EFFECTS OF STRAIN RATE ON THE SURFACE MORPHOLOGY OF *PINUS RADIATA* BROKEN BY TRANSVERSE TENSILE FORCES

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ABSTRACT

Small samples of **Pinus radiata** D. Don were broken by applying transverse tensile forces at a variety of strain-rates in order to determine the effects of strain-rate, moisture content, and tracheid structure on the morphology of the surfaces produced during the fracture. Microscopical examination of the surfaces showed that all three variables were of importance. In saturated earlywood, the proportion of tracheids broken in transwall failure increased as strain-rate was increased, and reached 55% at the highest strain-rate of $10^2 sec^{-1}$. In airdry earlywood, 20% of the tracheids were broken at all rates, and in latewood fewer than 5% of tracheids were broken at both moisture contents and at all strain rates.

INTRODUCTION

When wood is broken by transverse tensile forces there are two quite distinct types of failure that can occur. The first, called transwall failure, is produced when a split crosses both tracheid walls and exposes the lumen, as indicated by a . . . . a in Fig. 1. The second, intrawall failure, occurs when the fracture plane lies within the tracheid wall at the position shown by b . . . . b in Fig. 1 and results in the separation of two adjacent tracheids exposing the lumen of either.

Koran (1967, 1968) measured the relative amounts of the two types of failure that occurred when samples of black spruce were split by radial and tangential tensile forces. At a strain-rate of 10^{-1} sec^{-1}, and at 0°C, transwall fracture occurred in 50% of the

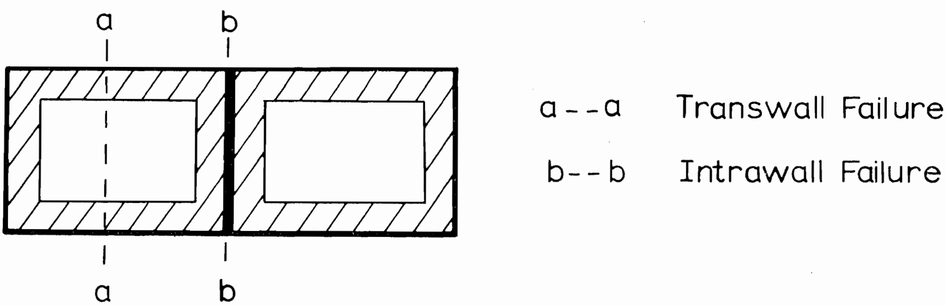


FIG. 1—Transwall and intrawall failure

tracheids in the fracture surface. As the temperature was raised to 150°C, the amount of transwall failure decreased to 10% of the surface tracheids, and the strength of the samples decreased by 80%. Furthermore, scanning and transmission electron microscopic examination of the surfaces produced by the fracture suggested that intrawall failure always occurred within either the P or the S_1 layers of the tracheid wall, but never in the middle lamella, the S_2 layer, or at the S_1-S_2 interface.

However, very few machining processes result in such low rates of deformation of wood as those employed by Koran. Therefore, this present study was initiated in order to determine experimentally the effects of varying strain-rate on the transverse fracture of wood.

EXPERIMENTAL PROCEDURE

Small rectangular specimens of *Pinus radiata* were broken by tensile loads applied in either the radial or the tangential directions at strain-rates ranging from 10^{-5} sec^{-1} to 10^{2} sec^{-1}. Two moisture contents were used, airdry and saturated, and fractures were initiated by means of symmetrically placed notches in either the earlywood or the latewood regions of the growth ring. Specimen dimensions are detailed in Fig. 2.

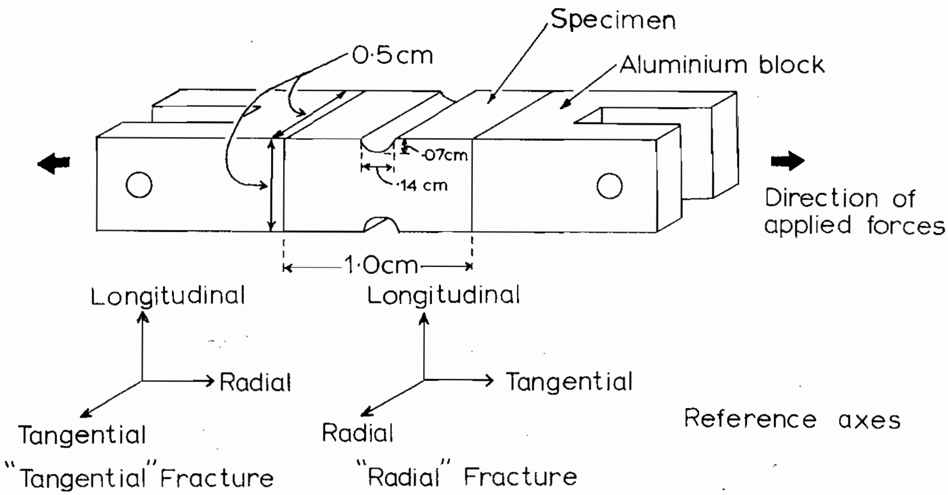


FIG. 2—Specimen shape and dimensions

At low strain-rates specimens were broken in an Instron tensile testing machine, while at strain-rates higher than 10^{-2} sec^{-1} a machine described by Cousins (1972) was used. Attachment to each specimen was made by gluing small aluminium blocks to its ends with epoxy resin as shown in Fig. 2. Provided that the specimen was kept in the airdry condition until the adhesive had hardened it could later be soaked without seriously weakening the joint. Very few specimens failed at the glued surfaces during the tests.

After fracture, variations in surface morphology were studied using a scanning electron microscope, and thin cross-sections of the specimens were examined in an optical microscope in order to determine the proportions of fracture surface tracheids that were broken in transwall failure. To quantify the latter the number of broken tracheids was expressed as a percentage of the total number of tracheids along the section edge. The figure obtained was called the "percent transwall failure" of the specimen.

EXPERIMENTAL RESULTS AND DISCUSSION

(1) *Intrawall Failure*

In general, the surfaces produced by intrawall failure seemed to be very similar to those described by Koran. Failure appeared to have occurred in a layer which was reinforced by fibres lying almost at right angles to the tracheid longitudinal axis, as is evidenced by the horizontal lines of tearing in Fig. 3. The only such layers are the S_1 and S_3. However, edge views such as those shown in Figs. 3 and 4 rule out the possibility of failure within the S_3 layer.

(2) *Transwall Failure*

Two distinct types of transwall failure were observed. The first type, which was produced when specimens were fractured by tangential forces, is illustrated in Fig. 5. In the upper part of the photograph the fracture plane lies parallel to the exposed row of tracheids and failure is predominantly intrawall. Then, near the centre of the photograph, the fracture plane dips sharply across the row of tracheids to a new intrawall position one tracheid thickness lower. As the fracture plane crosses the row of tracheids it breaks a small portion of each one in transwall failure in the manner shown schematically in Fig. 6 (a). In Fig. 5 the regions of transwall failure can be identified by the presence of the convex upper pit borders.

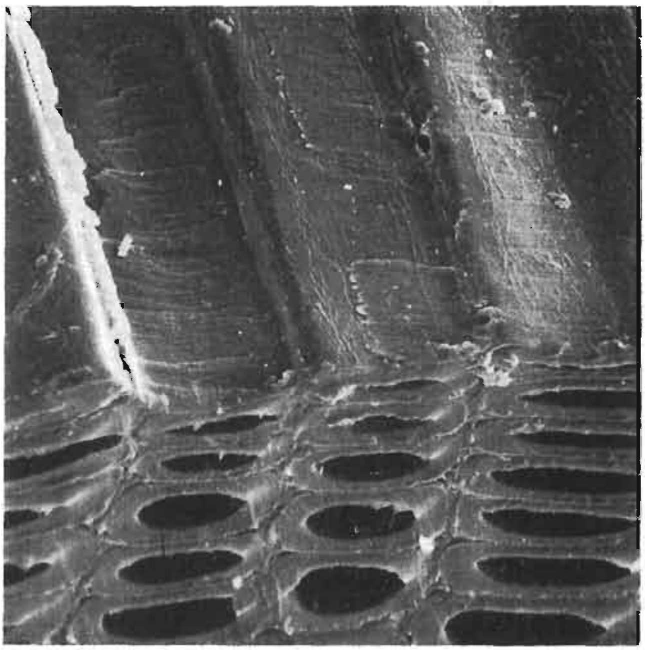


FIG. 3—Intrawall failure in latewood (×2200)

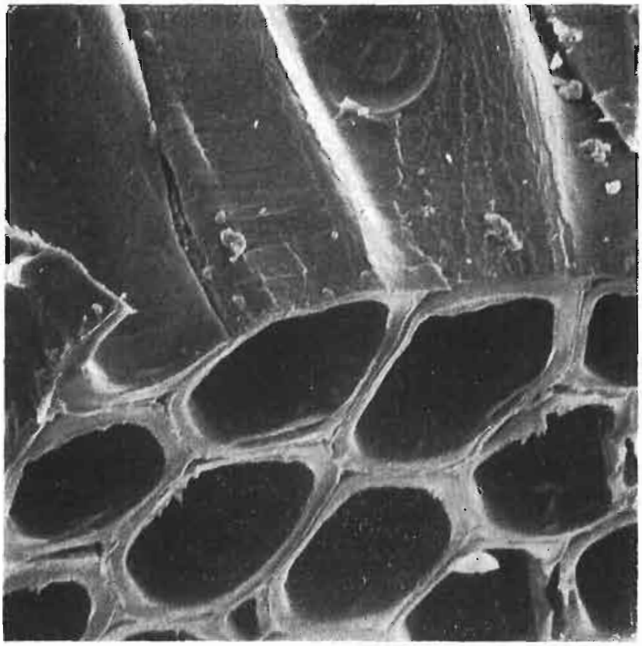


FIG. 4—Transwall and intrawall failure in earlywood (×2100)

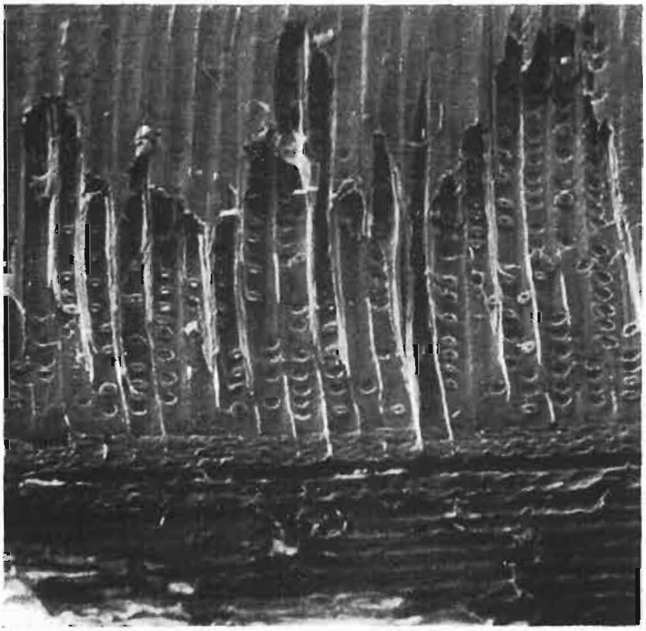


FIG. 5—Transwall failure produced by radial loading (×300)

A likely reason for the occurence of both types of failure is as follows. In wood, tracheids are well aligned in a radial direction, and, therefore, planes of intrawall splitting will tend to lie parallel to the radial-longitudinal plane. If fractures can be initiated at points of weakness within the sample it is possible that non-coplanar regions of intrawall splitting will form. Two such fractures can coalesce only by breaking through the interleaving rows of tracheids, thus producing regions of transwall failure.

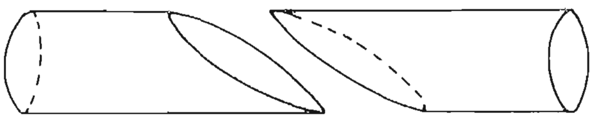
The second type of transwall failure results from radial loading and is simply the lengthwise splitting of a tracheid into two portions as illustrated in Fig. 6 (b). Examples of this type of failure are given in Figs. 7, and 8. These show a part of the fracture surface of a block of *Pinus radiata* which was broken at a strain-rate of $10^2 sec^{-1}$ while in the saturated state. A large proportion of the surface tracheids are broken in transwall failure.

Cousins (1972) studied this type of transwall failure in some detail, and his experimental findings are summarised in Fig. 9 in which percent transwall failure is plotted as a function of strain-rate, moisture content, and tracheid structure. Five replicate specimens were broken at each set of experimental conditions and the mean values and standard deviations of the results obtained are shown. It can be seen that all three variables are of considerable importance. Possible reasons for the observed effects are outlined below.

(a) Tracheid structure

In this context the pertinent aspects of tracheid structure are those which differ from earlywood to latewood. The most significant of these are tracheid wall thickness and the degree of radial offset between adjacent tracheids (the latter being partly dependent on tracheid diameter). The possible importance of each factor is described briefly.

(i) Wall thickness: The effects of variations in tracheid wall thickness are most easily studied in a situation in which there is zero radial overlap, i.e., there is perfect alignment of tracheids in both the radial and tangential directions. If radial loading is assumed, and the idealised model tracheid of Cousins (1972) is used, the situation



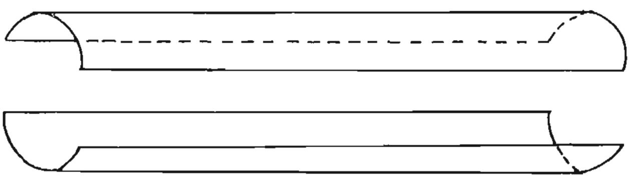


FIG. 6—(a) "Radial" transwall failure
(b) "Tangential" transwall failure

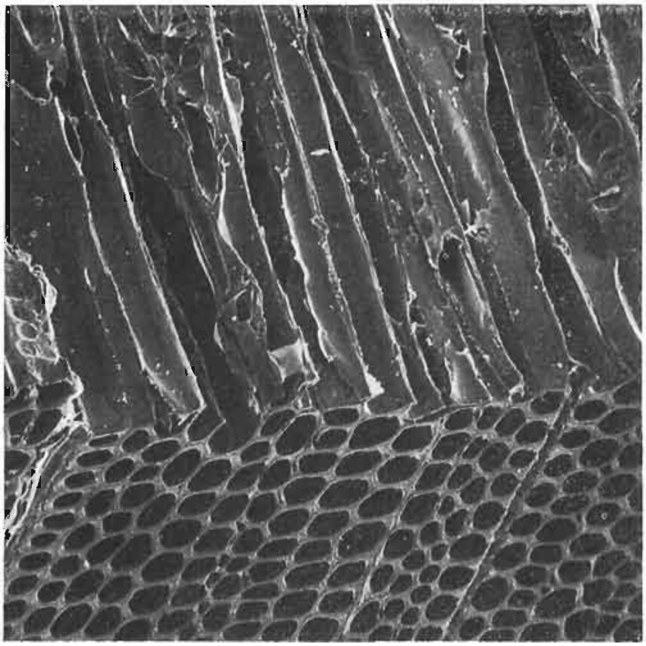


FIG. 7—Surface of an earlywood specimen broken while saturated at a strain-rate of 10^2sec-1 ($\times$420)

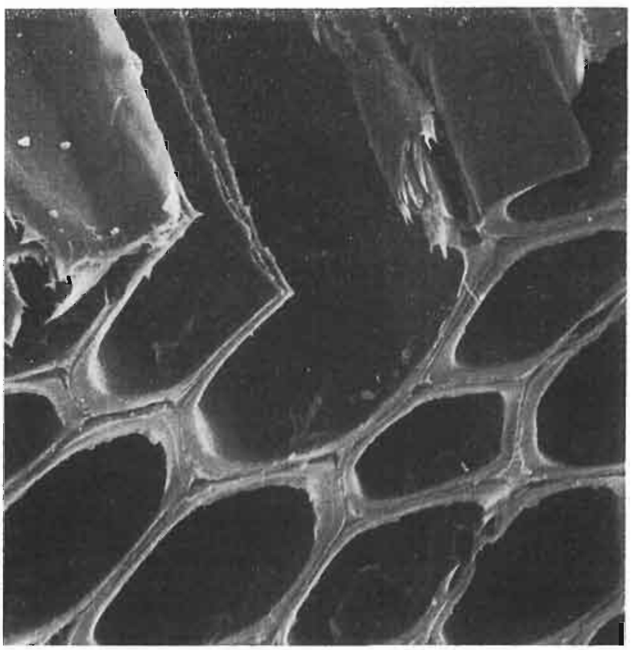


FIG. 8—Close up view of transwall failure ($\times$2100)

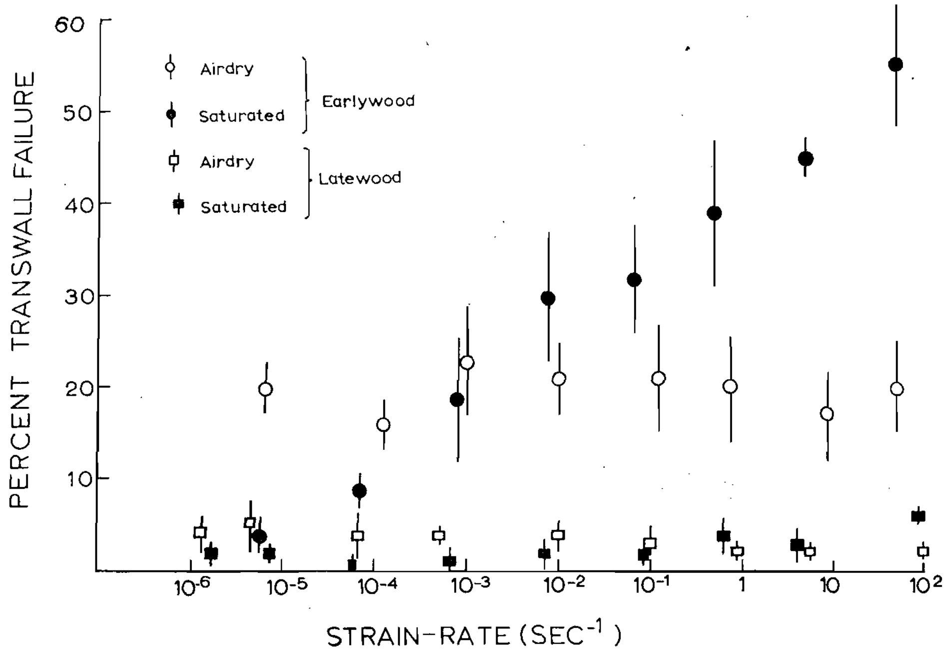


FIG. 9—Effects of strain-rate, moisture content and tracheid structure on the amount of transwall failure produced during the fracture of **Pinus radiata** by radial forces ....

illustrated in Fig. 10 results. The tangential portions of the tracheid walls can be regarded as continuous "plates" which are uniformly loaded by remaining portions of the radial walls over their regions of contact. Adjacent "plates" in turn load the thin tangential layer of middle lamella which separates them.

By following the procedure described by Cousins (1972) it is possible to derive the relationship between the uniform stress in the radial wall (σ_W) and the maximum value of σ_{ML}, the radial stress in the tangential middle lamella. The resulting values of the ratio σ_{ML} (max.)/σ_W for wet and dry earlywood and latewood are listed in Table 1.

It can be seen intuitively that the smaller the value of σ_{ML} (max.)/σ_W the greater is the likelihood of transwall failure of the tracheid. In other words, if the stress in the wall is high and the stress in the middle lamella is low, then transwall failure is more likely to occur than if the converse is true. Thus Table 1 suggests that transwall failure is more likely to occur in the thin-walled early wood tracheids than in the thicker walled latewood tracheids. Note, however, that no comparison can be made between "saturated" and "airdry" results because middle lamella and wall strengths are dependent on moisture content.

(ii) Tracheid overlap: In order to study the effects of this factor it is necessary to treat earlywood and latewood separately.

Earlywood: To simplify calculations assume that all earlywood tracheids have the same radial diameter of 45 μm, which is the measured average value for the samples

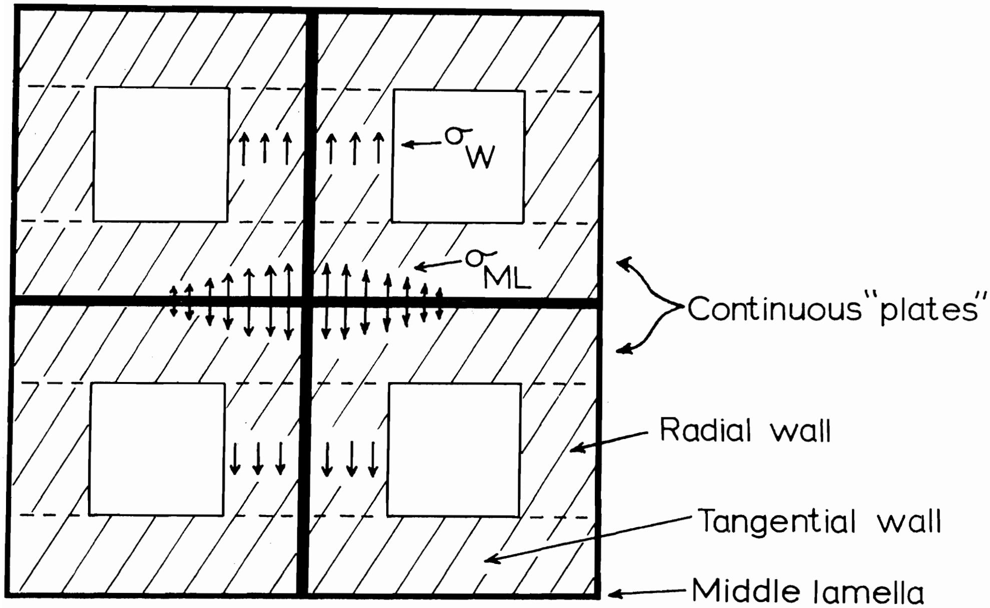


FIG. 10—Perfectly aligned latewood tracheids showing wall (σ_W) and middle lamella (σ_{ML}) stresses.

TABLE 1—Early-latewood variation of the ratio σ_{ML} max.)/σ_W

Moisture Content	Earlywood	Latewood
Wet	.68	.84
Dry	.84	.93

of wood actually broken. The maximum amount of overlap that can then occur is $22\frac{1}{2}$ μm as shown in Fig. 11, and zero overlap is simply the situation of Fig. 10.

When overlap is present the resistance of the radial portions of the middle lamella to shear deformation provides coupling between adjacent radial walls at A - A' and B - B' of Fig. 11. If then the wall at C is stiffer than the middle lamella at C' the wall will bear more than half of the total load, and the amount of load transfer to the wall will be dependent on the degree of overlap that is present.

Cousins (1972) makes use of a simple finite-element technique to study the effects of varying overlap and obtains the values of σ_{ML} (max.)/σ'_W listed in Table 2. These suggest that the likelihood of transwall failure of the highly stressed wall increases greatly

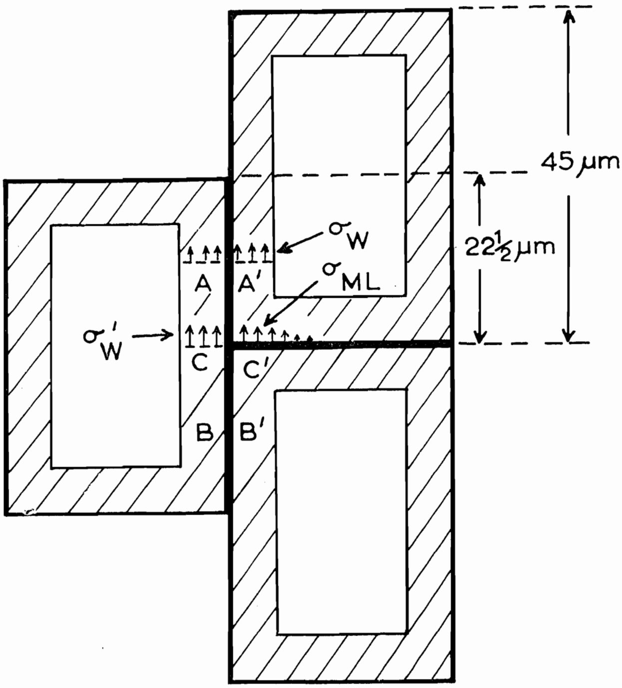


FIG. 11—Earlywood tracheids showing the maximum radial offset.

TABLE 2—Effect of overlap on the ratio σ_{ML} (max.)/σ'_{W} in earlywood

Overlap (μm)	0	9	22½
Wet	.68	.48	.46
Dry	.84	.72	.72

as the degree of overlap increases in wet earlywood, but that changes occurring in the case of the dry earlywood wall as much less significant. At the same time shear stresses in the "coupling" regions of middle lamella were found to be small.

Latewood: Two distinct types of latewood tracheid were present in the samples of wood studied. One type was almost square in cross-section and had an average radial diameter of 25 μm, whereas the other type had a radial diameter of only 8μm. The two types occurred in bands lying parallel to the fracture plane and the fractures were approximately equally divided between the two. However, no significant differences between the two were observed in either strength or percent transwall failure, so only the "worst" case of 25 μm diameter was studied theoretically. Following the same procedure as for earlywood gave the σ_{ML} max.)/σ'_W values listed in Table 3. Once again these suggest that transwall failure is more likely to occur when the degree of overlap is high, but the effects of changes in overlap are not great.

At the same time microscopic examination of the fracture surfaces showed that the failures had tended to follow paths of minimum overlap, giving in many cases a surface that was almost flat (*see,* for example, Fig. 3). This factor, coupled with the results of Table 3, suggests that variations in the degree of overlap are of little significance in latewood.

TABLE 3—Effect of overlap on the ratio σ_{ML} (max.)/σ'_W in latewood

Overlap (μm)	0	5	12½
Wet	.84	.77	.74
Dry	.93	.88	.86

In summary, the results of Tables 1 to 3 suggest that wet wood is more sensitive than dry wood to variations in wall thickness, and that wet earlywood is the most strongly influenced by variations in the degree of overlap. It seems reasonable to suggest that these factors are responsible for earlywood-latewood variations in percent transwall failure.

(b) Moisture-content: strain-rate

Because the effect of strain-rate is dependent on moisture content it is convenient to consider these two factors together. In airdry earlywood percent transwall failure does not vary greatly with strain-rate, but in saturated earlywood it increases dramatically as the strain-rate is increased. Cousins (1972) suggests that the prime reason for this behaviour is that the strengths of saturated hemicellulose and lignin, which are the major tracheid wall components involved in splitting during intrawall failure, increase greatly as strain-rate is increased, whereas the strength of crystalline cellulose, which governs the transverse strength of the tracheid wall, does not vary greatly. Therefore, as strain-rate is increased the strength of the tracheid wall varies only slightly, but the stress which it must bear in order to initiate intrawall splitting increases greatly. Therefore, more transwall failure is likely to occur at higher strain-rates in saturated wood. When wood is airdry, on the other hand, the strengths of hemicellulose and lignin do not vary greatly with strain-rate, and the constancy of percent transwall failure is to be expected.

CONCLUSIONS

When *Pinus radiata* is broken by transverse tensile forces, the strain-rate, moisture content, and tracheid structure all greatly affect the morphology of the surfaces produced by the fracture. Strain-rate is of importance only in saturated earlywood, in which the percentage of transwall failure increases as strain-rate is increased. In airdry earlywood, percent transwall failure is constant at 20%, and in latewood it is always very small.

Results of the theoretical discussion suggest that the occurrence of transwall failure is largely governed by tracheid structure and the strength of the tracheid wall components. It appears to be the sensitivity to moisture content and strain-rate of two of these components, the hemicellulose and lignin, that gives rise to the observed moisture content and strain-rate dependence of percent transwall failure.

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