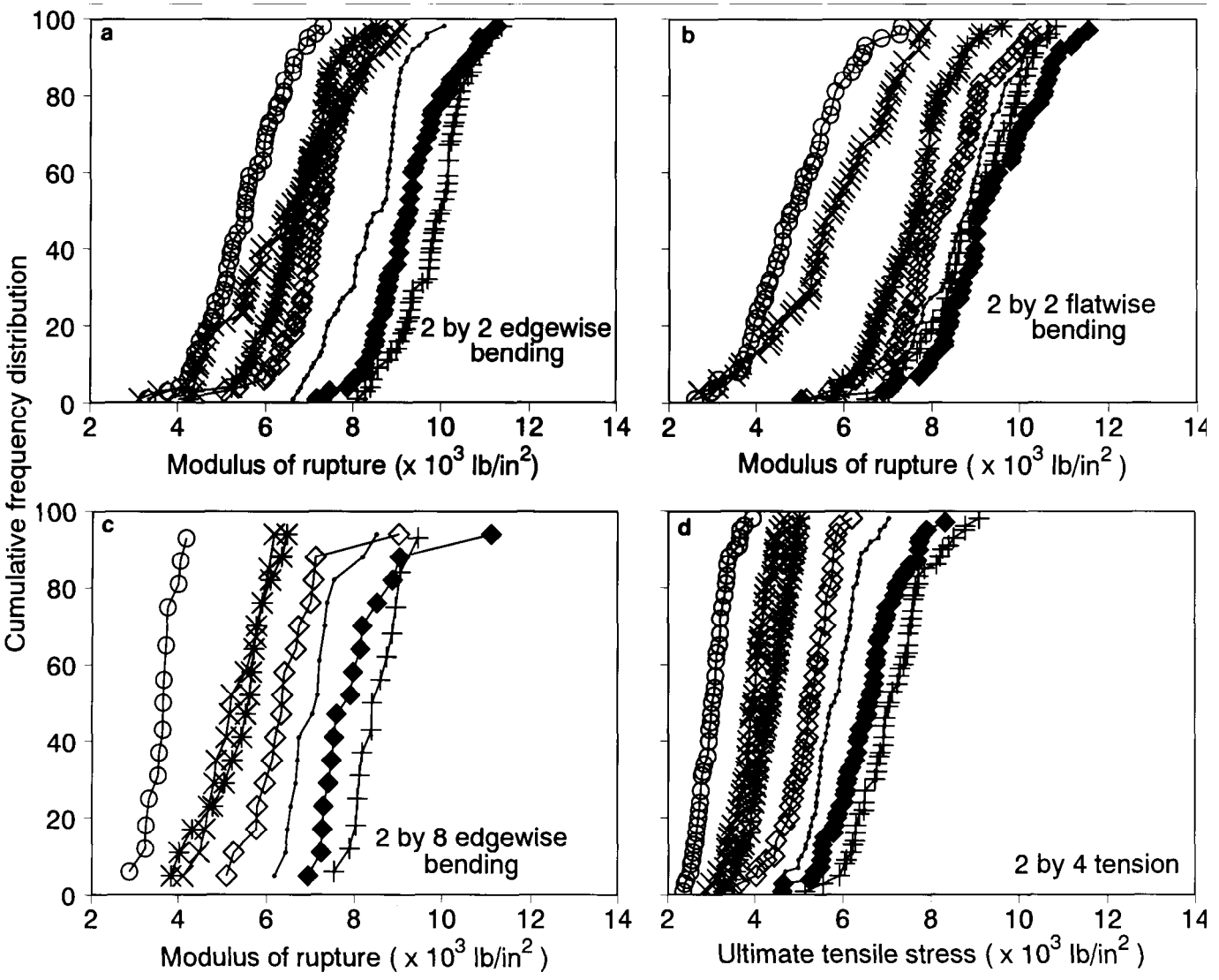

Figure C1–Cumulative frequency distributions for Douglas-fir strength test results for various combinations of low-grade core materials.

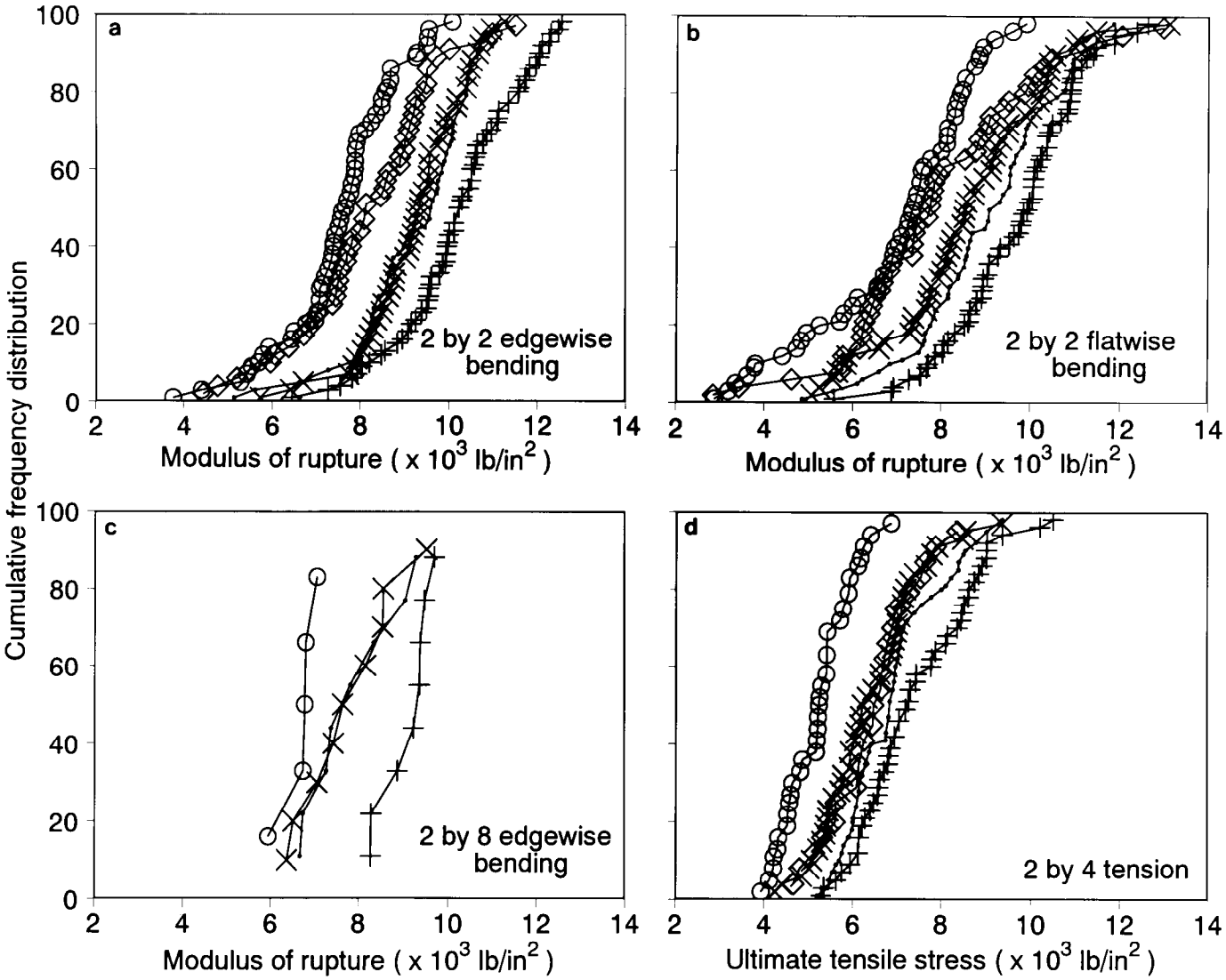

Figure C2–Cumulative frequency distributions for Southern Pine strength test results for various combinations of low-grade core materials.

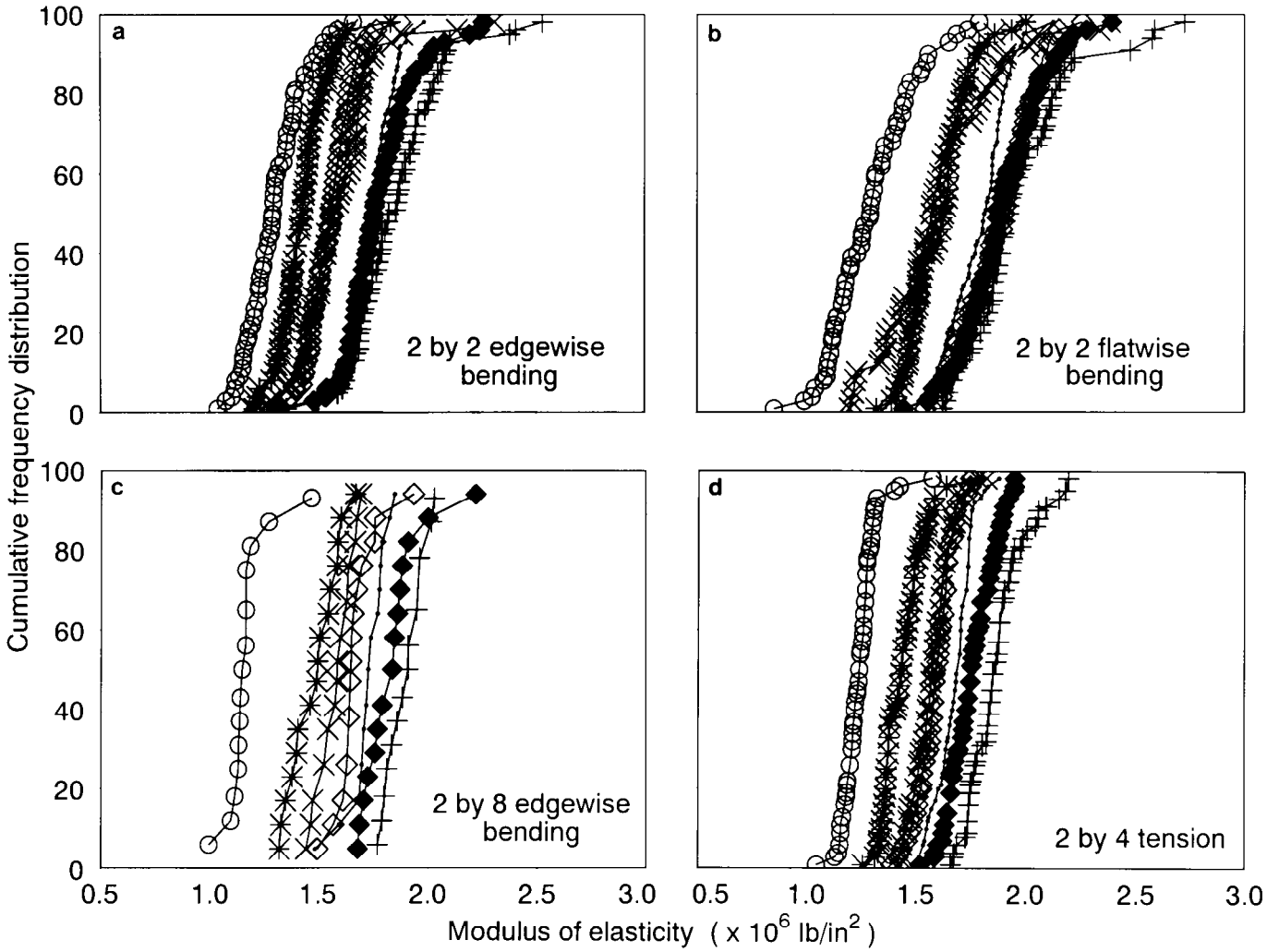

Figure C3–Cumulative frequency distributions for Douglas-fir MOE results for various combinations of low-grade core material.

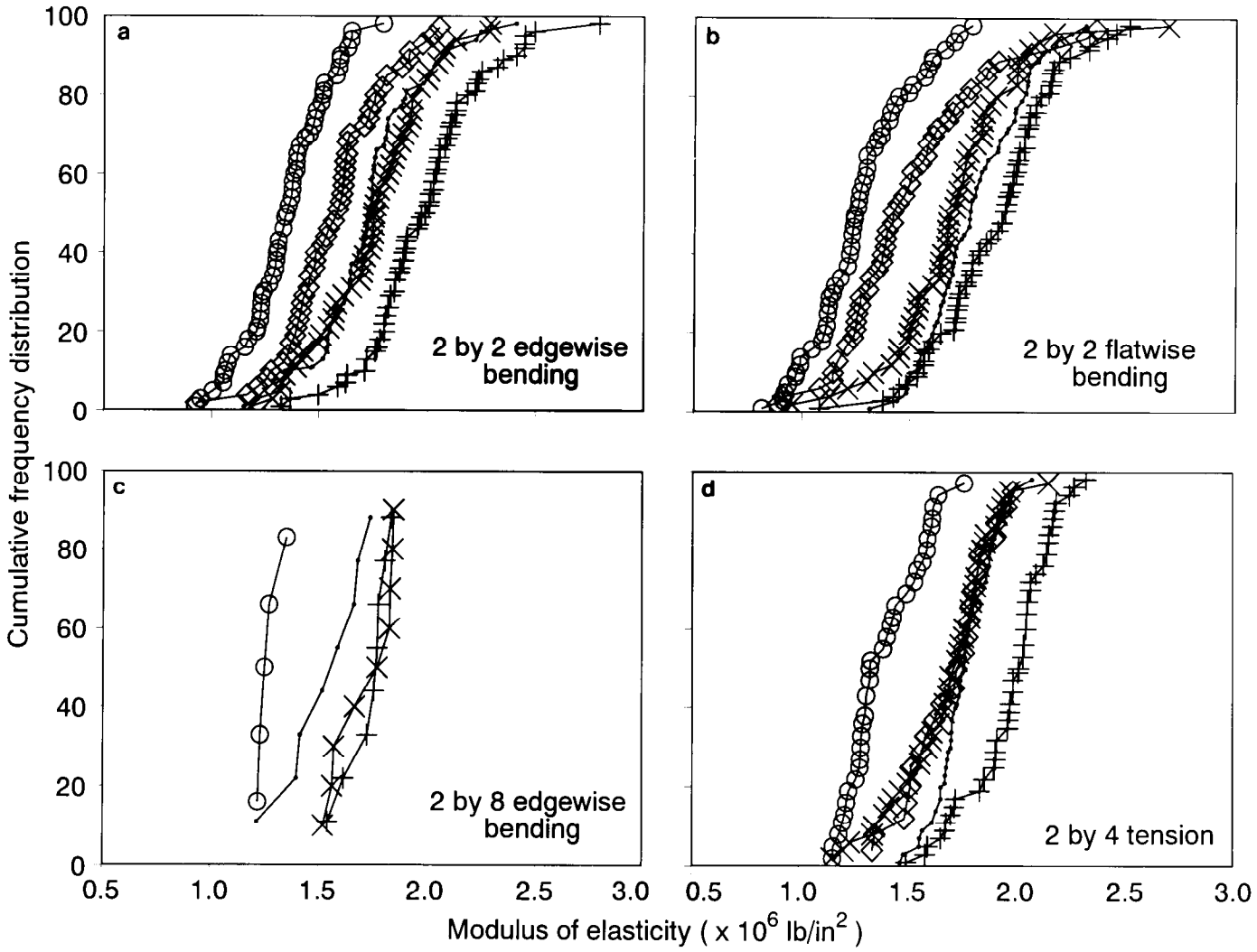

Figure C4–Cumulative frequency distributions for Southern Pine MOE results for various combinations of low-grade core material.

Appendix D-Failure Code Summary

Failure code information was collected on all tests; a three-digit failure code was used. The first digit represents failure location. Failures were categorized as failing at, between, or outside the load heads. The second digit of the failure code represents the type of failure observed: tension, compression, or shear. The third digit was an attempt to classify the cause of failure. Failures were determined to be a result of knots, joints, slope of grain, wood, or compression wrinkling rather than tension, compression wrinkling, or glueline. Table D1 summarizes the failure code information collected during testing.

Table D1—Douglas-fir and Southern Pine LVL testing failure codes

Test	Specimens	Low-grade core (%)	Failure code[a]																										
			111	112	113	114	115	121	122	124	126	134	137	211	212	213	214	224	225	226	231	232	234	311	312	314	331	334	337
Douglas-fir																													
2 by 2	1mE	0	9	2		42				1					1		4		1										
edgewise	D25j	Juvenile 25	4	1		43									1		15												
MOR	D50j	Juvenile 50	1			42											21												
	D50m	Mature 50	1			43										1	19												
	D75j	Juvenile 75	3		2	42								2	1		14												
	2j	Juvenile 100	3	1		30								1			22									3			
	2m	Mature 100	3	3		45									3		10												
2 by 2	1mE	0	1			18					1	1			2		6						4			1	1	24	1
flatwise	D25j	Juvenile 25	4	1		21			1		1	1		1	1	1	8			1			3	1	1	1		17	
MOR	D50j	Juvenile 50	4	2		38								1			9				1		3			5		1	
	D50m	Mature 50		2		37									2		11		5	3								4	
	D75j	Juvenile 75	1			41									1		18		3										
	2j	Juvenile 100	7	1	1	26						1		2	3		16								1	1		1	
	2m	Mature 100	4	2		29						1	2	1	2	1	21								1				
2 by 4	1mE	0		27		32									1														
tensile	D25j	Juvenile 25		18		45											1												
UTS	D50j	Juvenile 50		17		37																							
	D50m	Mature 50		27		37																							
	D75j	Juvenile 75		19		45																							
	2j	Juvenile 100		18	1	37											4												
	2m	Mature 100		30		31									3														
2 by 8	1mE	0				7					1						4	3											
edgewise	D25j	Juvenile 25				10											5									1			
MOR	D50j	Juvenile 50				13											3												
	D50m	Mature 50				10	1										4									1			
	D75j	Juvenile 75				16																							
	2j	Juvenile 100				9											6												
	2m	Mature 100				14											2												

Table D1—Douglas-fir and Southern Pine LVL testing failure codes-con.

Test	Specimens	Low-grade core (%)	Failure code[a]																										
			111	112	113	114	115	121	122	124	126	134	137	211	212	213	214	224	225	226	231	232	234	312	314	331	334	337
Southern Pine																													
2 by 2	1mE	0				42								1			21												
edgewise	D57j	Juvenile 57				33											13												
MOR	D57m	Mature 57			1	37											21												
	3	Juvenile 100				42											12												
	2m	Mature 100				37											12												
2 by 2	1mE	0				27											20		1	1			1				12	2	
flatwise	D57j	Juvenile 57				20											13								1		12		
MOR	D57m	Mature 57				38					1						4		3	1			1				10		
	2j	Juvenile 100	1			26						1			1		18							1		5	1		
	2m	Mature 100				29											5		1	2					1		11		
2 by 4	1mE	0				50																							
tensile	D57j	Juvenile 57				23																							
UTS	D57m	Mature 57				51											3												
	2j	Juvenile 100				35																							
	2m	Mature 100				45																							
2 by 8	1mE	0				7														1									
edgewise	D57m	Mature 57				8																							
MOR	D57m	Juvenile 100				4											1												
	2m	Mature 100				9																							

[a] First digit is location: 1, between load heads; 2, at load heads; 3, outside of load heads.
Second digit is type of failure: 1, tension; 2, compression; 3, shear.
Third digit is cause of failure: 1, knot; 2, joint; 3, slope of grain; 4, wood; 5, compression rather than tension; 6, compression wrinkling; 7, glueline.

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Appendix E-Economic Analysis

The 1mE material produced represented typical strength and stiffness of material produced by LVL manufactures. The test results obtained from the inclusion of juvenile wood material allows for a preliminary look at what will be the economic impact that increased juvenile wood in the resource will have on LVL production. Different combinations of production and veneer cost at various mixtures of juvenile and mature materials using the strength and stiffness results from Tables 2 and 3 are tabulated in Table El. It is assumed that the customer purchasing the LVL product is willing to pay a unit price regardless of the juvenile content as long as the LVL product will satisfy current performance requirements. The amount of increased volume needed to compensate for the low-quality juvenile material was determined by expanding the width or depth of the original test specimens to produce members of the same load-carrying or deflection capacity as the 1mE material for the same test mode. Table El can be used by a manufacturer to roughly estimate the value of the juvenile veneer for a given mixture and determine at what point it is inadvisable to add further juvenile material.

The calculations are defined as follows:

$$Rm + Rj = 1 \text{ and } Cm + Cv + Cj \cdot (1+w) = 1 \text{ (unit price)}$$

$$Zr = \text{strength of the D billet/1mE strength}$$

$$Ze = \text{stiffness of the D billet/1mE strength}$$

where

Cm is manufacturing costs

Cv is veneer costs for product with all high-quality veneer

Cj is veneer costs required for juvenile material to produce one unit

Zr is relative strength of juvenile wood (from Tables 2 and 3)

Ze is relative stiffness of product containing juvenile wood

Rj is relative amount of low-grade material in the core

Rm is relative amount of mature wood on faces (1 - Rj)

w is percentage of additional low-grade material lost in processing

Relative volume of the material needed for new products containing juvenile wood was calculated as follows.

If the member is acting as an edgewise bending member to meet the performance requirement, the beam is made with additional depth. The section modulus and the moment of inertia increase, causing the volume required to increase as follows:

$$\text{Strength } Vr = \frac{2}{\sqrt{1/Zr}} \text{ (additional beam depth)}$$

$$\text{Stiffness } Vr = \frac{3}{\sqrt{1/Ze}}$$

where

Vr is relative volume needed for new product containing juvenile wood

If the member is in place flatwise or is acting as a tension member to meet the performance requirement, the beam is made wider. Thus, only the area of material is increased, causing the volume to increase as follows:

$$Vr = 1/Zr = 1/Ze \text{ (increases the area of member)}$$

Manufacturing costs were determined by assuming manufacturing costs are proportional to volume.

$$Vr \cdot CM = \text{new manufacturing costs}$$

$$1 - Vr \cdot Cm = \text{value of veneer}$$

$$Rm \cdot Vr \cdot Cv = \text{value of high-grade veneer}$$

$$Cj = (1 - Vr \cdot Cm) - Rm \cdot Vr \cdot Cv = \text{value of low-grade veneer}$$

Therefore, the cost per unit for

$$\text{high-grade core} = (Rm \cdot Vr \cdot Cv)/(Rm \cdot Vr) = Cv$$

$$\text{low-grade core} = [(1 - Vr \cdot Cm) - Rm \cdot Vr \cdot Cv]/Rj \cdot Vr \cdot (1 + w)$$

$$= [\{1 - Vr \cdot (Cm + Rm) \cdot (1 - Cm)\}]/[Vr \cdot (1 - Rm)(1 + w)]$$

The overall new unit cost would be

$$\text{Unit cost} = 1 = Vr \cdot Cm + (Vr \cdot Cv \cdot Rm) + [Vr \cdot (1 + w) \cdot Cj \cdot Rj]$$

Table El-Economic analysis of the relative worth of juvenile veneer per unit volume for other veneer cost combinations

Performance criteria	Juvenile veneer (%)	Low-grade/ 1mE	Veneer volume needed	Value of juvenile veneer per unit cost[a]			
				Veneer cost			
				0.6	0.5	0.4	0.3
				Other cost			
				0.4	0.5	0.6	0.7
Douglas-fir							
2 by 2 edgewise bending							
Strength	25	0.94	1.03	0.40	0.32	0.24	0.15
	50	0.73	1.17	0.25	0.17	0.09	0.00
	75	0.68	1.21	0.30	0.22	0.14	0.05
Stiffness	25	0.96	1.01	0.45	0.37	0.29	0.20
	50	0.84	1.06	0.41	0.32	0.24	0.16
	75	0.77	1.09	0.41	0.32	0.24	0.16
2 by 2 flatwise bending							
Strength	25	1.04	0.96	0.63	0.54	0.46	0.38
	50	0.92	1.09	0.36	0.28	0.20	0.11
	75	0.84	1.18	0.33	0.24	0.16	0.08
	25	0.96	1.04	0.36	0.27	0.19	0.11
Stiffness	50	0.95	1.05	0.42	0.34	0.25	0.17
	75	0.82	1.23	0.30	0.21	0.13	0.05
2 by 4 tension							
Strength	25	0.92	1.09	0.24	0.15	0.07	-0.01
	50	0.73	1.37	0.05	-0.04	-0.12	-0.20
	75	0.61	1.64	0.06	-0.02	-0.10	-0.19
Stiffness	25	0.94	1.06	0.40	0.22	0.13	0.05
	50	0.85	1.18	0.24	0.16	0.08	-0.01
	75	0.77	1.30	0.24	0.16	0.08	-0.01
2 by 8 edgewise bending							
Strength	25	0.95	1.03	0.41	0.33	0.24	0.16
	50	0.76	1.15	0.28	0.20	0.12	0.03
	75	0.63	1.26	0.27	0.19	0.10	0.02
Stiffness	25	0.97	1.01	0.47	0.38	0.30	0.22
	50	0.88	1.04	0.43	0.35	0.26	0.18
	75	0.78	1.09	0.41	0.33	0.25	0.16
Southern Pine							
2 by 2 edgewise bending							
Strength	57	0.80	1.12	0.35	0.26	0.18	0.10
	100	0.74	1.16	0.38	0.30	0.22	0.13
Stiffness	57	0.79	1.08	0.39	0.31	0.22	0.14
	100	0.68	1.14	0.40	0.32	0.23	0.15
2 by 2 flatwise bending							
Strength	57	0.81	1.23	0.22	0.14	0.06	-0.03
	100	0.72	1.39	0.27	0.18	0.10	0.02
Stiffness	57	0.79	1.27	0.19	0.11	0.03	-0.06
	100	0.67	1.49	0.23	0.14	0.06	-0.02
2 by 4 tension							
Strength	57	0.87	1.15	0.31	0.23	0.14	0.06
	100	0.70	1.43	0.25	0.17	0.08	0.00
Stiffness	57	0.86	1.16	0.30	0.21	0.13	0.05
	100	0.70	1.43	0.25	0.17	0.08	0.00
2 by 8 edgewise bending							
Strength	100	0.74	1.16	0.30	0.21	0.13	0.05
Stiffness	100	0.73	1.11	0.42	0.33	0.25	0.17

[a]Unit cost = 1.

* U.S. GOVERNMENT PRINTING OFFICE: 1993-746-040/80004