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Fracture-failure behavior of western larch and some relationships with anatomical and mechanical properties of the wood

Bryan H. River
The University of Montana

THE FRACTURE-FAILURE BEHAVIOR OF WESTERN LARCH AND SOME RELATIONSHIPS WITH ANATOMICAL AND MECHANICAL PROPERTIES OF THE WOOD

By

Bryan H. River

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Approved by:

John P. Krier
Chairman, Board of Examiners

John M. Stewart
Dean, Graduate School

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INTRODUCTION

The inherent variability in the fracture-failure behavior or normal, nondegraded western larch (Larix occidentalis Nutt.) wood is the subject of this study. It is generally understood that compression wood and mechanical or chemical injury can cause brashness in wood. It has also been suggested that brashness may be an "abnormal" occurrence in so-called "normal" wood. Personal observation of bending tests of a large number of western larch specimens suggested this abnormal behavior (brashness) was actually one of two or three normal types of fracture-failure behavior of normal wood.

The objective of the study was to identify and describe the types of fracture-failure behavior and to determine, if possible, the source of its variation in "normal" western larch wood.

These goals are of practical importance in grading lumber for structural use where both safety and economy are important. Secondly, if the causes of variation in fracture-failure behavior can be found, there may be some opportunity to select parent stock and control or reduce this variation in fracture-failure behavior.

LITERATURE REVIEW

Fracture-Failure Behavior of Wood

The fracture-failure behavior of wood has been described by numerous authors (12,13,17,21,34,44,53).[1] Their descriptions are either inconsistent or inadequate in depth or breadth. Most of them agreed that two principal types of behavior occur, i.e., brashness and toughness. One source (12) recognized that a third type, intermediate, between brash and tough occurs. Preliminary results of this study indicated at least three distinct types of behavior do occur in western larch. The types are referred to throughout this report as brash, intermediate, and tough. There has been general agreement that brash and tough wood differ in the speed of failure and the degree of splintering (17,34,44,53). Some authors also referred to differences in the amount of energy absorbed to failure (34,44), the amount of deflection required to cause complete failure (34,44,53), shock resistance (44), and strength (34).

Koehler (34) reported that brashness may be caused by adverse conditions during growth or by damage arising after growth. Among the causes and characteristics of brash wood, Koehler lists: low density, low percent cell wall substance, large microfibril angle, very narrow growth rings or very wide ones in conifers, low fiber content in hardwoods, compression wood, compression failures, prolonged exposure to high temperatures, and the effects of decay organisms. Forsaith (13) has studied the morphology of brashness in tulip poplar (Lirodendron tulipifera L.), white ash (Fraxinus americana L.), and baldcypress

[1] Numbers in parentheses are literature citations at the end of this report.

(Taxodium distichum L.). He found that the amount of latewood, cell-wall thickness, and the size and number of bordered pits influence brashness in baldcypress. The percentage of fibers and the volume of rays and vessels influence brashness in the hardwoods. He also concluded that fiber length is not a factor of brashness.

Composition of the Cell Wall and Its Effect Upon Behavior

Wood cell-wall structure normally consists of a middle lamella, primary wall, and a three-layered secondary wall, designated ML, PW, and S-1, S-2, and S-3. Notable exceptions to this structure are in compression wood in which the S-3 layer is usually absent and in tension wood which has an additional gelatinous layer inside the S-3. A cellulose lattice and a lignin matrix comprise the primary mechanical systems (i.e., tension and compression) in woody plant tissues, although recent work indicates that hemicelluloses may play an important role in cell-wall bonding hitherto unrecognized (58). In 1932 Freudenberg (15) drew the analogy between wood cell-wall structure and reinforced concrete, where the crystalline cellulose acts as the reinforcing rods and lignin fills the role of the concrete. In recent years, filament-wound structures of reinforced plastics have been developed which closely approximate the wood cell wall and the cell itself. Mark (42) has used techniques evolved for analyzing the stresses in filament-wound structures to make a tensile stress analysis of coniferous tracheids.

In all of the above composite materials there is a rigid, usually brittle, incrusting matrix and a lattice of tough, flexible reinforcing material. The mechanical properties of the composite structure will vary

according to the properties and ratio of the component materials. If the ratio is increased toward the incrusting material, the composite may gain some compression strength but will lose some of its toughness and flexibility (38,54). It is not unreasonable to suppose, therefore, that wood with more than the normal percentage of lignin will be more brittle than wood with the normal percentage of lignin.

Clarke (5) found tropical timbers to have greater crushing strength but lower toughness than temperate woods of similar density. He concluded this difference was due to the higher lignin content of the tropical timbers. He estimated the different degrees of lignification by observing the staining reactions of the two groups with safranine and fast green. Hildebrandt (21) related that greater amounts of lignin increase crushing strength, also brittleness, and decrease tensile strength. Upon chemical analysis, Dadswell and Hawley (10) found brash oak to have higher lignin and lower cellulose content than tough oak specimens.

The distribution of lignin throughout the cell wall may also be of importance. Several workers have found that lignin occurs throughout the cell wall (6,45) with regions of highest concentration in the middle lamella and in the S-3 layer (50). Visual evidence presented by Côté et al. (6) has shown most of the lignin in softwoods to be in the secondary wall. Berlyn and Mark (2), in analyzing recent data, believed that less than 40 percent of the lignin of softwoods occurs in the compound middle lamella. Lignin forms a continuous matrix (50) incrusting the cellulose microfibrils (45). Dadswell and Hawley (10) speculate that an increase in wood lignin content which occurs within the cell wall may increase certain properties (it is assumed the authors refer to compression

strength parallel to the grain), while an increase occurring in the middle lamella may decrease certain properties (here it is assumed the reference is to toughness and shock resistance). Specific types of tissues which are brash and have high lignin contents are overmature wood which is formed in the outer portions of the stems of degenerate trees (18,19), earlywood (65), and compression wood (64).

From the above reports there would seem to be enough evidence to indicate lignin content and distribution as causes of variation in fracture-failure behavior. However, as noted by Hale and Clermont, variation in lignin content is interrelated with certain aspects of cell anatomy, such as cell-wall thickness and microfibril angle (19). They point out that, while latewood has a higher percentage of cellulose than the typically brash earlywood, the latewood also has a higher percentage of longitudinally oriented cellulose. High lignin content has been directly related to thin cell walls of juvenile wood (37), earlywood (19,37), and overmature wood (18,19). Hiller found that microfibril angle (see definition below) increases with decreasing cell-wall thickness in the latewood of two species of pine (24). She also found that juvenile wood (22) and earlywood (23) have large microfibril angles compared to mature wood and latewood, respectively. Therefore, high or low lignin content may only be an effect of variations in cell structure, while structure is the primary cause of variation in fracture-failure behavior.

Microfibril Angle

Microfibril angle (MFA) is the acute angle between the longitudinal cell axis and the direction of the cellulose microfibrils in the cell

wall. Generally, the angle refers to the microfibrils of the S-2 layer but may be specific to any layer or to the wall as a whole. There are strong implications that the S-2 microfibril angle may be a factor of variation in fracture-failure behavior. Compression wood, long recognized as a brash tissue, has a larger MFA than normal tissue of the same growth ring (64). And a striking example of the connection between MFA and brashness is afforded by a comparison of compression and tension woods (63,64). Compression wood with an MFA of 40 or more degrees is brash, while tension wood with an angle of 5 or less degrees is tough. Juvenile wood (9) and earlywood (25) have large MFA's and are typically brash (65).

Brashness is generally most evident in bending failure. Since ultimate failure from which brashness or toughness is determined occurs in the tension zone of the bending specimen, it follows that the structure and tensile properties of the cells are most important to brashness, although Koehler (33) does point out that the ratio of tensile to compressive strength may be of importance also. Tamolang et al. (57) found that the hardwood fiber breaking load was predominantly influenced by the cell-wall area but that fiber stiffness and strength per unit of cell-wall area increased with decreasing MFA. Jayne (28) and Leopold and McIntosh (39), working with individual fibers, and Ifju and Kennedy (26) and Wellwood (65), working with microtensile specimens,[2] have shown that latewood fibers of conifers have much higher tensile strength per unit of cell-wall area than do earlywood fibers. Ifju and

[2]Both studies were conducted on samples of Douglas-fir taken from the area between the 16th and 25th annual rings of three logs studied by Kennedy and Jaworsky (31).

Kennedy found the correlation between tensile strength and cellulose content (earlywood r = 0.698, latewood r = 0.787) to be significant at the 95 percent level of confidence, while the correlation between tensile strength and microfibril angle (latewood r = 0.688) was significant only in latewood fibers. The multiple correlation coefficient equaled 0.833.

The general conclusion (19,28,39) is that the disproportionate difference in the tensile strength per unit area of early- and latewood fibers is due to the higher percentage of cellulose and specifically the higher percentage of longitudinally oriented cellulose in the latewood. This is explained by the fact that cell-wall thickness variation is due mainly to variation of the S-2 layer (32). A thin-walled cell, such as in earlywood, has a lower percentage of its cell-wall area in the cellulose-rich S-2 layer and so has a lower cellulose content and a larger mean microfibril angle (19,24) than a thick-walled cell such as in latewood. A hypothetical example of this effect of cell-wall thickness upon microfibril angle is shown in figure 1.

If microfibril angle is a factor, it might be interesting to speculate the reason for its effect upon the nature of failure of wood. Earlywood is normally brash and has large microfibril angles (20°-30°) in the S-2. Latewood is normally tough and has smaller microfibril angles (3°-10°) in the S-2 layer. Since earlywood MFA is large, longitudinal cell stress creates large tension stresses perpendicular to the microfibrils in the call wall (fig. 2A). In latewood cells, longitudinal cell stress creates nearly parallel shear stress between the microfibrils (fig. 2B). Mark (43) has calculated the theoretical strength values for crystalline native cellulose as 3,690 kg./mm.^{2} in shear and only

Figure 1.--A hypothetical example of the influence of cell-wall thickness upon the S-2 layer and the cell average microfibril angle. The thin-wall cell representing earlywood is drawn to half scale in the radial direction in relation to the thick-wall latewood cell.

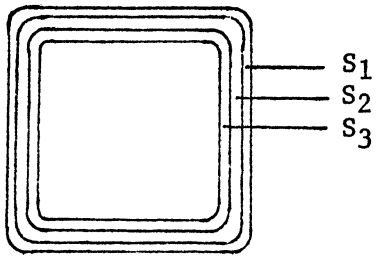
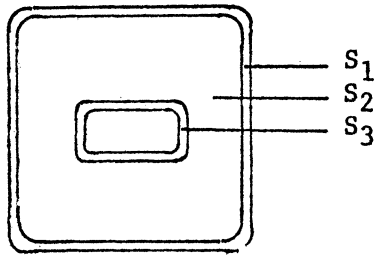
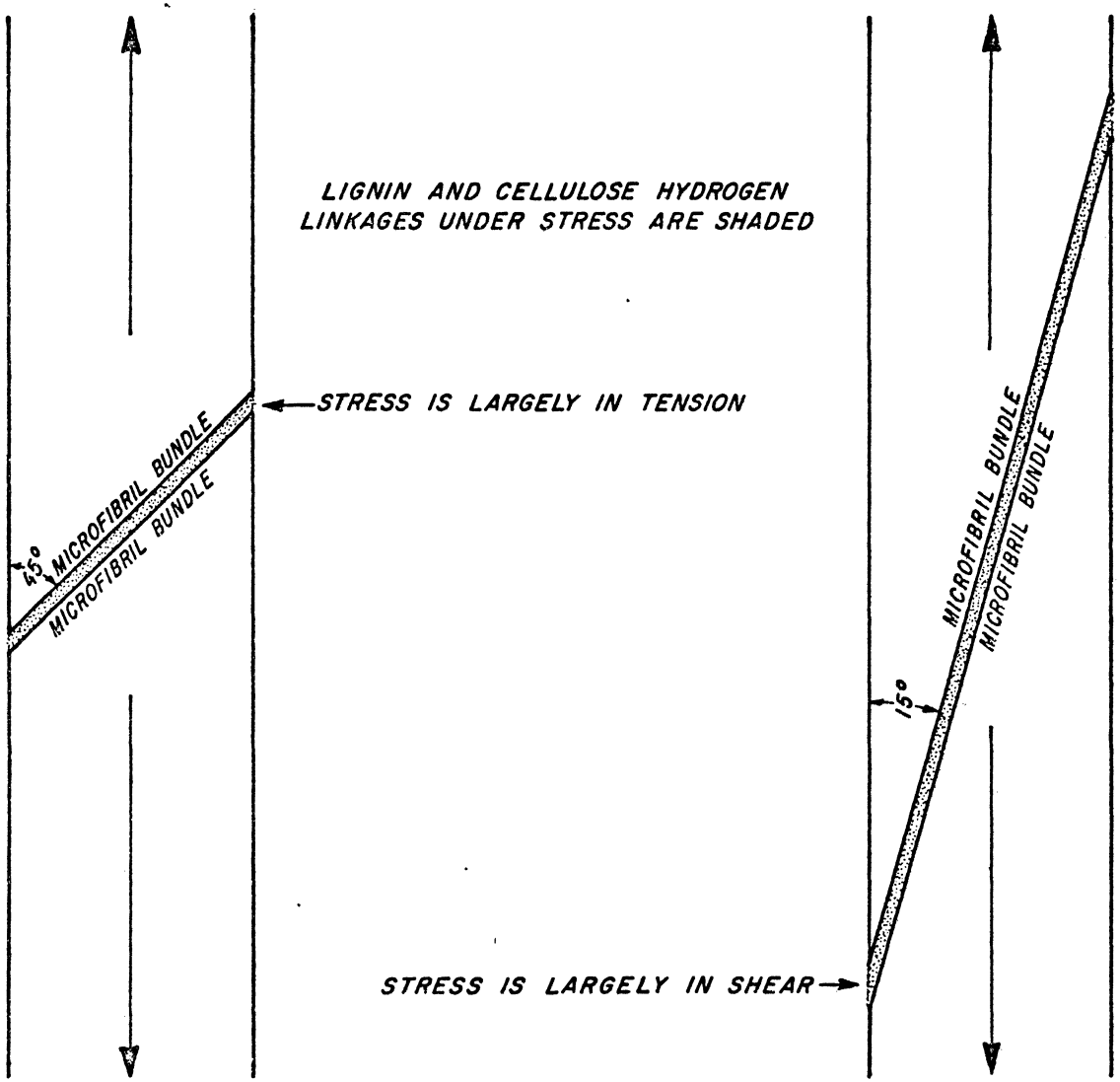
				
Wall layer	MFA	Percent composition	MFA	Percent composition
Primary	--	10	--	5
S-1	50-60	20	50-60	10
S-2	20	50	8	75
S-3	70	20	70	10
	Average weighted microfibril angle 35° from the vertical cell axis.		Average weighted microfibril angle 18° from the vertical cell axis.	

Figure 2A and B.--Representing the different types of stress between the cellulose microfibrils at large (A) and small (B) microfibril angles. At the large angle the stress is primarily in tension. At the small angle the stress is primarily in shear. (See text for discussion.)


LIGNIN AND CELLULOSE HYDROGEN
LINKAGES UNDER STRESS ARE SHADED
STRESS IS LARGELY IN TENSION
45°
MICROFIBRIL BUNDLE
MICROFIBRIL BUNDLE
15°
MICROFIBRIL BUNDLE
MICROFIBRIL BUNDLE
STRESS IS LARGELY IN SHEAR

116 kg./mm.^{2} in tension normal to the cellulose chains. In the best design of an adhesive joint, the adherends are arranged to develop the shear strength, not the tensile strength, of the adhesive (51). At large microfibril angles, such as occur in earlywood, the joints between microfibrils are under tensile stress. The microfibrils do not assume the tensile load as they should. On the other hand, at small microfibril angles such as in latewood, the microfibrils are under shear stress. Longitudinal cell stress is transmitted efficiently throughout the cell wall from microfibril to microfibril. When microfibril angles are small, the toughness of the cellulose and shear strength of the lignin are utilized to the maximum. When microfibril angles are large, the cellulose merely acts as a weak filler in the lignin matrix, which must assume the tensile stress.

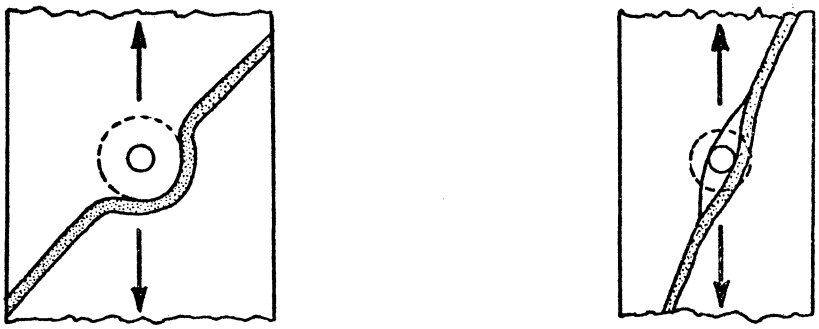
In support of this speculation, Garland (16) reported that earlywood cells fail transversely, completely rupturing the cell wall and exposing the lumen. Latewood of moderate microfibril angles may fail spirally between the microfibrils, while at smaller MFA's the failure occurs mostly along the S-1 to S-2 interface or in some instances actually breaking the microfibrils in tension parallel to the long axis. The following quotation from the observations of Ifju and Kennedy (26) indicates similar findings.

> "Springwood and summerwood specimens each displayed a typical type of failure. Failures in the springwood were strictly in tension across the cell walls, often at a slight diagonal to the horizontal axis of the section. Summerwood exhibited failures that were to at least some degree in longitudinal shear. Where tension failures occurred, the rupture appeared to be largely between cells rather than across their walls."

Bordered Pits

Forsaith (13) concluded that bordered pits are regions of weakness and are influential in determining brashness of Taxodium distichum. But in a later report, he stated that pits are not important to bending strength (14). Recent work by McIntosh led him to believe that large, circular-bordered pits in the earlywood are zones of weakness and that failure of the cell wall may begin at the top or bottom of the pit border where the microfibrils become perpendicular to the longitudinal cell axis (41). This concept is depicted in figure 3A. McIntosh's findings recall the previous discussion as to the effect of microfibril angle on the manner of cell-wall failure (see fig. 2). Extending that discussion in light of McIntosh's findings, it might be expected that latewood pits are not sources of weakness. In latewood cells the pit canals and apertures are usually elliptical. The flow of microfibrils past the pit is more streamlined with less deflection toward the perpendicular cell axis (fig. 3B). Therefore the potential source of weakness found in earlywood cells (i.e., where the microfibrils are perpendicular to the longitudinal cell axis) does not exist or is diminished in latewood cells.

Koehler (34) recognized that earlywood has more pits than latewood but dismissed the possibility of their influence on brashness. He contended that the concentric orientation of microfibrils around the pit border tends to strengthen rather than weaken the cell wall in this area. Garland, after microscopic examination of isolated fibers of tension specimens, concluded that bordered pits are not sources of weakness (16).



A

EARLYWOOD
TRACHEID

B

LATEWOOD
TRACHEID

Figure 3.--Portions of earlywood (A) and latewood (B) tracheids are shown in figure 3. The shaded areas represent separation between microfibrils in the cell wall due to longitudinal cell stress. Extreme deviation of the microfibrils at the earlywood pit (A) may be a source of weakness in earlywood cells.

In view of these conflicting reports, it is probable that pits may be a source of weakness in some instances, particularly in earlywood tracheids, but not in others, such as latewood tracheids. The answer will come only from microscopic observation of the cell wall at the initiation of and during fracture.

Moisture Effect

The loss of moisture below the fiber saturation point increases many strength properties in proportion to the loss. The Wood Handbook (59) shows percentage changes in strength properties corresponding to a 1 percent change in moisture content below the fiber saturation point.

Properties related to compressive strength show the greatest gains due to an increase in density and lateral bonding (hydrogen bonding)(66). Koehler (33) stated that a piece in which tensile strength is several times compressive strength (common in green wood) can be bent a great deal before it breaks. This is due to buckling of the fibers on the compression side. However, if tensile strength is not much greater (common in dry wood), the piece will snap abruptly across the grain on the tension side with relatively little bending (33). The fracture is brash. The wood is stiffer on a strength-to-weight basis, but brashness is caused by the low ratio of tensile to compressive strength. Thus, low moisture content, the presence of extractives, and/or additional cell-wall lignin may have the effect of increasing compressive strength, but not tensile strength, and so may be contributors to brash failure, just as other factors which detract from tensile strength may be.

Compression Failures

Jacobs (27) and Dadswell (9) studied the effects of growth stresses on wood in trees. They showed that longitudinal compression reactions of increasing intensity were found as the pith was approached. The accommodation of these stresses, according to Boyd (3), results in cell-wall deformations called "minute compression failures." Brashness has been shown to be associated with extensive compression failures lined up horizontally across many layers of cells (9,27). The displacement and separation of microfibrils lead to mechanical weakness and low impact strength that characterize brashness (11).

"Minute compression failures" may result from local concentrations of compressive forces. Such forces arise during severe windstorms or from impact by felling across logs or rocks, as well as from the weight of the standing tree.

Effect of High Temperature

Temperature has been blamed for brash behavior of wood. MacLean (40) reported the properties, toughness, and work to maximum load in static bending are much more sensitive to the deteriorating effects of heat than modulus of elasticity or modulus of rupture. For example, his results showed that 320° F. for 16 hours caused a 50 to 80 percent loss in shock-resistance properties. At a lower temperature (215° F.) over longer time periods, work to maximum load was reduced 74 percent, modulus of rupture 45 percent, and modulus of elasticity 17 percent after 11 months of exposure. Jayne proposed that these losses are due to a decrease in the length of the cellulose chain molecules (28).

Decay Organisms

Decay is certainly a cause of brashness in wood when such decay is evident to the naked eye. Incipient decay may also be a cause of brashness in apparently sound wood. The enzymatic action of fungal organisms is to hydrolyze or depolymerize the polysaccharides of the cell wall (7). In the initial stages, the degree of polymerization of cellulose in wood is reduced from about 1,600 to 1,300 glucose anhydride units by a white rot of sweetgum and from 1,600 to 70 units by a brown rot of sweetgum (8). In advanced decay, the long chain cellulose molecules are reduced to the basic repeating unit, cellobiose, and ultimately to glucose (8). If it is true that tensile strength and toughness rely upon the cellulose microfibril, it is easy to understand how brashness may arise from decay organisms which reduce the length of the cellulose chains within the microfibrils.

Koehler (30) recognized this factor in his treatise on brashness. He declared that toughness was the property most rapidly diminished and compression parallel to the grain the property least altered in the early stages of decay, while in the advanced stages all mechanical properties declined rapidly.

Age of the Tree During Wood Formation

Age connotes the condition of the tree and the vigor of the cambium when a given growth increment is formed. The terms juvenile wood, mature wood, and overmature wood refer to wood formed in the juvenile, mature, and overmature periods (periods of vigor) in the tree's life cycle and to

the anatomical characteristics peculiar to the type of wood formed. The table below shows evidence that juvenile and overmature wood typically possess many of the traits of brashness already discussed.

Table 1

Characteristic	Juvenile	Mature	Over-mature	Partial list of references
Specific gravity	Low	Med. to high	Low	19, 44, 49, 55, 67
Percent latewood	Low	Med. to high	Low	19, 44, 62
Tensile strength	Low	Med. to high	Low	44, 65
Cell-wall thickness	Thin	Thick	Thin	19, 36, 62
S-2 layer	Thin	Thick	Thin	19, 62
Cellulose content	Low	High	Low	10, 19, 31, 37, 44, 66, 68
Lignin content	High	Medium	High	10, 20, 36, 44
Microfibril angle	Large	Small	Large	9, 46
Cell diameter	Small	Small-med.-large	Large	36, 62
Cell length	Short	Med.-long	Med.-long	36, 62

METHODS

Selection of Material

Two samplings of western larch wood were made. Both samples included specimens of the brash, intermediate, and tough groups. The specimens were selected objectively to obtain a wide range in both specific gravity and rings per inch. These criteria ensured a wide range of cell configuration and wall structure. Specimens found upon visual examination to have defects such as compression wood, minute compression failures, decay, shake, or cross grain were not included in the samples since this study concerned the fracture-failure behavior of anatomically normal and undamaged wood.

Sample 1 consisted of specimens cut from freshly sawn green lumber collected during the summer of 1963 from 11 sawmills in Montana, Idaho, and Washington. Seventy-seven specimens were collected from 77 different boards. Seventeen of these were subsequently eliminated after testing and microscopic examination, upon the discovery of hidden defects such as those mentioned in the previous paragraph.

Specimens in sample 2 were from kiln-dried lumber collected in the summer of 1965 from two sawmills in northwestern Montana. The intent of this second sample was to obtain information about the fracture-failure behavior of the wood after the maximum load had been surpassed. This type of information was not obtained from sample 1. Here again, specimens with defects discovered after testing were eliminated from further consideration. The 76 specimens included in the final sample were cut from 38 boards.

Properties Measured

The anatomical properties and relationships listed below (items 1 through 12) were selected on the basis of the literature review as those which had the most probability of influence upon the strength and fracture-failure behavior of larch wood. The available equipment and the materials at hand also were important in determining those properties which could be measured. The mechanical properties listed (items 13 through 17) were measured with the hope they would provide a quantitative measure of the fracture-failure behavior in western larch.

		Symbol
1.	True (extractive free) specific gravity	TSG
2.	Dry (unextracted) specific gravity	DSG
3.	Rings per inch	RPI
4.	Percent latewood	PLW
5.	Percent cell-wall substance	PCWS
6.	Mean cell area	MCA
7.	Microfibril angle	MFA
8.	Extractive content	EXT
9.	Average radial diameter	ARD
10.	Cell-wall thickness	CWT
11.	Mean cell area ÷ cell-wall thickness	MCA/CWT
12.	Cell-wall thickness ÷ average radial diameter	CWT/ARD
13.	Modulus of elasticity	MOE
14.	Modulus of rupture	MOR

15. Fiber stress at proportional limit FSPL

16. Maximum load ML

17. Work to maximum load WML

The methods and units of measurement of these characteristics are described in the following paragraphs.

Static Bending Tests and Mechanical Properties

Static bending tests performed with sample 1 were conducted according to ASTM D143-52 (1) with specimens measuring 1.5- by 1.5- by 28-inch dimensions on a 30,000-pound-capacity test machine. Deflections were recorded in thousandths of an inch as read from a dial micrometer at load intervals of 50 pounds. Tests of sample 2 specimens were performed according to the same ASTM specification but with 1- by 1- by 16-inch specimens on a 60,000-pound-capacity test machine. The second machine, recently installed, had the capability of continuously recording load and deflection to and beyond the maximum load. These extended test data yielded useful information about the characteristics of the individual specimens at and immediately after failure which could not be obtained previously.

The area under the load-deflection curve, whether it was hand plotted or machine recorded, was measured with a polar planimeter and the proportional limit was determined by ocular estimate from the modulus line.

The data thus obtained, i.e., load and deflection at proportional limit and at maximum load, and the area under the load-deflection curve to the proportional limit and the maximum load were used to make the following calculations:

$$\text{Modulus of elasticity (MOE)} = \frac{P_1 L^3}{4ybh^3}$$

$$\text{Modulus of rupture (MOR)} = \frac{3P_2 L}{2bh^2}$$

$$\text{Fiber stress at the proportional limit (FSPL)} = \frac{3P_1 L}{2bh^2}$$

$$\text{Work to maximum load (WML)} = \frac{AQ}{V}$$

Symbols:

P_1 = load in pounds at proportional limit

P_2 = load in pounds at maximum load

L = specimen length of span

y = center point deflection at proportional limit

b = specimen breadth

h = specimen depth

A = area under the load-deflection curve

Q = work represented by 1 square inch of the load-deflection diagram

V = volume of the specimen over the beam span

Specific Gravity Determinations

Specific gravity determinations were made from 1-inch-long transverse slices of the bending specimens taken near the point of failure. Standard ovendry-water immersion technique was employed (60) with a major modification. Standard technique calls for coating the weighed ovendry specimen with hot paraffin before immersion in water for the volumetric determination. This was to prevent the specimen from absorbing water which would result in an error in the volume measured. It was found this coating procedure

could be eliminated with less than 1 percent resultant error by using a fast, direct-reading, top-loading balance (accuracy ± 0.03 g.) to measure the water displacement. This modification of procedure allowed the same blocks to be used for extractive content and true specific gravity (extractive-free) determinations.

Water Extraction

Extraction was performed on the specific gravity specimens to determine the water-soluble fraction of the unextracted ovendry wood. The blocks were placed in a pressure-vacuum vessel, which was filled with hot water (approximately 180° F.), and subjected to alternating 30-minute periods of pressure (50 to 60 p.s.i.) and vacuum (24 in.) while immersed. This treatment continued for 3 weeks with 1-day air-drying interruptions at the ends of 1 and 2 weeks. The air drying was an attempt to keep some air within the blocks so the pressure-vacuum cycles would create a flushing action within the blocks. Leaching was continuous while the specimens were immersed. At the end of 3 weeks, the blocks were slowly air dried and then ovendried. Extractive content was calculated by the equation:

$$\text{Percent extractive content} = \frac{W_1 - W_2}{W_1} \times 100$$

where:

W_1 = ovendry weight before extraction

W_2 = ovendry weight after extraction

The result is the water-soluble fraction expressed as a percentage of the original ovendry weight of the wood. After ovendrying, the specimens'

volumes were again measured by immersion and the extractive-free or true specific gravities were calculated.

Microtechnique

Blocks approximately 0.5 by 0.5 by 1.5 inches in the radial direction were cut from near the point of failure. These were softened by soaking in a 4 percent aqueous potassium hydroxide solution for 48 hours at 50° C. The softened blocks were next washed in fresh running tap water for 48 hours before being transferred to molten polyethylene glycol (PEG) 1,000 at 50° C. After 24 hours of soaking in PEG, the blocks were transferred to fresh molten PEG 1,000 to increase the concentration. Best results were achieved by chilling the PEG-saturated blocks before sectioning on a sliding microtome. Section thicknesses varied from 25μm to 40μm.[3] The horizontal angle of the knife to the path of travel varied from 10° to 45° and the vertical angle to the face of the block varied from 10° to 20° according to the knife employed and the texture of the wood. Staining was accomplished with a 0.5 percent aqueous hematoxylin solution, while destaining and mordanting were done with 2 percent aqueous iron alum (29). The stained sections were permanently mounted in HSR synthetic mounting media after dehydration in an alcohol-xylene series.

A different technique was used to prepare specimens for measuring microfibril angle. It is discussed separately under microfibril angle (page 25).

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[3] The 13th General Conference on Weights and Measures (69) has dropped the term micron and its symbol (μ) and standardized upon the term micrometer and its symbol (μm). Henceforth, measurements which previously would have been reported in microns in this paper are reported in micrometers (μm).

Anatomical Properties

Anatomical measurements, except microfibril angle, were made upon the transverse sections previously described.

Rings per inch were measured on a duolinear traversing microscope at a magnification of 100. The number of rings counted in traversing the radial length of the section was converted into rings per inch.

Percent latewood also was measured on the above instrument. One of the two parallel movements of the instrument traversed and recorded latewood, while the other movement traversed and recorded earlywood. The distance of latewood traversed was divided by the total distance traversed by both movements and multiplied by 100 to yield the percent latewood.

Percent cell-wall substance, mean cell area, and average radial diameter were all measured with one instrument. This instrument was a microprojector made from a microscope, a high-intensity light source, and a projection grid after the method of Ladell (35). The grid was marked with 10 random points. A 2-inch calibrated square was also marked on the grid, such that one side of the square was equal to a 370μm-long segment of the object under the microscope or a total object area of 136,900μm^2. The linear magnification of a projected image was 137.5 times.

The ratio of cell-wall substance to total area was found by projecting images from 10 random locations on the transverse section and counting the number of grid points intercepting cell wall and the number intercepting cell lumena at each location. The ratio times 100 is the percent cell-wall substance. Since rays constitute transverse rather than longitudinal elements, they were not counted.

The number of cells in the projected image which were included in the grid in the radial and tangential directions of the wood were counted at the same 10 random locations on each slide. The total number of cells at a given location (radial No. x tangential No.) divided into the object area (136,900μm^2) yielded the mean cell area. The average radial diameter was found by dividing the average number of radially aligned cells into 370μm.

Cell-wall thickness was calculated from the measurements of mean cell area and percent cell-wall substance using a model for the cell configuration. The accuracy of this estimate depends on how well the model agreed with the actual cell configuration of each specimen. The model chosen was that of concentric squares. In many specimens, the actual cell outline is rectangular or polygonal, but the square was chosen as a reasonable approximation for ease of computation. The formula was developed as shown below.

$$\text{Percent lumen area} = 100 - \text{percent cell-wall area (not including ray tissue or middle lamella)} \quad (1)$$

$$\text{Mean cell area} \times \text{percent lumen area} = \text{mean lumen area} \quad (2)$$

Since these areas (MCA and MLA) are squares, the values of X and Y are equal to $\sqrt{MCA}$ and $\sqrt{MLA}$, respectively. Therefore, cell wall thickness (CWT) may be computed by the following:

$$CWT = \frac{\sqrt{MCA} - \sqrt{MCA \times MLA}}{2} \text{ micrometers} \quad (3)$$

or

$$CWT = \frac{X - Y}{2} \text{ micrometers} \quad (4)$$

Microfibril angle was measured in the latewood of radial sections made from blocks cut near the region of failure in the neutral stress zone. Pretreatment of the blocks consisted of saturating with water followed immediately by ovendrying at 102° C. This was intended to form microchecks in the cell walls and facilitate the determination of microfibril angle. The pretreatment was not completely successful. With some specimens, it was necessary to measure the inclination of the pit apertures in the absence of microchecks.

Sectioning was accomplished after soaking the blocks overnight in soapy water. No other softening or embedding was necessary. Sections were cut at 25μm thickness. Staining the sections was not necessary since polarized light was to be used in their examinations.

Examination was made with a Zeiss petrographic polarizing microscope having a graduated rotating stage. By swiveling the entire eyepiece mount, the vertical crosshair of the eyepiece could be aligned with the longitudinal tracheid walls. Then the stage was turned until the vertical crosshair of the eyepiece became aligned with the microchecks or pit apertures in the latewood cell wall. The use of polarized light helped to reveal the cracks in the cell wall. The microfibril angle was read

directly from the stage index in degrees. Twenty measurements were made on each specimen at random points in the latewood.

Scanning Electron Microscopy

A scanning electron microscope was used to observe fracture surfaces of specimens from each fracture-failure type. The instrument was Cambridge Instrument Company's "Stereoscan" scanning electron microscope. Specimens were splinters or other fragments taken from the fractured specimens. Before observation, the specimens were coated with a thin layer of gold-palladium alloy to provide a conductive surface. Examination was made in the emissive mode of operation.

The great advantage of the scanning electron microscope over the transmission electron microscope or the light microscope lies in the depth of focus, which is at least 300 times greater at comparable magnifications. This is a tremendous advantage since fractured surfaces can be observed in depth. The clarity of the image and depth of focus ease morphological interpretation of the surface. The scanning electron microscope is a powerful tool for identifying the types of fracture which occur on a cellular and subcellular level.

Data Analysis

A set of hypothesized fracture-failure criteria were developed in the first section of the results beginning on page 30. These criteria represent the three basic types of fracture-failure behavior. They are qualitative in nature. The criteria were used to classify the broken specimens into behavior groups so an analysis could be performed to

determine the source of variation of the behavior. When the 60 specimens of sample 1 were classified according to these criteria, they were very close to being equally distributed among the three fracture-failure behavior groups. Several specimens which were on the borderline between the brash-intermediate or intermediate-tough groups were placed to make the three groups equal. This step facilitated computer programing and the statistical analysis. Once the specimens had been classified, the measured values of the quantitative characteristics listed on pages 18-19 were tabulated by specimen group association as shown in Appendix A.

The first step in the analysis of the data was to test for quantitative differences among the qualitative groups. If such differences were detected, this was taken as evidence that the three fracture-failure groups represented distinct types of behavior. Tukey's Test of Comparisons Among Means, as outlined by Snedecor (52), provides a method of testing for these differences by comparing the numerical difference between the means of any two groups against the "Honestly Significant Difference" (HSD).

$$HSD_{.05} = \frac{EMS}{N} Q$$

where HSD = honestly significant difference at the 95 percent level of confidence

EMS = error mean square (variance)

Q = a factor drawn from the table of the Studentized Range entered by L groups and L(N - 1) degrees of freedom

N = number of specimens in each group

A difference between any two groups means greater than the HSD was accepted as significant at the 95 percent level of confidence.

A special technique had to be found to assess the effects of the quantitative anatomical characteristics upon the qualitative fracture-failure behavior. Discriminant function analysis seemed to offer such a technique. A program by Church (4) which included both discriminant function analysis and the Mahalanobis D^2 statistic was used. Computations and discussion of the analysis and the Mahalanobis D^2 statistic are provided in Appendix B.

Two assumptions were made in order to use the technique. The first assumption was that fracture-failure behavior is either the result of a given characteristic or the interaction between a group of characteristics. This assumption is fairly safe since care was taken as previously described to remove all the specimens with defective anatomy from the sample. The second assumption was that the anatomical characteristic(s) which determine fracture-failure behavior will show distinct quantitative separations among the qualitative groups. The latter assumption was confirmed or rejected by the results of the Tukey's tests of the grouped data.

The discriminant function technique used the measured quantitative values of the anatomical characteristics in the discriminant function to classify specimens into one of the three qualitative groups: brash, intermediate, or tough. The classification of each specimen by the discriminant was then compared to that specimen's classification according to the fracture-failure criteria. A close association between a given anatomical characteristic and fracture-failure behavior was implied when there was close agreement between the results of the two systems of classification of all 60 specimens. The relative sizes of the characteristics' D^2 statistics, which are computed during the program, also offer information

about discriminatory capability and imply a degree of association between the characteristic and fracture-failure behavior.

RESULTS[4]

Observations

Fracture-Failure Criteria and Specimen Classification

Three groups were identified: brash, tough, and intermediate. To illustrate the fractures, five specimens drawn from each of the visually classified groups are shown in radial face view (fig. 4) and tangential face view (fig. 5). The brash specimens (group A in each photograph) do not have splinters or may have one or two thick stubs. The intermediate specimens (group C) have relatively few coarse, stubby splinters generally wide along the growth ring (tangential view--fig. 5). Tough specimens (group B) have numerous splinters, needlelike in both the radial and tangential views.

Load-deflection diagrams were recorded for 76 specimens of sample 2. Three general types corresponding to brash, intermediate, and tough are shown in figures 6, 7, 8, 9, and 10. The characteristics of these diagrams are as follows:

Brash (fig. 6).--Complete catastrophic failure at the maximum load--complete instantaneous release of stored energy.

Intermediate (fig. 7).--Incomplete, but still catastrophic, failure at maximum load--still retained some ability to resist bending for a period beyond maximum load--failure in several releases of energy.

---

[4]Sample 1 is implied throughout these observations unless the specimens are specifically identified as sample 2.

Figure 4.--(A) Side (radial face) view of the broken bending specimens showing the nonfibrous fracture typical of the brash group. (B) Needlelike splinter fracture typical of the tough group. (C) Large, stubby splinter fracture typical of the intermediate group. (See text pages 30 to 40 for discussion.)

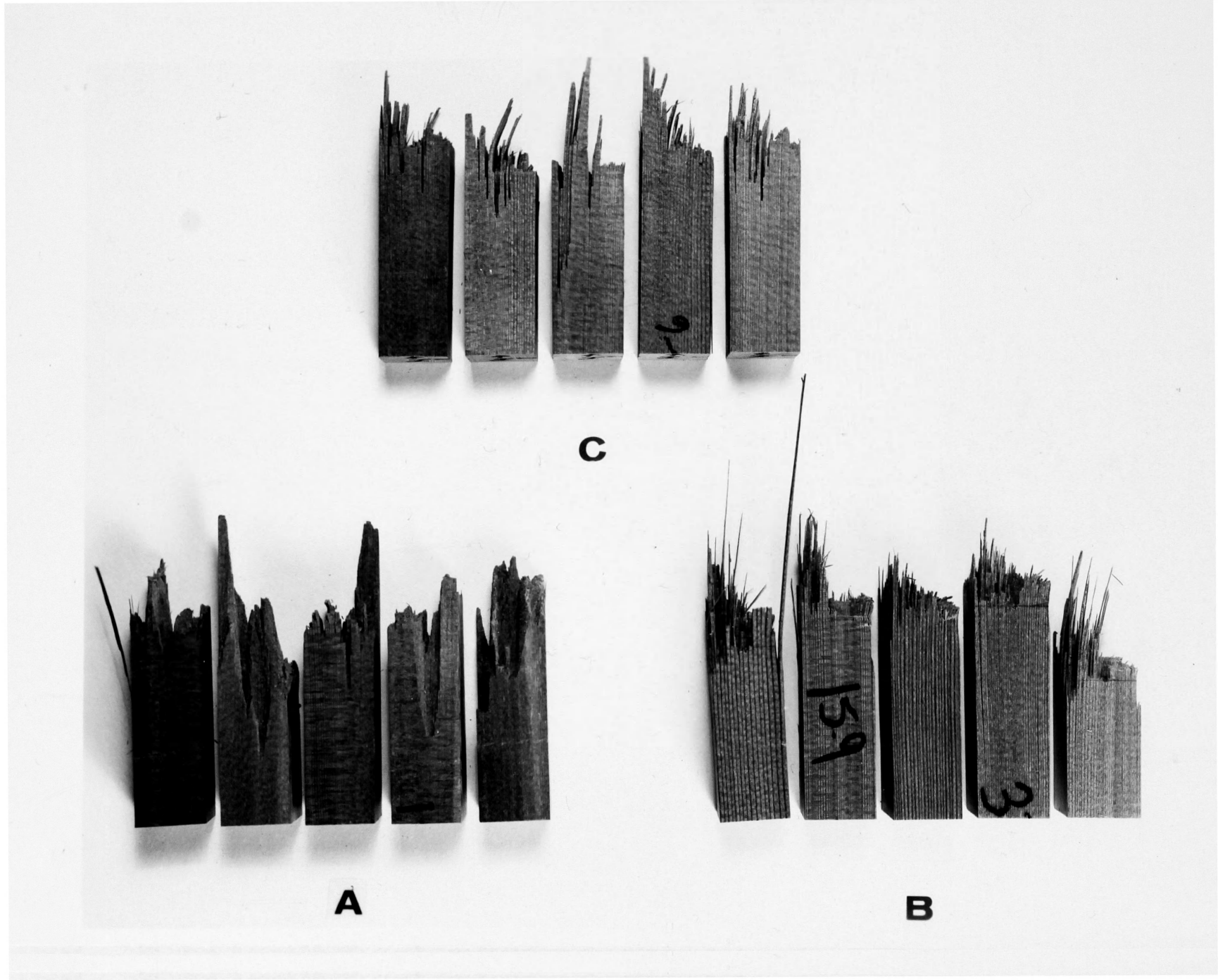

C
A
B

Figure 5.--Top (tangential face) view from the pith side of the same specimens shown in figure 4. (A) Brash, (B) tough, and (C) intermediate.

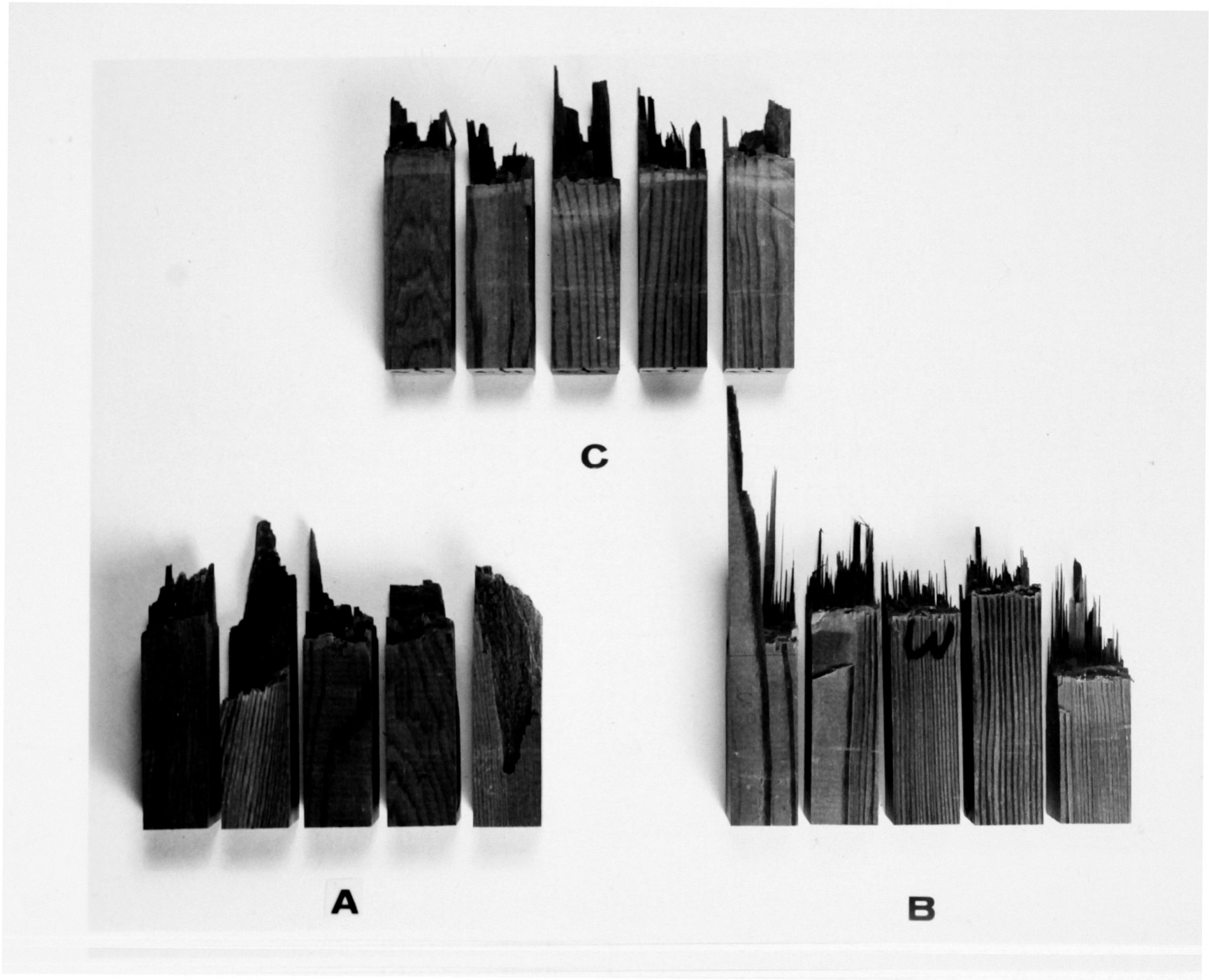
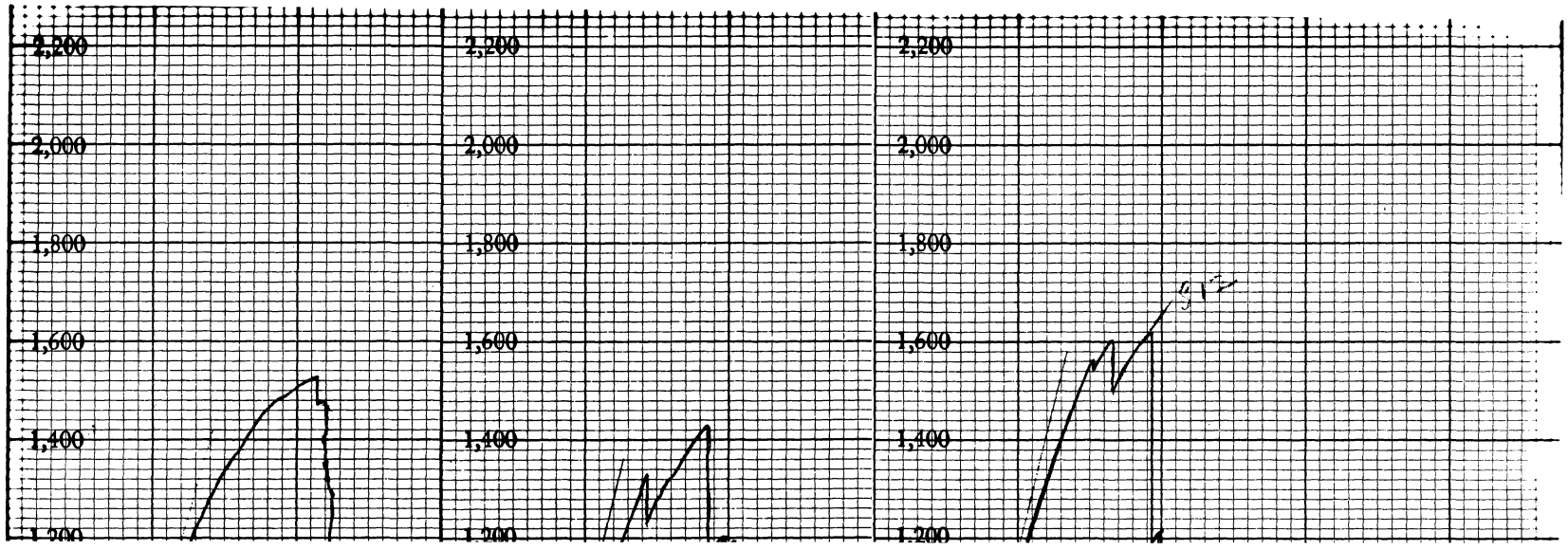

C
A
B

Figure 6.--The three load-deflection curves show actual recordings taken during bending of three different brash specimens. Failure is abrupt and essentially complete. NOTE: The Y scale for load is 2X. The X scale for deflection is 0.025 inch per division.

1,000
1,200
1,400
1,600
1,000
1,200
1,400
1,600

Figure 7.--The three load-deflection curves show actual recordings taken during bending of three different intermediate specimens. Failure was catastrophic but not immediately complete. NOTE: The Y scale for load is 2X. The X deflection scale is 0.025 inch per division.


2,200
2,000
1,800
1,600
1,400
1,200
2,200
2,000
1,800
1,600
1,400
1,200
2,200
2,000
1,800
1,600
1,400
1,200

Tough (figs. 8, 9, and 10).--Incomplete, tenacious, slow failure after maximum load--possessed great resistance to continued bending beyond maximum load--failure in many small releases of energy extending over a long period of time.

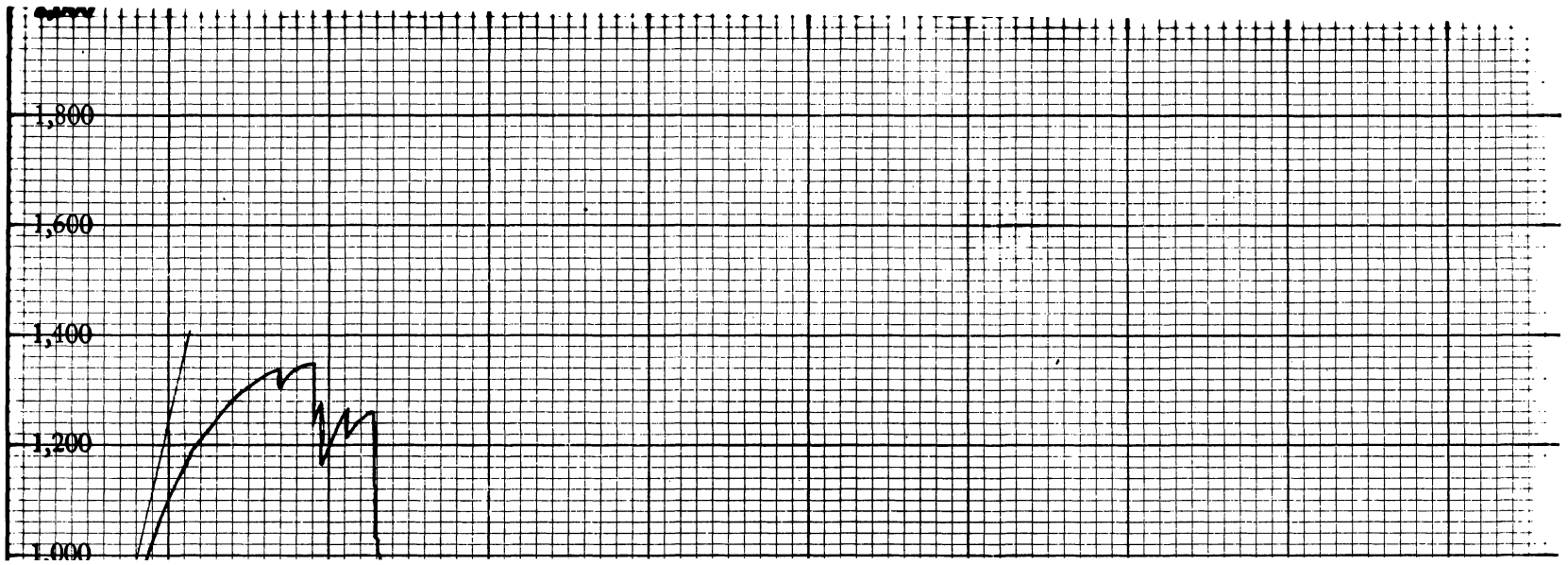
From these observations, the set of fracture-failure criteria shown in figure 11 was developed to classify specimens and tabulate data for further analysis.

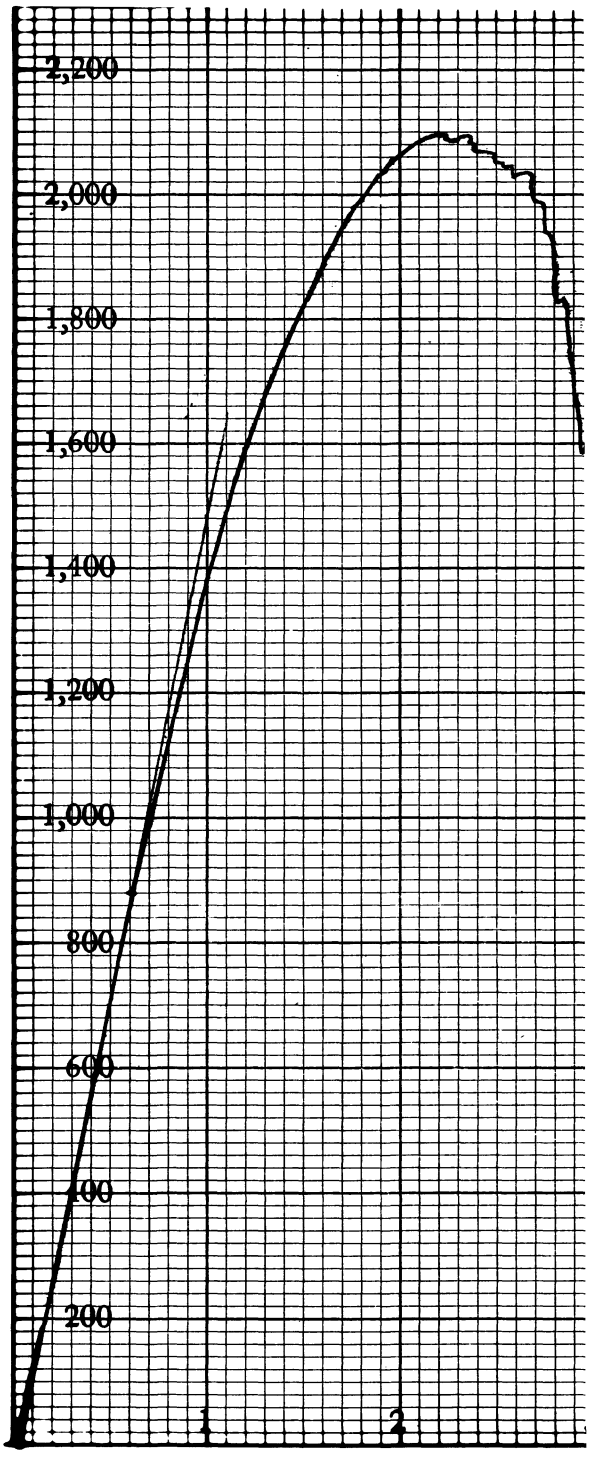
Observed Patterns of Shear and Tensile Fracture Among Groups

Differences in the appearance of fracture surfaces of the three types of specimens are especially prominent in figure 12. In brash specimens, transverse tensile fracture of the wood was uninterrupted by weak, poorly developed bands of latewood cells (fig. 6). The latewood cells of brash laid apparently are not much stronger than the earlywood cells. The wood texture is homogeneous in the sense that prominent alternating bands of light and dense wood are not evident. Minor shear failure occurred below the neutral axis of the test specimen. Before large shear surfaces developed, the transverse tensile fracture passed into the next deeper growth ring. In general, brash latewood cells seem to lack the elasticity of tough latewood cells.

Intermediate specimens are characterized by large tangential shear areas forming long, flat splinters. The splinters are generally one growth ring wide. Shear in the tangential plane always occurred in the first formed earlywood cells. Radial shear occurred less frequently, so the splinters formed are broad along the tangential direction. There is little or no taper in either the radial or tangential directions. Transverse

Figures 8, 9, and 10.--The three load-deflection curves show actual recordings taken during the bending of three different tough specimens. Failure was slow and great resistance to bending was maintained after maximum load. NOTE: The Y scale for load is 2X. The X deflection scale is 0.025 inch per division.


1,800
1,600
1,400
1,200
1,000


2,200
2,000
1,800
1,600
1,400
1,200
1,000
800
600
400
200
1
2

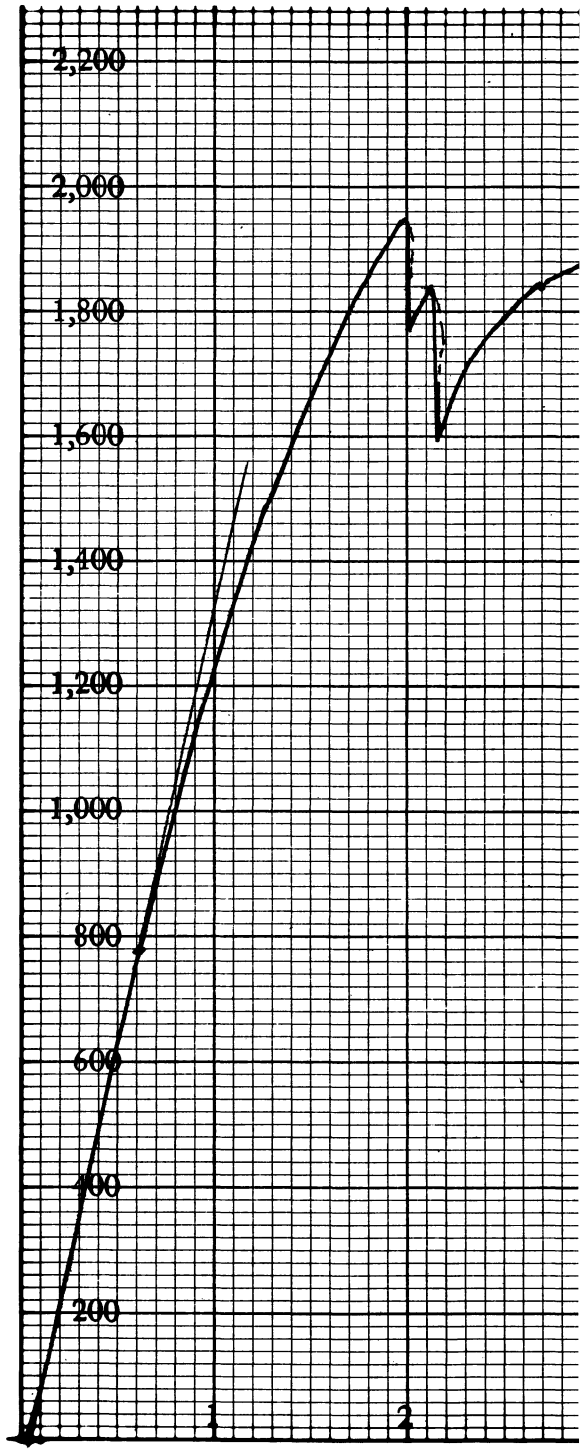
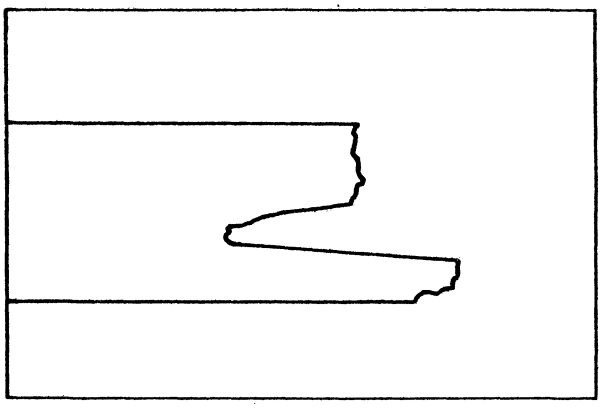

2,200
2,000
1,800
1,600
1,400
1,200
1,000
800
600
400
200
1
2

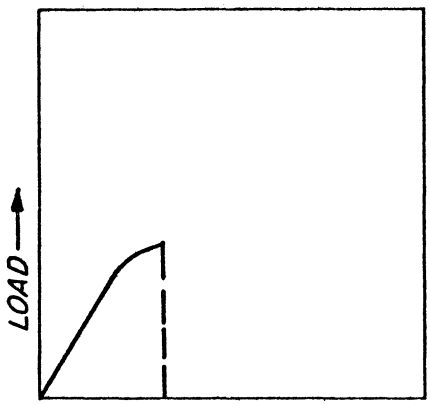
Figure 11.--The fracture-failure criteria used in assigning specimens to the brash, intermediate, or tough groups for the purpose of tabulation and analysis of physical properties.

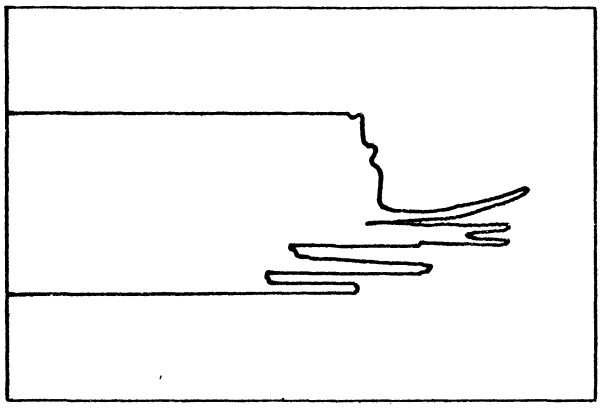
RADIAL FACE VIEW OF TYPICAL FRACTURES

LOAD DEFLECTION DIAGRAMS

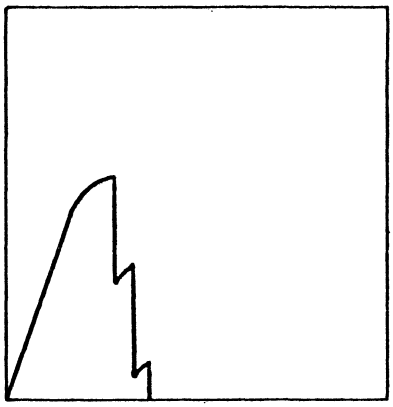


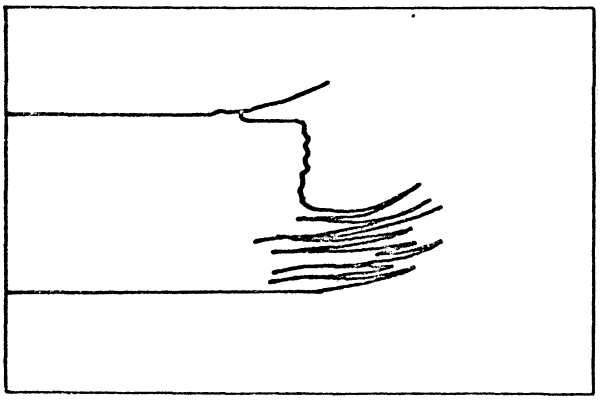
BRASH





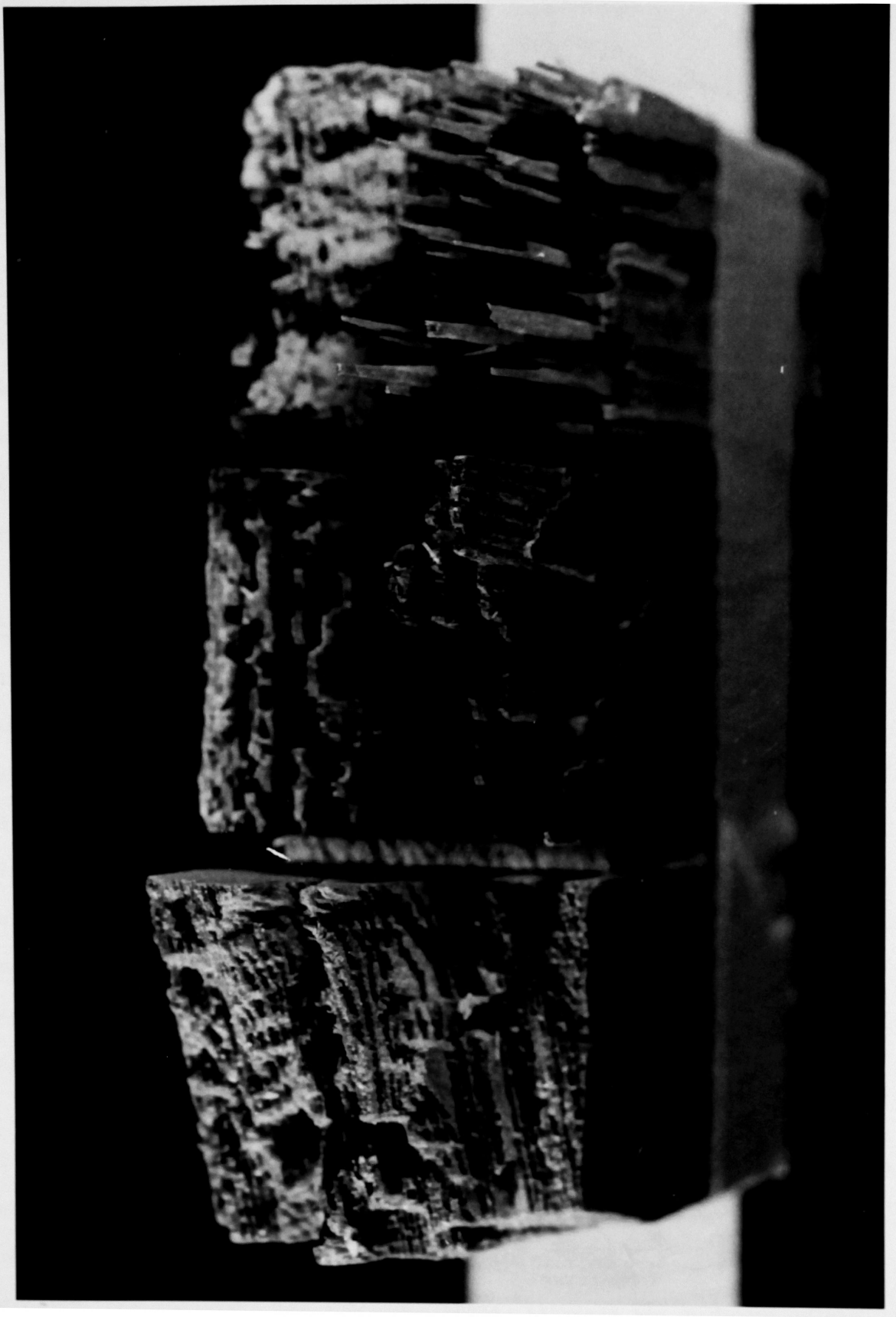
INTERMEDIATE





TOUGH

Figure 12.--End view of representative specimens showing (from left to right) brash, intermediate, and tough fractures. The lower portion of each specimen was in tension during the bending test. The upper portions were damaged by compression during the bending test and that is why they have a brash appearance in all three specimens. Only the lower portion is considered in judging fracture-failure behavior.



tensile fracture, typical of brash specimens, occurred at the splinter tips. The transverse fracture passed uninterrupted through both the latewood and earlywood until the next layer of latewood was encountered.

The latewood of the intermediate specimens appears to be stronger than latewood of brash specimens. This is evident from the fact that transverse tensile fracture in one growth ring was interrupted by the latewood of the next growth ring (fig. 7). Shear forces built up between the fractured growth ring and the unfractured growth ring until either (1) shear failure occurred in the first formed earlywood between the two rings or (2) the latewood of the next growth ring fractured in tension.

Latewood of tough specimens sheared from both earlywood interfaces. The splinters formed to not taper in the radial direction, but do taper in the tangential direction. Transverse tensile fracture seldom passed through the latewood with the exception of the splinter tips. This exception is discussed under the electron microscope analysis. Shear fracture in the radial plane is unlike that which occurred in brash and intermediate specimens. Radial shear in the brash and intermediate specimens traveled parallel to the wood grain. In the tough specimens, radial shear passes laterally from one row of cells to the next, thus moving in a path diagonal to the longitudinal cell axis. This was designated diagonal-radial-shear.

Diagonal-radial-shear accounts for tapering of splinters to a needle-like point in tough wood. This type of fracture was particularly prevalent when the growth rings were at some angle to the direction of loading other than perpendicular. When the ring direction was very close to perpendicular, the splinters are sometimes broad, although not so broad as the intermediate specimens' splinters.

Failure associated with the tough fracture just described occurred stepwise with each minute splinter. Once the latewood band was fractured, the associated earlywood failed in transverse tension. Transverse tensile fracture was interrupted by the next strong, elastic latewood band. The energy stored in the specimen at the maximum load did not carry the fracture through the entire specimen as in brash specimens. It seldom carried the fracture through more than one band of latewood as in the intermediate specimens. Such localized shear fracturing caused a gradual decrease in load-bearing capacity as shown in figures 8, 9, and 10.

The difference in latewood strength, particularly in the ability to withstand transverse tensile fracture, is even more significant when the difference in modulus of elasticity (MOE) and consequently stored energy levels and energy level decay are considered. The brash specimens had low moduli of elasticity and stored a low level of energy. Because of the low elasticity, the energy level decayed rapidly at first failure. Yet, even the small amount of stored energy in the brash wood was enough to propagate fracture to the point of zero load-bearing capacity.

In intermediate specimens, the MOE and the stored energy level were higher. Unlike the brash specimen, the transverse fracture could only be propagated through a portion of the intermediate specimen before it was stopped by a latewood band.

Tough specimens had a high MOE and a high level of stored energy. However, the stored energy at maximum load produced only several small splinters before the fracture was stopped. Two to four times as much energy was required to extend the fracture to zero load-bearing capacity after the maximum load, as was required by the intermediate and brash specimens, respectively. (See page 53.)

Types of Cell-Wall Fracture and Their Association With Fracture-Failure Behavior of Larch Wood

Four principal types of cell-wall fracture were observed on examination of brash, intermediate, and tough fracture surfaces by scanning electron microscopy. The types have been termed transverse tensile, internal shear, internal shear with limited tensile, and external shear for the purposes of this discussion. Scanning electron micrographs of the various types are shown in figures 13 through 16.

Transverse tensile fracture.--Cells are fractured in their entirety perpendicular to the longitudinal cell axis, exposing the lumen. Examples are shown in figures 13A, B, C, D, and E. Tensile fracture occurs across the entire transverse surface of brash specimens, the intermediate splinter tips, and the earlywood and latewood splinter tips of tough specimens. There is little indication of slippage between the cellulose fibrils. Fracture seems to have occurred as a complete and instantaneous scission of the cellulose chains.

It may seem unusual that such a fracture would occur in tough latewood cells. The most likely explanation lies in the radial tapering of the splinters, causing large stress concentrations at the splinter tip apparently great enough to rupture the cellulose primary valence bonds.

A comparison of transverse tensile fractures of brash (fig. 13C) and tough (figs. 13D & E) latewood cells reveals that the brash fracture has an amorphous appearance while the tough fracture has a more fibrous and somewhat crystalline appearance (fig. 13E). This difference may be related to differences in the chemical composition of the cell walls of the two types of wood.

Figure 13.--Transverse tensile fracture:

A. Adjoining walls of two earlywood cells in cross section. Arrows indicate the middle lamella region. The markings of the S-3 layer microfibrils can be seen in the lumen of the near cell. The rough portions of the fracture surface are probably cellulose; the smooth portions are probably areas with a high percent of lignin. The double-wall thickness is 4.4μm. Magnification -- 7410X.

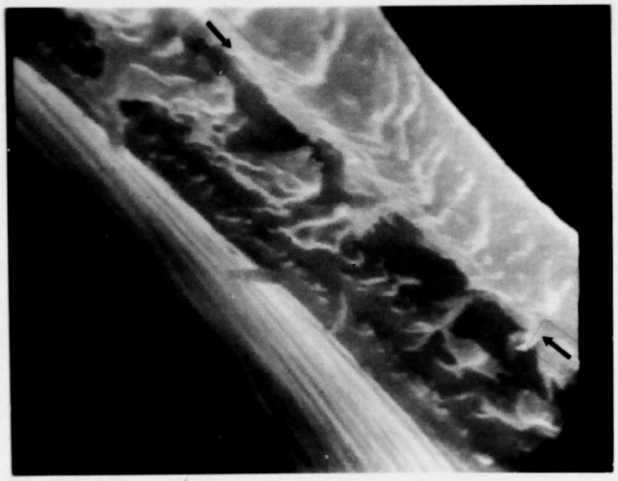
B. A portion of a latewood cell of an intermediate specimen. On the right side the S-2 layer has separated from the S-1 compound middle lamella. This smooth transverse fracture is also seen in brash latewood (13C) and tough latewood (13D). The radial cell diameter is about 30μm. Magnification -- 1410X.

C. The fracture surfaces of these two brash latewood cells actually appear glossy in comparison with the intermediate (13B) and tough (13D) fracture surfaces. The latter surfaces appear more like plastic than glass. Radial cell diameter of the lower cell is 22μm. The double cell-wall thickness is 13.6μm. The white markings on the lower and left sides of the photograph are due to imperfections on the original polaroid photographs. Magnification -- 1480X.

D. Three of six cells which formed a splinter tip of latewood from a tough specimen are shown. A fibrous portion at the left of the upper cell was crushed some time after fracture. But otherwise these fractures have much the same appearance as the brash and intermediate latewood fractures. Radial cell diameter of the center cell is 26μm and the double wall thickness between the two upper cells is about 16μm. Magnification -- 920X.

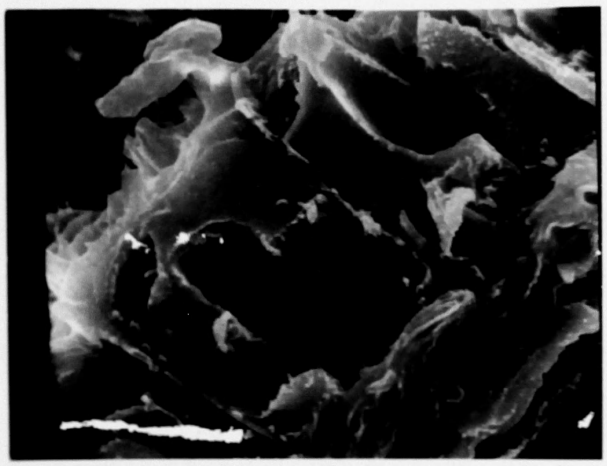
E. The leftmost corner of figure 13D is shown enlarged. The three secondary wall layers are easily distinguished although the primary wall cannot be distinguished from the S-1 layer. This figure is interesting because it shows the ratio between the secondary wall layers, which is S-1, 18.3%; S-2, 69.4%; and S-3, 12.3%. Wall Thickness is 10.7μm. Magnification -- 4590X.

TRANSVERSE TENSILE FRACTURE

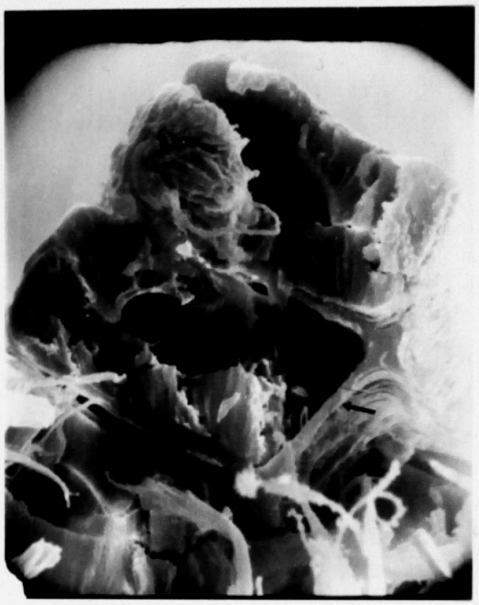


A

B



C



D

E

Internal shear.--Cells were sheared in their entirety through the longitudinal cell axis exposing the lumen. Figures 14A, B, and C are examples. This type of fracture occurred in the earlywood of all types of specimens, but particularly in the tangential plane in the first formed cells of earlywood. The strength seemed to be at its lowest in the first formed earlywood regardless of the overall toughness of a specimen.

Internal shear with limited tensile fracture.--This is a modification of internal shear fracture. Cells were sheared as described above, but the fracture either originated or terminated with localized tensile fracture of the cell wall. The tensile fracture was either of a fibrous nature, parallel to the cellulose fibrils, as shown in figure 15B, or of a nonfibrous nature almost perpendicular to the fibrils as shown in figure 15A. Garland also reported these types of fracture (see page 10). The fibrous tensile fracture occurred in the radial shear of latewood in tough specimens. The nonfibrous tensile fracture occurred in the tangential shear of first formed earlywood in brash specimens. The fibrous fracture indicates the scission of cellulose primary valence bonds or chain slippage, and consequently great strength. Nonfibrous fracture probably indicates rupture perpendicular to the cellulose chains and low strength according to current estimates of cellulose bond energies for tension parallel and perpendicular, and shear parallel to the cellulose chains (43).

To my knowledge, it has not been determined whether cellulose in tension parallel to the microfibrils fails at the primary bonds or by chain slippage. Evidence is available, however, which suggests the theoretical force required to separate cellulose chains along their

Figure 14.--Internal shear fracture:

A. Radial longitudinal fracture of earlywood cells is shown to the right of the arrows. This type is typical of all the earlywood cells observed. The area to the left of the arrows shows a type of latewood fracture shown in figure 16. Magnification -- 160X.

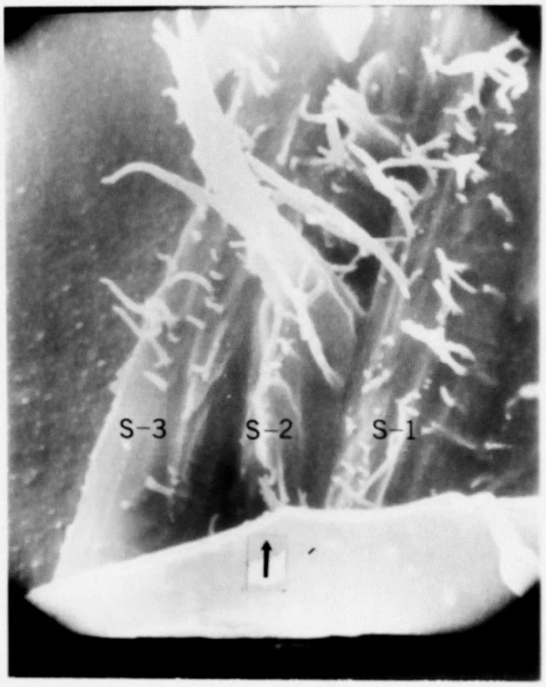
B. Tangential longitudinal fracture of the first formed earlywood cells in this figure is especially predominant in intermediate and tough specimens. All the cell lumens are exposed. Magnification -- 80X.

C. The radial cell wall shows the three layers and the orientation of the cellulose fibrils to the shear plane. The wall layers are in a ratio of about 1:1:1. The arrow indicates the approximate direction of the cellulose fibrils in the S-2 layer. The larger flap of cellulose was bent downward after failure occurred. Wall thickness is about 2μm. Low cellulose content of such thin-walled cells is evident in the sparsity of the cellulose fibrils protruding from the fracture surface. Magnification -- 20,200X.

INTERNAL SHEAR FRACTURE

A

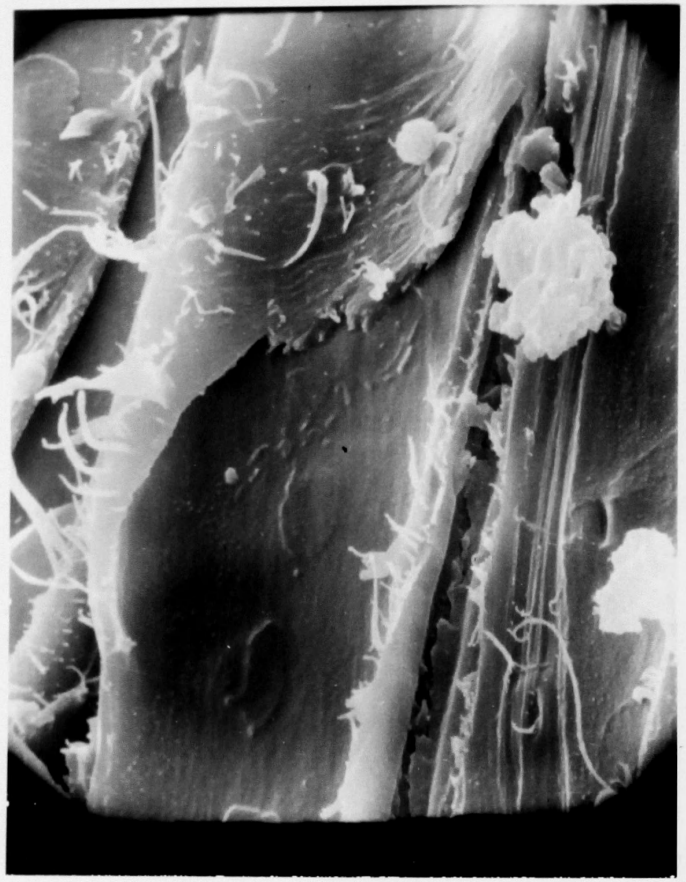
B



C

Figure 15A.--An earlywood cell is shown. The radial cell wall in the upper portion of the photograph is collapsed. In the lower portion, the lumen is exposed. Typical internal shear fracture occurred in the tangential cell walls that sheared the cellulose fibrils. Fracture of the radial wall, however, was in tension between the microfibrils, resulting in the diagonal form exhibited. Notice very few cellulose fibrils were torn loose. Magnification -- 1080X.

Figure 15B.--A group of tough latewood cells are shown. The cells to the right of (1) failed by internal shear fracture, but only after tensile failure of the longitudinally oriented cellulose fibrils. At (2) external shear fracture occurred, followed by tensile failure of the longitudinally oriented cellulose fibrils. The mass of cellulose fibrils torn loose is in sharp contrast to figure 15A. Magnification -- 610X.



A

B

INTERNAL SHEAR FRACTURE WITH LOCALIZED TENSILE FRACTURE

longitudinal axis may be from 3 to 70 times the force required to separate them perpendicular to their long axis (43). Thus, it is logical that a situation where tensile forces normal to the cellulose fibrils develop will result in much weaker wood than when tensile forces act parallel to the cellulose fibrils.

The two micrographs in figure 15 support the hypothesis that microfibril angle can be a factor in fracture-failure behavior (see page 10 and figure 2).

External shear.--In all the examples shown in figure 16, the cell wall sheared along the longitudinal cell axis within the outer layers of the cell wall. The fracture occurred in the region of the primary wall, S-1, or the transition zone between the S-1 and S-2 layers. The S-2 and S-3 layers were left intact. I have termed this type external shear fracture because it does not penetrate the lumen. External shear fracture occurred in the radial shear area in the latewood of all types of specimens. It is indicative of great tensile and shear strength in the S-2 layer. Since the shear fracture was channeled by the S-2 portion of the cell, it followed the cell until it reached a cell tip (fig. 16C) or a ray crossing or until enough stress was concentrated to rupture the S-2 in tension as described in the preceding section (fig. 15B). At these points, the line of shear moved laterally, resulting in the diagonal-radial-shear described previously on page 39.

Figure 16.--External shear fracture:

A. A group of intermediate latewood cells is shown, which have been stripped of some of their outer layers. The S-2 layer is intact and the lumen has not been breached. The arrow indicates some remnants of the outer cell-wall material that was left behind. Magnification -- 710X.

B. A portion of figure 13D is shown enlarged. The light-colored material marked by the arrow corresponds to the material marked by the arrow in 13D. This includes the compound middle lamella and the S-1 layers of two adjoining cells. The flat windings of the S-1 layer are plainly visible in upper-left corner. The S-2 cylinder has been extracted from the S-1 cylinder. The lumen apparently was not breached unless transverse tensile fracture occurred beyond the field of focus. Magnification -- 1840X.

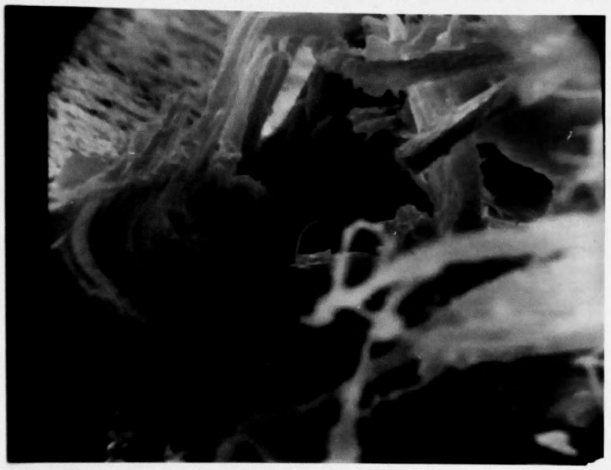
C. A group of stripped tracheids from tough latewood is shown. The tip of each tracheid ends in a ray that has been completely destroyed. The S-2 layer is exposed in the bottom and third from the bottom cells. All or part of the S-1 layer remains on the other two cells. The lumens are intact. Magnification -- 740X.

D. Parts of two cells are shown. The cell on the left is covered with indistinguishable bits of cell-wall material; however, the area indicated by the left pointing arrow seems to be part of the S-1 layer. The right-hand portion of the photograph is a longitudinal half cylinder made up of a longitudinal half of the middle lamella, primary wall, and S-1 layer. The right pointing arrow marks where longitudinal shear fracture passed through the cylinder. The rupture in the middle of the half cylinder probably occurred in handling. Magnification -- 710X.

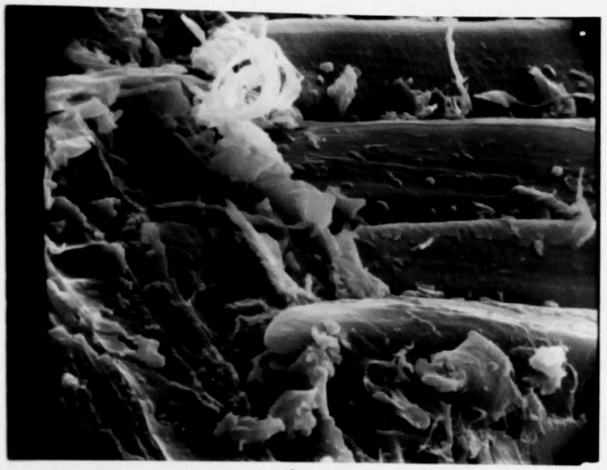
E. The portion of 16D in the vicinity of the arrows is enlarged. The surface (1) roughly corresponds to the mating surface that was sheared from (2). The smoothness of the fracture surface at (2) suggests that weak interfaces exist between lamellae of the S-1 layer or the S-1 - S-2 layers. Magnification -- 1410X.

EXTERNAL SHEAR FRACTURE

A



B



C

D

E

Statistical Analysis

Some Anatomical and Mechanical Properties of the Fracture-Failure and Tukey's Comparison Among Means

Table 2 lists the entire set of characteristics observed, the measured sample group means, and the results of Tukey's procedure for testing for significance of the differences among the group means. The differences among group means are significant for most characteristics, with the exceptions of WML (the value for work to the maximum load) and MFA (microfibril angle). In most cases, the distance between the brash and intermediate group means is equal to or larger than between the intermediate and tough means. That is to say, in terms of measured characteristics, the intermediate specimens more closely resemble the tough group than the brash group. It is recalled that, in the type of fracture and manner of failure, the intermediate group resembles the brash group more closely than the tough group. The reason for this discrepancy is not apparent.

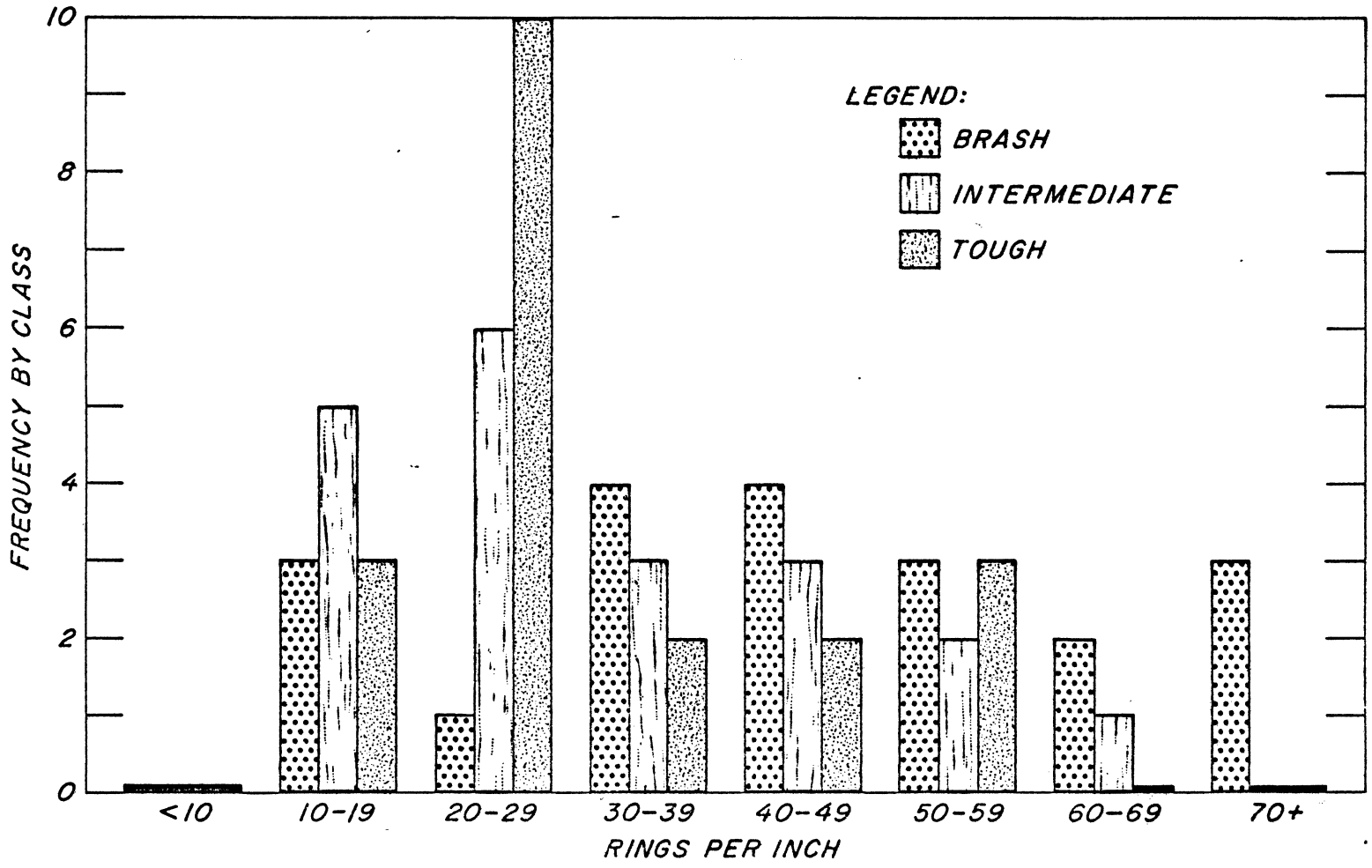
A comparison of the group differences in RPI (rings per inch) provides some insight into the purported relationship between growth rate and brashness (page 15 and table 1). Table 2 shows that brash specimens average 45 rings per inch while intermediate and tough specimens average about 30 rings per inch. In terms of frequency in intervals of 10 rings per inch, figure 17 shows there are 13 of 20 tough and 11 of 20 intermediate, but only 4 of 20 brash specimens with less than 30 rings per inch. Conversely, there are 16 brash specimens above 30 rings per inch and only 9 and 7 tough and intermediate,specimens. The breakdown of the frequency of specimens by group and intervals of 10 rings per inch is given on the following page.

Table 2.--Group means with Tukey's "W" procedure for testing group mean differences

Characteristic	Unit	Group means			Tukey's "W"	Group mean differences & significance[1]		
		Brash	Intermediate	Tough		Brash-tough	Brash-intermediate	Tough-intermediate
MCA/CWT		478	327	277	49.4	201.0(*)	151.8(*)	49.2(NS)
CWT/ARD		.0859	.1146	.1316	.0115	.0457(*)	.0286(*)	.0170(*)
CWT	μm_2	3.9	4.8	5.0	.443	1.105(*)	.875(*)	.230(NS)
MCA	μm^2	1842	1535	1356	155.3	486.2(*)	307.2(*)	179.0(*)
ARD	μm	46	42	38	2.8	7.4(*)	3.9(*)	3.4(*)
MFA	Degree	11.3	9.3	8.4	2.80	2.96(*)	2.04(NS)	.92(NS)
PCWS	Percent	.33	.43	.47	.039	.135(*)	.094(*)	.040(*)
TSG	Percent	.37	.43	.48	.027	.110(*)	.054(*)	.056(*)
DSG	Percent	.51	.55	.65	.052	.148(*)	.046(NS)	.101(*)
PLW	Percent	.21	.27	.34	.031	.135(*)	.060(*)	.075(*)
RPI		45	30	31	12.7	14.2(*)	13.8(*)	.5(NS)
MOE	P.s.i. x 10^3	1018	1407	1642	148.6	624.8(*)	388.9(*)	235.8(*)
MOR	P.s.i.	6423	7839	9046	706.7	2622.6(*)	1415.6(*)	1207.0(*)
FSPL	P.s.i.	4283	5198	5745	457.5	1597.3(*)	915.1(*)	682.2(*)
WML	In.lb./$in.^3$	6.56	7.98	8.88	1.544	2.330(*)	1.420(NS)	.910(NS)
ML	Lb.	695	799	984	111.0	288.0(*)	103.5(NS)	184.5(*)

[1]The difference was considered significant at the 95% level of confidence (*) if it exceeded the calculate "W" value, otherwise it was nonsignificant (NS).

Figure 17.--The distribution of specimens by fracture-failure criteria among growth rate classes at intervals of 10 rings per inch.

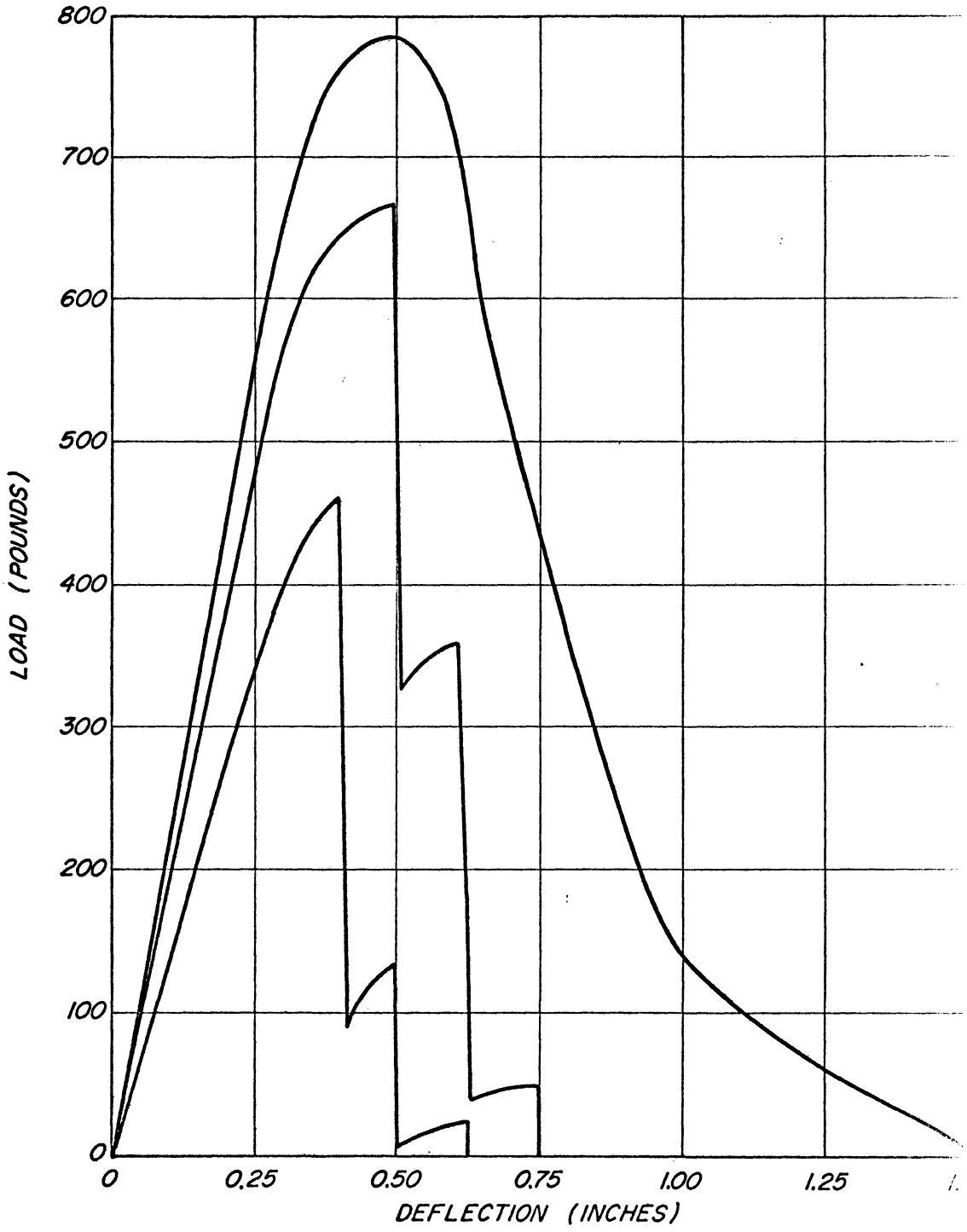

10
8
6
4
2
0
FREQUENCY BY CLASS
LEGEND:
BRASH
INTERMEDIATE
TOUGH
<10
10-19
20-29
30-39
40-49
50-59
60-69
70+
RINGS PER INCH

RPI class	No. of specimens in the class		
	Brash	Intermediate	Tough
<10	0	0	0
10-19	3	5	3
20-29	1	6	10
30-39	4	3	2
40-49	4	3	2
50-59	3	2	3
60-69	2	1	0
>70	3	0	0

The number of brash specimens remains about constant throughout the range of growth rates in sample 1; however, there is a noticeable decrease in the number of tough specimens as the growth rate decreases. Apparently the nature of the characteristic(s) responsible for brash behavior may occur under any condition of growth rate. On the other hand, the nature of the characteristic(s) responsible for toughness are less likely to occur as growth rate diminishes. The optimum range of growth rate for nonbrash behavior of western larch wood seems to center between 10 and 30 rings per inch.

A gross difference in the average deflection to zero load-bearing capacity of the three groups--brash, intermediate, and tough--is seen in figure 18. The brash and intermediate specimens reached zero load-bearing capacity almost immediately after the maximum load was reached. But, the

Figure 18.--Average load-deflection diagrams of specimens of sample 2. Each diagram was obtained by plotting the group average load at selected deflections. The minor peaks in the brash and intermediate diagrams were placed by eye, but the size and general shape of each diagram were determined by the plotting.


800
700
600
500
400
300
200
100
0
LOAD (POUNDS)
0
0.25
0.50
0.75
1.00
1.25
DEFLECTION (INCHES)

tough specimens continued to deflect and support considerable loads long after the maximum load had been passed.

Figure 18 also serves to illustrate differences in the suddenness of failure at maximum load and energy required to cause failure to the point of zero load-bearing capacity. The tough specimens lost 12 percent of the maximum load at the initial failure. Intermediate specimens lost 52 percent and brash specimens lost 78 percent of their maximum load at the initial failure. Since the total work in bending varies directly as the area under the load-deflection diagram and since the specimens of the sample were of uniform cross section, a comparison can be made of the average energy absorbed in bending among groups by measuring the areas under the curves in figure 18. Based on this comparison, tough specimens absorbed three to four times more energy than did brash specimens at the point of zero load-bearing capacity and two times more energy than did intermediate specimens.

The differences between the corresponding group means for the characteristics DSG (dry specific gravity) and TSG (true specific gravity) are due to the highly variable water-soluble extractives content of western larch. The extractive content, which varied from 2 to 33 percent of the ovendry weight of the unextracted wood, can completely mask the true specific gravity of the wood.

An extreme example of the effect of extractives was found in specimen No. 22. The dry specific gravity of this specimen was 0.64, well above the species' average. Since density usually infers toughness, specimen 22 should have been tough. However, the extractive content was 33 percent and the true specific gravity was only 0.37, which is well

within the range of TSG indicative of brashness. As classified by the visual fracture-failure criteria, specimen 22 was typically brash. This points out the hazard of grading lumber by hand.

Description of the Three Fracture-Failure Groups

Table 2 shows that the brash specimens generally came from wood of more than 30 rings per inch, of low true specific gravity, and low percentage of latewood. The cells of brash specimens are typically large diameter and thin walled with a somewhat greater than average microfibril angle. These specimens had low moduli of elasticity and rupture, low fiber stress at the proportional limit, and low load-bearing capacity.

Tough specimens generally have the opposite characteristics. The intermediate specimens have properties midway between brash and tough specimens with very few notable exceptions. The descriptive characteristics of the three fracture-failure groups are summarized below.

Brash	Intermediate	Tough
Brittle	Brittlish	Shock resistant
Weak	Average strength	Strong
Nonfibrous fracture	Stubby splinters	Needlelike splinters
Abrupt failure	Abrupt but incomplete failure	Gradual failure
Low deflection at zero load-bearing capacity	Low deflection at zero load-bearing capacity	High deflection at zero load-bearing capacity

Brash	Intermediate	Tough
Loses about 80% of load-bearing capacity at initial fracture	Loses about 50% of load-bearing capacity at initial fracture	Loses only about 10% of load-bearing capacity at initial failure
Requires little energy to cause complete failure	Requires about twice as much energy to produce complete failure as do brash specimens	Requires from three to four times as much energy to cause complete failure as do brash specimens

Indications on the Anatomical Determinants of Fracture-Failure Behavior According to Discriminant Function Analysis

Table 3 lists the results of the discriminant function analyses and the D^2 values for single characteristics which may affect fracture-failure behavior. D^2 was used as a chi-square with M(L-1) degrees of freedom[5] to test the null hypothesis that the three group mean values for each characteristic are the same. As shown in the table, the null hypothesis is rejected for all the characteristics listed.

The results of Tamolang et al. (57) were briefly discussed in the literature review on page 6. Specifically, they found that although microfibril angle and cell wall area each had a highly significant effect upon fiber (cell) breaking load, the cell-wall area accounted for 90.7 percent of the total variance while microfibril angle accounted for only 4.4 percent. On the other hand, microfibril angle accounted for 88.8 percent of the total variance in the strength per unit area of the cell wall. They concluded that the influence of microfibril angle upon fiber breaking load, although significant, was almost entirely masked by the dominant influence of cell-wall area.

---

[5]Degrees of freedom are based on the number of characteristics (M) in the [illegible] and the number of [illegible] (L).

Table 3.--Test results for the ability of a single characteristic to discriminate between brash, intermediate, and tough groups

	D^2	Degrees of freedom	Expected chi-square	Test result[1]	Null hypothesis[2]	Error of prediction	
						No. of misclassifications (60 possible)	Percent wrong
CWT/ARD	92.1	2	5.99	*	Rejected	15	25
MCA/CWT	103.9	2	5.99	*	.....do.....	19	32
TSG	96.4	2	5.99	*	.....do.....	14	23
MCA	58.0	2	5.99	*	.....do.....	20	33
CWT	40.0	2	5.99	*	.....do.....	27	45
ARD	39.2	2	5.99	*	.....do.....	24	40
MFA	7.0	2	5.99	*	.....do.....	37	62

[1] * indicates the differences between group means are significant at the 95% level of confidence.

[2] The null hypothesis states there is no significant difference between the three groups--brash, intermediate, and tough--as delineated by the single characteristic discriminant function considered.

Referring to table 3, the same relationships are evident in the results of the discriminant function analyses. Both microfibril angle (MFA) and cell-wall area (represented in this study by any one of the three characteristics TSG, MCA/CWT, or CWT/ARD) are significantly different between fracture-failure groups--an indication of effect upon fracture-failure behavior. However, the magnitude of the effects is seen in the relative sizes of the D^2 statistics (for example, 7.0 for MFA, 92.1 for CWT/ARD). CWT/ARD, which apparently represents the dominant or <u>total</u> effect, was able to correctly classify 77 percent of the specimens. MFA, which apparently represents a <u>partial</u> effect, was able to classify only 48 percent of the specimens correctly. Based on the size of their D^2 statistics and their number of misclassifications, CWT, MCA, and ARD must also be <u>partial</u> effects whose effects are obscured in the total effect of cell-wall area. The sum of these partial effects is best expressed by a ratio of the cell cross-sectional size to cell-wall thickness (cell-wall area).

In the intermediate group (table 4), there are three examples (specimen Nos. 8, 62, and 75) where extremely thick cell walls (indicating toughness) are combined with very large-diameter cells (indicating brashness). The end result or the "total effect" was intermediate fracture-failure behavior.

Although the "partial effects" are usually obscured by the "total effect" of the ratio of cell cross-sectional size to cell-wall thickness, examples were found in the data where an extreme of one partial effect may have dominated fracture-failure behavior. Specimen No. 3 was classified intermediate by both CWT/ARD and MCA/CWT (measures of the ratio

Table 4.--A summary of the discriminant function analyses of sample 1 by total effect characteristics, partial effect characteristics, and combined partial effect characteristics

Specimen No.[1]	Characteristics used in the discriminant function											
	Total			Partial							Combined partial	
	MCA/CWT	TSG	CWT/ARD	MCA		CWT		ARD		MFA	CWT + ARD + MFA	
BRASH												
3	I		I			I						
4								I		I		
5										T		
6	I			I				I				
7										I		
10										T		
12								I		T		I
20								I		T		
22						I				T		I
55	I		I	I		I		I				I
64										T		
66								I				
76	T	I	I	T				T		I		I
80										I		
INTERMEDIATE												
1		B		B				B		B		B
8		B		B		T				T		T
9										B		
13						T				T		
15	B		B			B						B
23						T		B		T		
24										B		B
42						T				T		
43						B		T		T		T
49		B		B				B		T		
57	T	T		T		T				T		
62			T	B		T		B		T		
67	T		T	T		T		T		B		
69	T	T	T	T		T		T		B		T
70	T			T				T		T		T
71	T			T				T		T		
72	T	B	T	T		T		T		B		
73	T	T		T		T				T		
75				B		T		B		T		
78	B		B			B		B		T		
TOUGH												
14	I		I	B				B		B		I
16		I				I				B		
17	I	I	I			I		I				I
19						I						
27						I				B		
29										B		
30										I		
34				I				I				
35	I	I	I	I		B		B				I
40										B		
41	I		B			B						
48		I		I								
50		I	I			I						
51	I	I	I	I		B				B		I
53	I					I				B		
60								I				

[1]Brash specimen Nos. 11, 32, 65, 79, 80, and 81 and tough specimen Nos. 26, 28, 37, and 58 were always classified correctly and so were deleted from the table to save space.

cell size to wall thickness) in discriminant function analyses as shown in table 4. The appearance of the fracture and other criteria indicates the specimen was truly brash. The apparent cause of this discrepancy is a very large average microfibril angle[6] (table A-4). Microfibril angle correctly predicted brashness in the discriminant function analysis (table 4). As a matter of fact, the brash specimens which were never misclassified by a discriminant function analysis (specimen Nos. 11, 32, 66, 79, 81, and 82) all have large to very large microfibril angles.

The possibility that a partial-total relationship exists was further tested by combining the three complementary individual partial effects in one discriminant function analysis and comparing the results with individual-total and individual-partial effects results. The combined partial effects represent a measure of cell size (ARD), a measure of wall thickness (CWT), and a measure of wall structure (MFA). The comparisons are shown below.

Individual-Total Effects	D^2 Statistic	No. of Misclassifications
TSG	96.4	14
CWT/ARD	92.1	15
MCA/CWT	103.9	19
Combined-Partial Effects		
CWT - ARD - MFA	110.5	15
Individual-Partial Effects		
CWT	40.0	27
ARD	39.2	24
MCA	58.0	20
MFA	7.0	37

[6] Large in terms of latewood microfibril angles.

None of the partial effects, with the possible exception of MCA, provide the distinct separation and group behavior prediction efficiency of the individual-total effects or the combined-partial effects in discriminant function analysis. This evidence does not prove the partial-total relationship, but it does add weight to the conclusion that no individual characteristic consistently controlled fracture-failure behavior.

Comments on the Discriminant Function Technique

The reader may rightfully question the use of coefficients developed from one sample of specimens in a discriminant function used to predict the behavior of individuals within the same sample. However, this is an essential part of this reiterative technique. The precision of the predictions depends not only on the size and range of the basic sample but also upon the distinctness of separation between behavior groups by the characteristic(s) used and the correctness of the *a priori* classifications upon which the group coefficients are based. Specimens with characteristic(s) values beyond the range of the values of the original sample cannot be validly classified.

The discriminant function analysis is constructed to account for errors. The probability of a given specimen belonging to each of the three groups is determined and printed out. In this manner, specimens with a large chance of a wrong prediction can be identified (specimens which have only slightly more than a 50 percent chance of belonging to the predicted group).

Suggestions for Future Work of This Nature

Multiple regression analysis might provide an indication of the amount of variation in fracture-failure behavior which can be attributed to each causal anatomy characteristic, if some quantitative measure of fracture-failure behavior could be found to use as the dependent variable. None of the mechanical properties examined in this study were suitable. They all measure properties at the proportional limit or maximum load, while the real difference in fracture-failure behavior is only apparent after the maximum load is passed.

Examination of the complete load-deflection diagrams of sample 2 suggests two quantities which might serve as dependent variables. They are the deflection between maximum load and zero load-bearing capacity and the total work from initial load to zero load-bearing capacity.

Microscopical examination of stained sections of very slow-grown specimens with large-diameter thin-walled cells which are typically brash show evidence of high cell-wall lignin content. Based on this observation and the review of literature, chemical composition and the distribution of cell-wall components should be investigated as sources of variation in fracture-failure behavior along with elements of wood and cell anatomy.

SUMMARY

Normal, undamaged western larch wood exhibits at least three characteristic types of fracture-failure behavior--brash, tough, and intermediate. The differences among these types included visual appearance of the fracture surfaces, mechanical properties, and anatomical characteristics. All three types appear to be "normal" for the species based on their frequency of occurrence.

Visual examination of the broken specimens showed differences in the presence or absence of splinters and in the coarseness of splinters among the three groups. Low power magnification revealed that different patterns of shear and tensile fracture occurred through the latewood of each group, but that fracture through the earlywood was the same for all the groups. At high magnification some evidence was found that transverse tensile fracture of latewood cells differed among the groups, although there did not seem to be any difference at low magnification.

It was difficult to pinpoint a single constant cause of fracture-failure behavior due to the number of variables involved and the qualitative nature of such behavior and the interaction of positive and negative influences.

The evidence obtained in this study indicates that fracture-failure behavior of larch wood is predominately controlled by the ratio of cell size to wall thickness (cell-wall area). Microfibril angle, cell-wall thickness, and cell size probably have partial effects whose total or complementary effect is represented by the ratio of cell cross-sectional size to cell-wall thickness. It was pointed out that one or more of the partial effect

characteristics at an extreme of its range of variation may assume a dominant effect upon fracture-failure behavior.

APPENDIX A

INDIVIDUAL PROPERTY VALUES BY PROPERTY AND VISUAL GROUPING

Table Index and Key

Property	Unit	Table No.
Mean cell area	μm^2	A-1
Cell wall thickness	μm	A-2
Average cell radial diameter	μm	A-3
Microfibril angle	Degrees	A-4
Percent cell wall substance		A-5
$\frac{\text{Mean cell area}}{\text{Cell wall thickness}}$		A-6
$\frac{\text{Cell wall thickness}}{\text{Average cell radial diameter}}$		A-7
Rings per inch		A-8
Percent latewood		A-9
True specific gravity		A-10
Dry specific gravity		A-11
Modulus of elasticity	P.s.i.	A-12
Modulus of rupture	P.s.i.	A-13
Work to maximum load	In.-lb./cu. in.	A-14
Maximum load	Lb.	A-15
Fiber stress at proportional limit	P.s.i.	A-16
Deflection	In.	A-17
Extractive content	Pct. ovendry weight	A-18

The averages in the first row at the bottom of each table are for each of the three columns. The second row average is that of the brash and tough specimens together. The third row average is for all three columns together.

TABLE A-1

MEAN CELL AREA (MCA)

Brash		Tough		Intermediate	
Specimen No.	MCA	Specimen No.	MCA	Specimen No.	MCA
3	1,875	14	1,721	1	1,778
4	1,755	16	1,169	8	1,778
5	1,722	17	1,427	9	1,592
6	1,456	19	1,382	13	1,573
7	2,106	26	1,345	15	1,619
10	1,825	27	1,186	23	1,537
11	2,043	28	1,400	24	1,471
12	1,711	29	1,214	42	1,531
20	1,711	30	1,337	43	1,543
22	2,139	34	1,567	49	1,746
32	1,945	35	1,678	57	1,329
55	1,626	37	1,148	62	1,762
64	1,711	40	1,137	67	1,397
65	1,883	41	1,097	69	1,198
66	1,947	48	1,573	70	1,385
76	1,210	50	1,194	71	1,315
79	1,990	51	1,559	72	1,393
80	1,973	53	1,351	73	1,314
81	2,190	58	1,221	75	1,780
82	2,031	60	1,419	78	1,665
Average....	1,842	Average....	1,356	Average....	1,535
		Average....	1,603		
				Average....	1,578

TABLE A-2

CELL WALL THICKNESS (CWT)

Brash		Tough		Intermediate	
Specimen No.	CWT	Specimen No.	CWT	Specimen No.	CWT
3	4.8	14	5.2	1	4.7
4	3.6	16	4.8	8	5.0
5	3.8	17	4.5	9	4.6
6	3.9	19	4.7	13	5.0
7	3.9	26	5.5	15	3.4
10	3.4	27	4.6	23	5.0
11	3.8	28	5.0	24	4.7
12	3.9	29	5.2	42	4.9
20	3.4	30	5.4	43	4.0
22	4.6	34	5.6	49	4.6
32	3.6	35	4.2	57	5.0
55	4.4	37	5.8	62	5.6
64	4.1	40	5.1	67	5.1
65	3.4	41	3.5	69	5.0
66	3.8	48	5.4	70	4.6
76	4.0	50	4.4	71	4.4
79	3.2	51	4.0	72	5.2
80	3.8	53	4.4	73	5.0
81	4.0	58	7.0	75	5.4
82	4.4	60	5.6	78	4.1
Average....	3.89	Average...	5.00	Average...	4.76
		Average...	4.47		
				Average...	4.59

TABLE A-3

AVERAGE RADIAL DIAMETER (ARD)

Brash		Tough		Intermediate	
Specimen No.	ARD	Specimen No.	ARD	Specimen No.	ARD
3	46	14	46	1	46
4	41	16	35	8	41
5	45	17	41	9	41
6	41	19	37	13	41
7	53	26	38	15	41
10	46	27	35	23	44
11	53	28	39	24	43
12	41	29	37	42	42
20	41	30	38	43	38
22	48	34	43	49	45
32	48	35	45	57	41
55	43	37	37	62	45
64	46	40	35	67	39
65	49	41	32	69	36
66	43	48	39	70	39
76	37	50	36	71	39
79	46	51	39	72	38
80	46	53	34	73	43
81	52	58	38	75	48
82	48	60	42	78	45
Average.....	45.5 μ	Average.....	38.5 μ	Average.....	42.3 μ
		Average.....	42.0 μ		
				Average.....	42.0 μ

TABLE A-4

MICROFIBRIL ANGLE (MFA)

Brash		Tough		Intermediate	
Specimen No.	MFA	Specimen No.	MFA	Specimen No.	MFA
3	15.1	14	10.5	1	13.6
4	9.6	16	14.6	8	6.3
5	8.7	17	5.4	9	11.0
6	15.1	19	8.3	13	13.4
7	9.4	26	7.8	15	9.7
10	8.7	27	11.0	23	6.3
11	15.6	28	8.8	24	16.6
12	7.0	29	11.4	42	5.4
20	8.6	30	9.7	43	5.7
22	6.4	34	4.6	49	4.2
32	17.1	35	3.5	57	8.6
55	11.8	37	4.4	62	6.2
64	8.0	40	10.4	67	14.9
65	14.1	41	6.1	69	12.8
66	17.2	48	6.1	70	7.9
76	9.7	50	5.8	71	8.0
79	15.3	51	11.1	72	18.6
80	7.4	53	10.4	73	6.2
81	10.6	58	8.8	75	6.2
82	11.2	60	8.6	78	4.1
Average.....	11.3°	Average.....	8.4°	Average.....	9.3°
		Average.....	9.9°		
				Average.....	9.7°

TABLE A-5

PERCENT CELL WALL SUBSTANCE (PCWS)

Brash		Tough		Intermediate	
Specimen No.	PCWS	Specimen No.	PCWS	Specimen No.	PCWS
3	0.40	14	0.44	1	0.39
4	.32	16	.48	8	.41
5	.33	17	.42	9	.39
6	.36	19	.44	13	.44
7	.31	26	.51	15	.31
10	.31	27	.47	23	.45
11	.28	28	.46	24	.43
12	.34	29	.51	42	.44
20	.30	30	.50	43	.36
22	.36	34	.49	49	.39
32	.30	35	.37	57	.47
55	.39	37	.57	62	.46
64	.40	40	.52	67	.47
65	.29	41	.38	69	.49
66	.32	48	.47	70	.44
76	.40	50	.44	71	.43
79	.27	51	.36	72	.48
80	.31	53	.42	73	.48
81	.31	58	.60	75	.45
82	.35	60	.50	78	.36
Average.....	.33	Average.....	.47	Average.....	.42
		Average.....	0.40		
				Average.....	0.41

TABLE A-6

MEAN CELL AREA DIVIDED BY CELL WALL THICKNESS (MCA/CWT)

Brash		Tough		Intermediate	
Specimen No.	MCA/CWT	Specimen No.	MCA/CWT	Specimen No.	MCA/CWT
3	391	14	330	1	378
4	488	16	244	8	356
5	453	17	317	9	346
6	374	19	294	13	315
7	540	26	245	15	476
10	537	27	258	23	308
11	538	28	280	24	313
12	459	29	233	42	312
20	503	30	248	43	386
22	465	34	280	49	380
32	540	35	400	57	266
55	370	37	198	62	315
64	412	40	223	67	274
65	554	41	313	69	240
66	512	48	291	70	301
76	302	50	271	71	299
79	621	51	390	72	268
80	519	53	307	73	263
81	548	58	174	75	330
82	462	60	253	78	406
Average.....	478	Average.....	277	Average.....	327
		Average.....	377		
				Average.....	358

TABLE A-7

CELL WALL THICKNESS DIVIDED BY AVERAGE RADIAL DIAMETER (CWT/ARD)

Brash		Tough		Intermediate	
Specimen No.	CWT/ARD	Specimen No.	CWT/ARD	Specimen No.	CWT/ARD
3	0.1045	14	0.1130	1	0.1022
4	.0878	16	.1371	8	.1220
5	.0845	17	.1098	9	.1122
6	.0952	19	.1270	13	.1220
7	.0736	26	.1447	15	.0829
10	.0739	27	.1314	23	.1136
11	.0717	28	.1282	24	.1093
12	.0952	29	.1405	42	.1167
20	.0830	30	.1421	43	.1053
22	.0958	34	.1303	49	.1022
32	.0750	35	.1071	57	.1220
55	.1023	37	.1567	62	.1244
64	.0892	40	.1458	62	.1308
65	.0694	41	.1094	69	.1389
66	.0884	48	.1385	70	.1181
76	.1082	50	.1222	71	.1128
79	.0696	51	.1026	72	.1368
80	.0826	53	.1294	73	.1164
81	.0770	58	.1840	75	.1126
82	.0917	60	.1333	78	.0911
Average.....	.0859	Average.....	.1316	Average.....	.1146

Average..... 0.1089

Average..... 0.1106

TABLE A-8

RINGS PER INCH (RPI)

Brash		Tough		Intermediate	
Specimen No.	RPI	Specimen No.	RPI	Specimen No.	RPI
3	64	14	28	1	40
4	50	16	22	8	58
5	40	17	30	9	33
6	77	19	52	13	20
7	45	26	24	15	28
10	52	27	25	23	43
11	79	28	15	24	28
12	68	29	51	42	21
20	78	30	39	43	65
22	30	34	24	49	30
32	17	35	20	57	12
55	50	37	17	62	22
64	20	40	25	67	15
65	19	41	46	69	12
66	31	48	48	70	51
76	18	50	29	71	30
79	34	51	58	72	47
80	41	53	26	73	20
81	37	58	11	75	16
82	41	60	26	78	15
Average.....	45	Average.....	31	Average.....	30
		Average.....	38		
				Average.....	35

TABLE A-9

PERCENT LATEWOOD (PLW)

Brash		Tough		Intermediate	
Specimen No.	PLW	Specimen No.	PLW	Specimen No.	PLW
3	0.22	14	0.35	1	0.27
4	.20	16	.37	8	.23
5	.22	17	.26	9	.23
6	.18	19	.31	13	.24
7	.20	26	.40	15	.27
10	.17	27	.39	23	.23
11	.22	28	.33	24	.35
12	.24	29	.40	42	.31
20	.24	30	.40	43	.20
22	.23	34	.34	49	.33
32	.16	35	.26	57	.28
55	.28	37	.38	62	.25
64	.20	40	.34	67	.27
65	.24	41	.28	69	.25
66	.24	48	.36	70	.27
76	.26	50	.29	71	.29
79	.16	51	.35	72	.24
80	.13	53	.30	73	.32
81	.19	58	.39	75	.27
82	.17	60	.35	78	.25
Average....	.21	Average....	.34	Average....	.27
	Average.... 0.27				
			Average.... 0.27		

TABLE A-10

TRUE SPECIFIC GRAVITY (TSG)

Brash		Tough		Intermediate	
Specimen No.	TSG	Specimen No.	TSG	Specimen No.	TSG
3	0.39	14	0.49	1	0.38
4	.40	16	.57	8	.39
5	.38	17	.44	9	.45
6	.33	19	.44	13	.41
7	.37	26	.53	15	.42
10	.36	27	.49	23	.42
11	.36	28	.50	24	.44
12	.37	29	.55	42	.45
20	.39	30	.53	43	.44
22	.37	34	.49	49	.40
32	.40	35	.41	57	.47
55	.38	37	.50	62	.42
64	.39	40	.54	67	.41
65	.36	41	.46	69	.48
66	.40	48	.43	70	.42
76	.45	50	.42	71	.43
79	.34	51	.43	72	.37
80	.34	53	.48	73	.47
81	.35	58	.49	75	.45
82	.36	60	.49	78	.44
Average.....	.37	Average.....	.48	Average.....	.43
		Average..... 0.42			
				Average..... 0.43	

TABLE A-11

DRY SPECIFIC GRAVITY (DSG)

Brash		Tough		Intermediate	
Specimen No.	DSG	Specimen No.	DSG	Specimen No.	DSG
3	0.46	14	0.70	1	0.49
4	.55	16	.75	8	.46
5	.46	17	.55	9	.62
6	.38	19	.58	13	.51
7	.50	26	.76	15	.49
10	.47	27	.68	23	.51
11	.42	28	.65	24	.52
12	.54	29	.73	42	.59
20	.44	30	.75	43	.54
22	.64	34	.73	49	.50
32	.44	35	.50	57	.60
55	.48	37	.70	62	.58
64	.55	40	.74	67	.60
65	.51	41	.58	69	.64
66	.55	48	.67	70	.56
76	.58	50	.51	71	.55
79	.54	51	.54	72	.50
80	.54	53	.61	73	.64
81	.53	58	.66	75	.59
82	.55	60	.69	78	.57
Average....	.50	Average....	.65	Average....	.55
	Average.... 0.58				
			Average.... 0.57		

TABLE A-12

MODULUS OF ELASTICITY (MOE)

Brash		Tough		Intermediate	
Specimen No.	MOE	Specimen No.	MOE	Specimen No.	MOE
3	777	14	1,555	1	1,397
4	1,151	16	1,518	8	1,008
5	1,162	17	1,440	9	1,524
6	762	19	1,418	13	1,100
7	1,136	26	1,833	15	1,356
10	1,184	27	1,683	23	1,376
11	829	28	1,672	24	1,316
12	814	29	1,995	42	1,762
20	1,186	30	1,941	43	1,556
22	730	34	1,782	49	1,278
32	1,171	35	1,289	57	1,475
55	1,107	37	1,931	62	1,464
64	1,113	40	1,618	67	1,256
65	1,021	41	1,602	69	1,492
66	993	48	1,651	70	1,402
76	1,596	50	1,466	71	1,434
79	837	51	1,309	72	1,304
80	957	53	1,788	73	1,672
81	926	58	1,710	75	1,395
82	901	60	1,847	78	1,564
Average.....	1,018	Average.....	1,642	Average.....	1,406
		Average.....	1,330		
				Average.....	1,355

TABLE A-13

MODULUS OF RUPTURE (MOR)

Brash		Tough		Intermediate	
Specimen No.	MOR	Specimen No.	MOR	Specimen No.	MOR
3	6,189	14	8,872	1	7,264
4	7,338	16	8,567	8	6,238
5	6,618	17	6,967	9	8,211
6	5,198	19	9,076	13	7,080
7	6,735	26	11,050	15	7,185
10	5,299	27	10,567	23	7,188
11	6,259	28	9,119	24	8,521
12	6,054	29	9,992	42	8,928
20	6,122	30	9,250	43	7,650
22	6,505	34	9,135	49	7,061
32	6,568	35	6,903	57	9,270
55	6,406	37	9,907	62	7,578
64	7,322	40	10,144	67	7,415
65	6,636	41	8,657	69	9,914
66	6,224	48	9,085	70	7,501
76	8,662	50	7,772	71	7,911
79	6,087	51	7,716	72	6,844
80	6,071	53	8,680	73	8,744
81	6,126	58	10,060	75	8,375
82	6,048	60	9,400	78	7,901
Average.....	6,423	Average....	9,046	Average.....	7,853
		Average....	7,734		
				Average....	7,774

TABLE A-14

WORK TO MAXIMUM LOAD (WML)

Brash		Tough		Intermediate	
Specimen No.	WML	Specimen No.	WML	Specimen No.	WML
3	5.1	14	7.5	1	6.1
4	8.4	16	9.1	8	6.0
5	8.3	17	4.9	9	8.4
6	6.7	19	8.6	13	9.5
7	5.6	26	9.9	15	5.6
10	5.7	27	11.1	23	5.4
11	8.2	28	11.0	24	13.6
12	6.4	29	8.2	42	7.4
20	4.7	30	7.0	43	10.6
22	7.1	34	7.2	49	7.2
32	5.9	35	5.6	57	11.3
55	8.7	37	12.8	62	4.8
64	7.6	40	11.9	67	8.9
65	5.8	41	8.7	69	12.1
66	6.5	48	10.1	70	7.7
76	9.1	50	8.2	71	6.0
79	5.0	51	7.9	72	6.8
80	5.3	53	7.2	73	6.6
81	5.5	58	12.6	75	7.2
82	5.5	60	8.2	78	8.3
Average.....	6.6	Average.....	8.9	Average.....	8.0
		Average.....	7.7		
				Average.....	7.8

TABLE A-15

MAXIMUM LOAD (ML)

Brash		Tough		Intermediate	
Specimen No.	ML	Specimen No.	ML	Specimen No.	ML
3	685	14	980	1	795
4	785	16	940	8	675
5	720	17	760	9	885
6	570	19	990	13	735
7	690	26	1,195	15	790
10	770	27	1,145	23	780
11	555	28	995	24	935
12	680	29	1,090	42	970
20	660	30	1,005	43	845
22	670	34	995	49	780
32	710	35	755	57	840
55	715	37	1,065	62	820
64	785	40	1,100	67	795
65	710	41	945	69	1,075
66	670	48	995	70	815
76	930	50	845	71	850
79	650	51	845	72	745
80	650	53	935	73	945
81	655	58	1,075	75	895
82	655	60	1,020	78	855
Average.....	697	Average.....	984	Average.....	841
		Average..... 841			
				Average..... 841	

TABLE A-16

FIBER STRESS IN BENDING TO PROPORTIONAL LIMIT (FS_{PL})

Brash		Tough		Intermediate	
Specimen No.	FS_{PL}	Specimen No.	FS_{PL}	Specimen No.	FS_{PL}
3	4,382	14	6,382	1	5,756
4	5,071	16	5,241	8	4,436
5	4,228	17	5,225	9	5,196
6	2,781	19	6,280	13	4,094
7	4,271	26	6,103	15	5,048
10	4,687	27	7,106	23	5,253
11	3,962	28	5,911	24	5,377
12	4,096	29	6,646	42	5,937
20	3,945	30	6,535	43	6,201
22	4,431	34	6,151	49	4,481
32	3,940	35	4,480	57	4,729
55	4,455	37	6,000	62	5,683
64	5,083	40	5,487	67	4,897
65	3,785	41	5,955	69	5,902
66	4,088	48	6,392	70	4,878
76	5,681	50	4,875	71	4,700
79	4,164	51	5,616	72	4,593
80	4,156	53	5,616	73	5,598
81	4,489	58	5,989	75	5,849
82	3,971	60	5,622	78	5,360
Average.....	4,283	Average.....	5,745	Average.....	5,198
		Average.....	5,014		
				Average.....	5,075

TABLE A-17

DEFLECTION (D)

Brash		Tough		Intermediate	
Specimen No.	D	Specimen No.	D	Specimen No.	D
3	0.60	14	0.56	1	0.53
4	.76	16	.68	8	.62
5	.78	17	.48	9	.65
6	.80	19	.62	13	.84
7	.80	26	.60	15	.52
10	.65	27	.69	23	.50
11	.69	28	.73	24	.93
12	.82	29	.73	42	.54
20	.61	30	.50	43	.80
22	.58	34	.51	49	.64
32	.68	35	.54	57	.66
55	.60	37	.60	62	.44
64	.70	40	.76	67	.76
65	.61	41	.63	69	.79
66	.68	48	.69	70	.65
76	.67	50	.66	71	.52
79	.60	51	.66	72	.61
80	.60	53	.53	73	.51
81	.61	58	.78	75	.59
82	.61	60	.58	78	.65
Average.....	.67	Average.....	.59	Average....	.64

Average..... 0.63

Average..... 0.63

TABLE A-18

EXTRACTIVE CONTENT (EXT)

Brash		Tough		Intermediate	
Specimen No.	EXT	Specimen No.	EXT	Specimen No.	EXT
3	7.0	14	19.7	1	10.5
4	16.4	16	10.4	8	6.6
5	7.9	17	9.2	9	18.6
6	4.6	19	13.0	13	9.3
7	15.2	26	18.6	15	5.3
10	10.9	27	15.0	23	7.2
11	4.4	28	11.4	24	7.2
12	28.8	29	12.4	42	9.2
20	4.1	30	18.4	43	--
22	33.0	34	19.5	49	9.1
32	7.0	35	5.9	57	10.3
55	6.8	37	15.8	62	16.8
64	22.6	40	14.0	67	23.2
65	21.3	41	10.7	69	14.1
66	18.8	48	27.4	70	13.2
76	11.3	50	5.9	71	8.0
79	32.8	51	7.7	72	15.7
80	31.1	53	7.5	73	13.9
81	27.9	58	13.5	75	11.6
82	30.3	60	20.0	78	13.0
Average....	17.1	Average....	13.8	Average....	11.7
	Average.... 15.5				
			Average.... 14.2		

APPENDIX B

COMPUTATIONS IN THE DISCRIMINANT FUNCTION ANALYSIS PROGRAM OF CHURCH (4)

In a population with L subpopulations with M overlapping characteristics, the discriminant function procedure defines the M boundaries of the L subpopulations and assigns each specimen to a subpopulation so as to minimize the probability of a misclassification. In this study, the population is the western larch sample 1. The subpopulations are the groups--brash, intermediate, and tough. The characteristics are the measured anatomical and mechanical properties.

The discriminant function technique depends upon some a priori classification of the specimens into groups. In this study, the a priori groups are brash, intermediate, and tough based on the fracture-failure criteria described beginning on page 30 of the results. In the analysis, the sets of coefficients and constants used in the function (paragraph 6)[1] are developed from the pooled dispersion matrix (paragraph 4) and the characteristic(s) a priori group means (paragraph 3). One set of these terms is generated for each a priori group. After the sets of terms have been found, the individual specimens are classified by re-reading the measured value of the specimen and using it with the sets of coefficients and constants to find three values of the discriminant function, i.e., one value for each a priori group (paragraph 7). The probabilities are calculated (paragraph 8) that the specimen belongs in each one of the three groups in turn.

The specimen is assigned to, or classified into, the group for which it has the highest probability of belonging. Each of the 60 specimens is evaluated in this manner. Finally a list of the speciman classifications

---

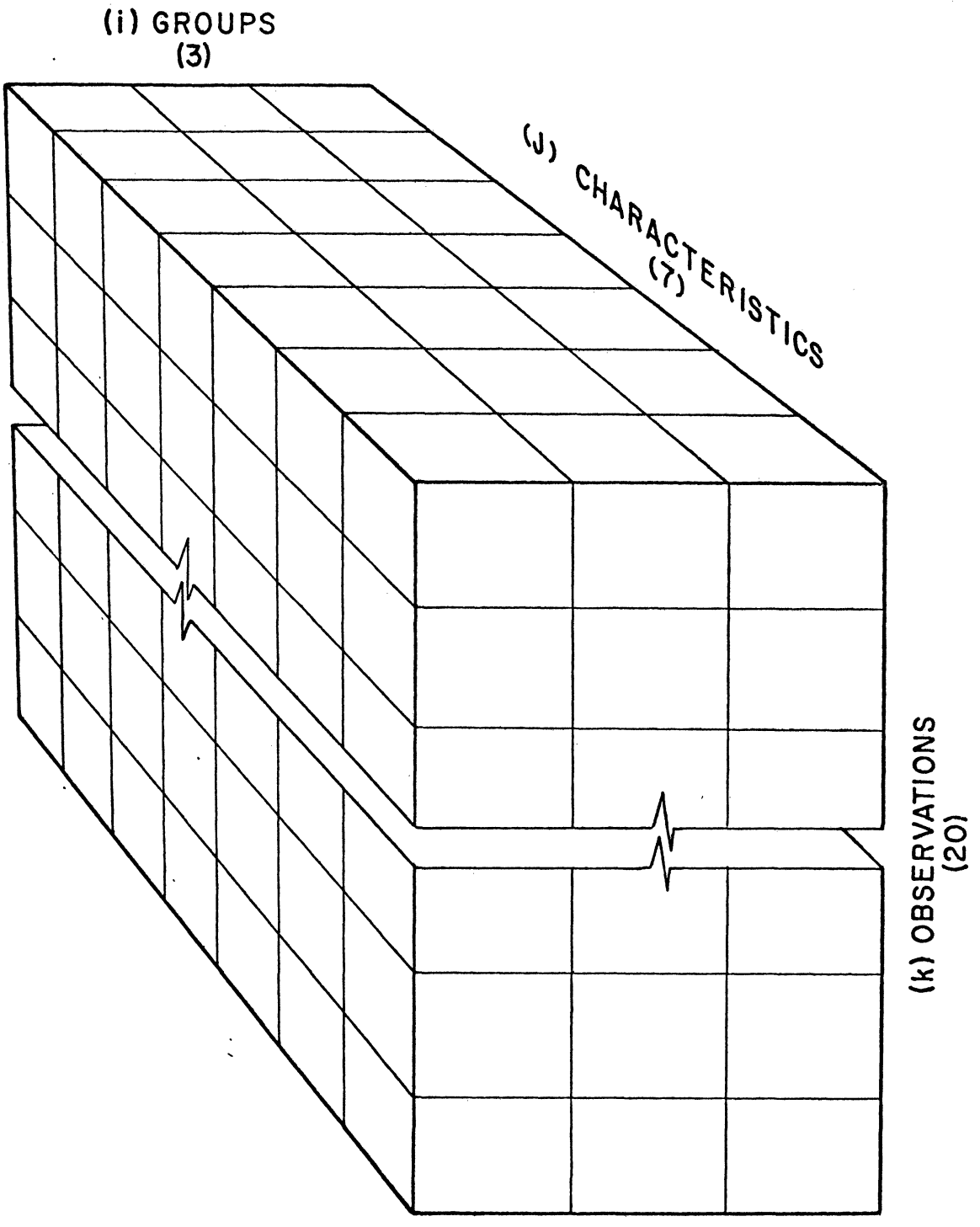
[1]The paragraphs referred to in parentheses are the numbered paragraphs in the following discussion of computations in the discriminant function analysis.

and their group probabilities along with a summary of the correct and incorrect classifications is computed.

Church's program included the Generalized Mahalanobis D^2 statistic (paragraph 5) in addition to the discriminant function. The D^2 statistic, along with the summary list of correct and incorrect classifications from the discriminant function analysis, provide means of judging the discriminatory or predictive capability of a given characteristic or set of characteristics.

Rao (48) provides a detailed discussion of the use of and problems involved in discriminant function analysis.

[X] OR [X_{ijk}] MATRIX



(1) $[X]$ or $[X_{ijk}]$ is a three-dimensional matrix of (i) groups, (j) characteristics, and (k) observations.

$$i = 1, 2, L \quad ; L = 3$$

$$j = 1, 2, \ldots M \; ; M = 7$$

$$k = 1, 2, \ldots N_i ; N_i = 20$$

(2) A sum of squares and cross products matrix $[S]$ is computed for each group as:

$$[S] = [F]'[F]$$

where $[F]$ is the two-dimensional array $[X_i]_{jk}$ for the $i^{\underline{th}}$ group and $[F]'$ is the transpose of $[X_i]_{jk}$.

(3) The matrix of means $[A]$ is computed as:

$$a_{ji} = \sum_{k=1}^{20} X_{ijk}/N_i$$

where a = the $ji^{\underline{th}}$ element of $[A]$

$i = 1, 2, 3$

$j = 1, 2, \ldots 7$

$N_i = 20$

(4) The pooled dispersion matrix [B] is computed as:

$$b_{tj} = \sum_{i=1}^{3} [s_{tj}]_i / Z$$

where b = the $tj^{\underline{th}}$ element of [B]

s = the $tj^{\underline{th}}$ element of [S]

t = 1, 2, ...7

j = 1, 2, ...7

and

$$Z = \sum_{i=1}^{3} N_i - L$$

The [B] is inverted to $[B]^{-1}$ using the Gaussian elimination method.

(5) The Generalized Mahalanobis D^2 statistic V is computed as follows:

$$V = \sum_{j=1}^{7} \sum_{t=1}^{7} b^{jt} \sum_{i=1}^{3} N_i (a_{ji} - \bar{X}_j)(a_{ji} - \bar{X}_j)$$

where b^{jt} = the $jt^{\underline{th}}$ element of $[B]^{-1}$

a_{ji} = the $ji^{\underline{th}}$ element of [A] for the $j^{\underline{th}}$ characteristic and the $i^{\underline{th}}$ group

$\bar{X}_j$ = the pooled mean for the $j^{\underline{th}}$ characteristic, pooled over the (i) groups.

The D^2 statistic may be interpreted as a chi-square (assuming normality) with M(L - 1) degrees of freedom to test the hypothesis that there is no real difference between the group mean values for a given characteristic.

M = No. of characteristics (7)

L = No. of groups (3)

(3) Each discriminant function contains a coefficient for each of the M characteristics plus a constant term. The coefficient matrix [C] is computed as follows:

$$c_{ji} = b^{tj} \; a_{ji}$$

where c_{ji} = the $ji^{\underline{th}}$ element of [C]

b^{tj} = the $tj^{\underline{th}}$ element of $[B]^{-1}$

a_{ji} = the $ji^{\underline{th}}$ element of [A]

and

i = 1, 2, 3

j = 1, 2, ...7

t = 1, 2, ...7

The vector of constants [H] is computed as:

$$h_i = -\frac{1}{2} \sum_{j=1}^{7} \sum_{t=1}^{7} b^{jt} \, a_{ji} \, a_{ji}$$

where h_i = the $i^{\underline{th}}$ element of [H]

b^{jt} = the $jt^{\underline{th}}$ element of [B]

a_{ji} = the $ji^{\underline{th}}$ element of [A]

and

$i = 1, 2, 3$

(7) Finally, each specimen is classified into one of the three groups. The procedure is to re-read the data and for each specimen obtain the vector of values for the discriminant function. The discriminant function (G_i) is computed as:

$$g_i = \left(\sum_{j=1}^{7} X_j C_{ji} \right) + h_i$$

where g_i = the $i^{\underline{th}}$ value of the discriminant function

$i = 1, 2, 3$

(8) The largest g_i is selected, and the vector of probabilities [P_i] that the specimen falls in the $i^{\underline{th}}$ group is calculated as:

$$p_i = \frac{e^{(G_i - G_{max})}}{\sum_{t=1}^{3} e^{(G_t - G_{max})}}$$

where p_i = the i^{th} element of [P]

$i = 1, 2, 3$

The largest p_i is selected and the specimen is then assigned to the i^{th} group.

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