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Effect of Temperature on Orthotropic Properties of Wood. II.†

Proportion of the Transwall Failure*1

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木材の強度異方性に及ぼす温度の影響(第2報)†

細胞壁破断の出現率について*1

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前報[1]の曲げ破壊試料について，破断面の観察を行い曲げ強さ異方性と組織構造との関連について検討を行った。ここでは特に，引張側破断面における「細胞壁破断の出現率」について観察を行ったが，その値は温度の上昇とともに減少し，また応力の方向がT方向に近づくにつれて減少することが明らかとなった。また出現率の温度による変化はT方向ではR方向よりも少なくなることが明らかとなった。温度ならびに角度の方向に対する曲げ強さの変化と細胞壁破断の出現率の変化は似た傾向をもっており(Fig. 1, Fig. 5)，特にラミン材についてはよく一致した。

R−T面における強さ異方性は主として放射組織と細胞の配列形態に起因するものと推定される。

To make clear the strength anisotropy of wood in RT plane, the influence of anatomic structure was observed in this study. As the index of the fracture type of the cells, the percentage of cells broken by transwall failure (the path of failure crossed the double cell wall) on the fracture surface was discussed.

It was found that the percentage of cells broken by transwall failure increased with a decrease in angle between radial direction and the stress direction, and with a decrease in testing temperature for both Ramin and Red meranti wood. And these tendency corresponded to the strength values in RT plane (Fig. 1 and Fig. 5). But the difference of the percentage caused by temperature decreased with an approach to the tangential direction.

And it could be considered that the difference of the strength values between radial and tangential directions was caused by the strength of the ray tissues and the arrangement of the cells chiefly.

1. INTRODUCTION

In the previous report[1] the effect of temperature was discussed on the orthotropic properties of green wood in RT plane. The orthotropic elasticity in RT plane conforms to the coordinate transformation law of the compliance at various temperatures. But the strength property conforms to neither Hankinson's nor Norris's equation. This is attributable to the fact that the fracture of wood is not elucidated by the linear theory. Even if the change of the stress direction conforms to the transformation law of the stress, the fracture condition of wood substance might be changed by the stress direction. Consequently, as a clue to elucidate the fracture condition, it is important that the fracture surface be analyzed by mean of microscopic observation.

When the cause of the anisotropy of wood are discussed in RT plane, the following three have to be pointed out in its anatomic structure; ray tissues, the arrangement of the cells with high

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degree of radial orientation, and the growth ring structure which characterizes the tangential direction. But there is little significance in discussing the growth ring structure on the species of this study (Ramin and Red meranti). Schniewind discussed the transverse strength in connection with the ray tissues.[2] Korán[3] and Hayashi et al.[4] pointed out that the percentage of cells broken by transwall failure decreased with rising the testing temperature.

In this report, the fracture surface was observed in relation to the testing temperature and the angle between radial direction and the stress direction in RT plane.

2. MATERIALS AND METHODS

This investigation was carried out succeeding the previous examination[1], and the materials prepared for microscopic observation were Ramin (*Gonystylus* sp.) and Red meranti (*Shorea* sp.) which were fractured in the previous bending test. The angle between long axis of the specimen and radial direction was defined in relation to the stress direction. The stress applied in the radial direction corresponded to 0 degree and in the tangential direction to 90 degrees stress angle. A term called 'stress angle' in this paper was introduced as the angle between the radial direction and the stress direction. Bending test, whose span was 15.0 cm, was carried out in the heat controlled water bath at 20, 40, 60, 80 and 97°C. Fig. 1 shows the strength values.

SEM was used for the observation of the fracture surface and the photographing. The optical microscope of stereoscopic type was used for the evaluation of the proportion of the transwall failure. After bending test, the transverse plane of the tension side of the specimen was sliced off by a razor, and the shape of the fracture of cells was observed while adjusting the focus. On each condition, about five hundred cells which stood in the fracture plane of tension side of the beams were divided into the transwall failure and the intrawall failure. Although it was difficult to distinguish strictly between the transwall failure and the intrawall failure, it seemed to be able to grasp the difference of the influence of the temperature and stress angle if the distinction were made under certain definition. In this study, 'the transwall failure' and 'the intrawall failure' were defined as follows: In the observation of the transverse plane, if the cell in the fracture surface indicated a tube shape (Fig. 2a), it was defined as 'the intrawall failure'. If the cell wall indicated a semicircle or a half of a tube (Fig. 2b), it was clear that the fracture path crossed the cell wall, then it was

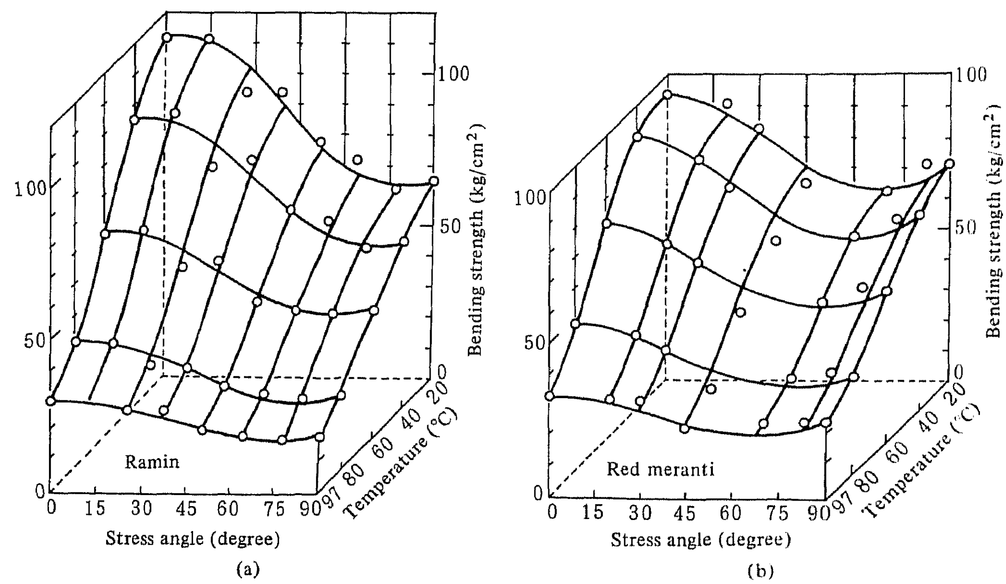
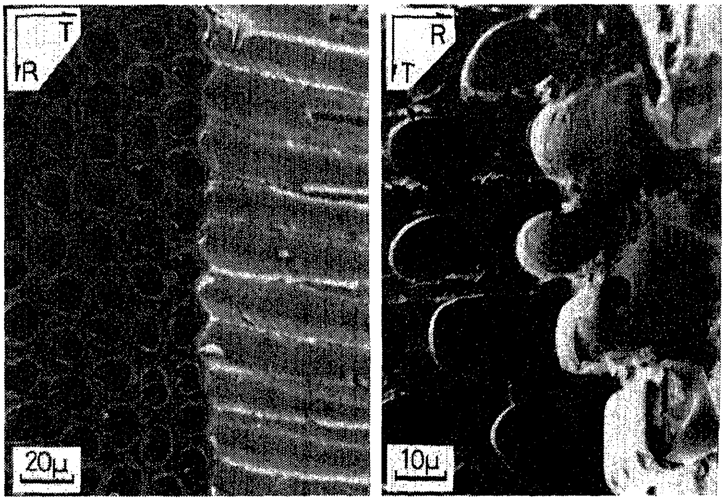


Fig. 1. Bending strength at various stress angles and at various temperatures.
Note; Each point represents the mean of 7–10 values.



(a) (b)

Fig. 2. Fracture type of the cells. (a) is a view of the intrawall failure in Red meranti wood at 20°C and (b) is a view of the transwall failure in Ramin wood at 20°C.

defined as 'the transwall failure'. By this definition 'the proportion of the transwall failure' was calculated in the form of $A/(B+A)\times 100(\%)$, where A and B were the numbers of the cells which were broken by transwall failure and intrawall failure respectively.

3. RESULTS AND DISCUSSION

3.1 The shape of the fracture

In the previous report[1], it was found that the modulus of elasticity in RT plane conformed approximately to the general formula of orthotropic elasticity. On the other hand, the strength values in RT plane appeared to not obey the scheme which was generally accepted in LR and LT planes. Therefore the gross anatomical discussion is important for the explanation of the behaviour of the strength values in RT plane.

The schema of the shape of the fracture is shown in Fig. 3. It shows the case of Ramin wood in transverse plane. These shapes of the fracture were able to be divided into three classes according to the relationship between the fracture path and the anatomic structure. In the two specimens of radial direction, the fracture develops straight along the growth ring, namely to the tangential direction. In the two specimens of 26 and 39 degrees stress angle, the crack occurs to the radial direction at first and develops independent on the direction of the ray tissues and the growth rings. And in the four specimens of 51, 64, 77 and 90 degrees stress angle, the fracture almost develops

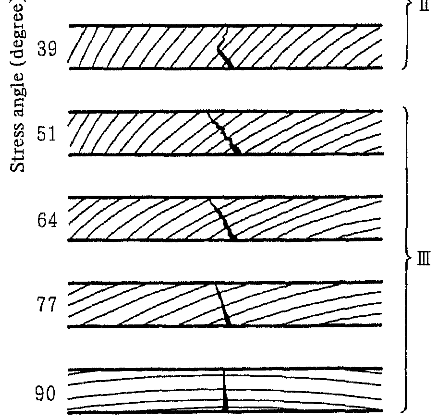


Fig. 3. Sketch of the fracture path on RT plane.
I. Fracture develops to the tangential direction.
II. Fracture path shows disordered line.
III. Fracture develops to the radial direction.

to the radial direction increasing the extent of zigzag with decrease of the stress angle. These groups of the fracture type seem to correspond to the strength values obtained from bending test as shown in Fig. 1. Examining these values closely, although every point agrees approximately with the line which was calculated from the empirical equation[1], these points can be broken into three groups; the two points of the radial direction and 13 degrees stress angle, the two points of 26 and 39 degrees stress angle, and the four points from the tangential direction to 51 degrees stress angle.

And the shapes of the fracture also have relation to the maximum deflection (Fig. 4). If the crack runs zigzag as shown in the specimens of 26, 39 and 51 degrees stress angle, maximum deflection indicates a large value in contrast to the specimens of tangential and radial direction which show a straight fracture line.

In green condition the fracture of the beam, whose long axis is perpendicular to the grain, is dominated by the crack of the tension side of the beam. Therefore the fracture of the only tension side of the specimen is dealt with here. Fracture in the tangential plane as a result of the radial stress will be expected in the part of the early wood if the wood has growth ring structure. But there is little reason to consider it on Ramin wood and Red meranti wood. Schniewind investigated the transverse anisotropy of California black oak

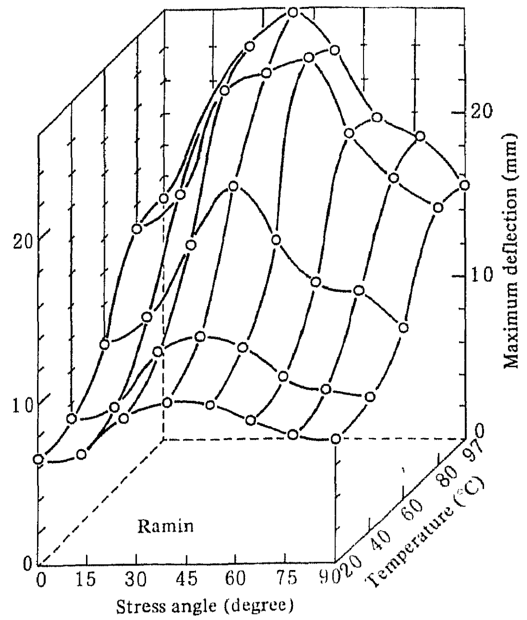


Fig. 4. Maximum deflection of Ramin wood in bending at various stress angles and at various temperatures.

and pointed out that the difference between radial and tangential maximum tensile strength values can be fully attributed to the high radial maximum tensile strength of the rays[2]. In this study the same results can be seen in the influence of ray tissues, but the rays of Ramin and Red meranti wood are not as broad as that of California black oak. Thus the cause of the difference of the

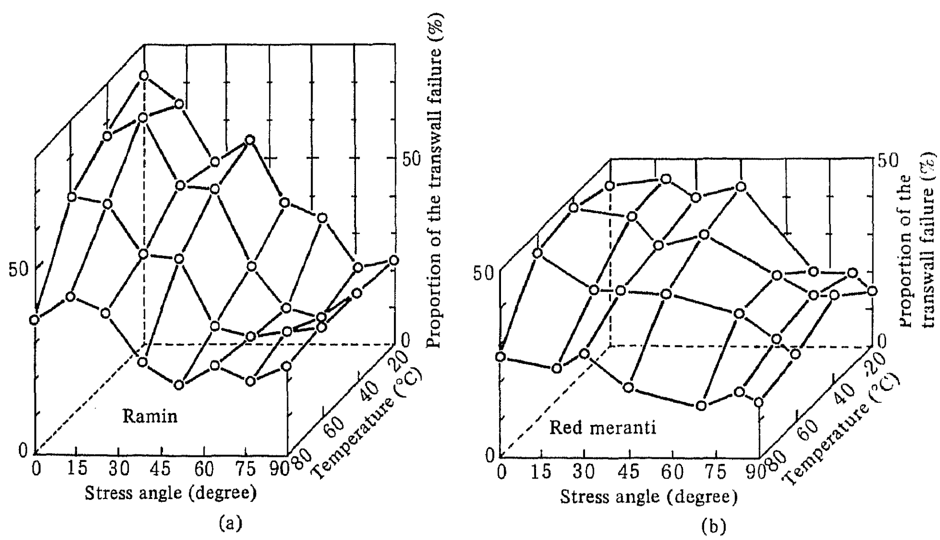


Fig. 5. Proportion of the transwall failure at various stress angles and at various temperatures. For each point about 500 cells were observed on the fractured surface.

strength values between radial and tangential directions is not only the influence of the ray tissues but also some factors, such as the arrangement of the cells, the direction of the crack, and so on.

3.2 *Relationship between the proportion of the transwall failure and the strength values*

Fig. 5 shows the proportion of the transwall failure, (a) and (b) are the case of Ramin and Red meranti wood respectively. In each figure the vertical axis indicates the proportion of the transwall failure, the horizontal axis indicates the stress angle and the diagonal axis temperature. In both species the proportion of the transwall failure increases with decreasing stress angle, i.e. with approaching to the radial direction. As for the relationship to the temperature, the proportion increases with a decrease in temperature within the range of this experiment. On the other hand, the bending strength of radial direction is higher than the value of tangential direction and increases with decreasing temperature as shown in Fig. 1. In Ramin wood, good correlation between the proportion and the strength value is found. The relationship between the proportion and temperature have already been investigated by some researchers.[3)4)] A relationship between the proportion and stress angle is indicated here in Fig. 6.

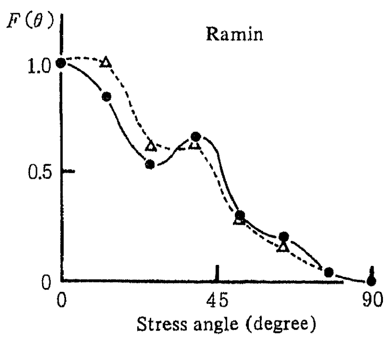


Fig. 6. Comparison of a proportion of the transwall failure to the strength value for Ramin wood at 20°C.

Note; Every point $F(\theta)$ was calculated as follows

$$F(\theta) = \frac{f(\theta) - f(90^\circ)}{f(0^\circ) - f(90^\circ)},$$

where $f(\theta)$ was a value of a proportion or a bending strength at stress angle θ.

—●—: proportion of the transwall failure
--△--: bending strength

It is found that the proportion corresponds to the strength value in change of stress angle.

From the above it can be considered that the proportion of the transwall failure corresponds to the strength properties, and that it is one of the causes of the strength anisotropy in RT plane.

3.3 *The effect of stress angle on the proportion of the transwall failure*

The direction to which the fracture develops has relation to the stress angle, and it must be emphasized that the correspondence to the arrangement of the cells in transverse plane. In general, the cells of wood indicate high degree of radial orientation as compared with the arrangement in the tangential direction. This can be explained by the process of the tangential division of the cambial initial as is known generally. The cell walls of the new wood tissues, which are formed just inside the bark, increase in their radial diameters during the growing season and divide into two. This process of division continues, a radial row of cells being thus produced. No matter how each cell has isotropic properties in the transverse plane, wood does not have the same strength values about different direction in RT plane because of its difference of the arrangement of the cells. On the anisotropy of the fracture type, one of the conclusion becomes clear. Namely, if the fracture takes place in the radial plane, there is a fair chance for the occurrence of the intrawall failure, and if it takes place in the tangential plane, there is more possibility of the transwall failure as compared with the case of the fracture in the radial plane.

Therefore, as it is presumed that the strength value increases with increasing possibility of the transwall failure, it can be considered that the strength property of wood in RT plane is affected by the arrangement of the cells.

The actual section observed by a SEM is shown in Fig. 2. Fig. 2a is a view of radial plane fracture of Red meranti wood at 20°C. At lower temperature in the range of this study, fracture in the radial plane as the result of the tangential stress tends to occur in some areas along and within the double cell wall. In contrast with this, the fracture path in the tangential plane of the radial specimen, as the result of the radial stress, tends to cross the cell wall. Fig. 2b shows a view of tangential plane

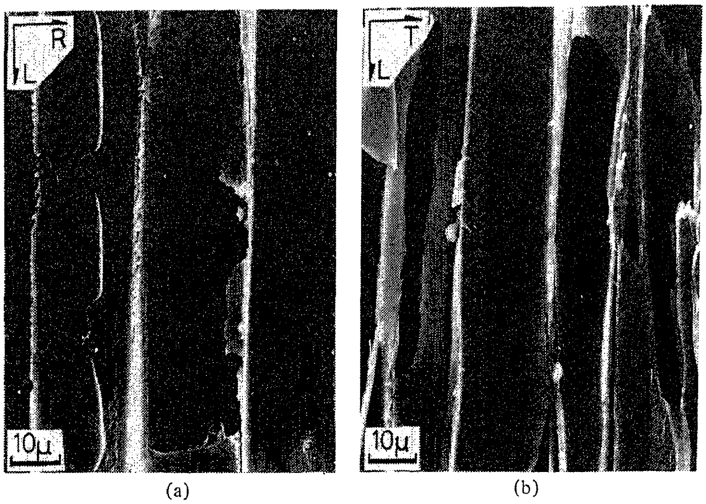


Fig. 7. Fracture surface of Red meranti wood at 20℃. (a) In the radial plane. (b) In the tangential plane.

fracture of Ramin wood at 20°C. Fracture apparently goes through the cell and hence breaks the cell into two pieces. Fig. 7 shows the separated surface of Red meranti wood. Fig. 7a is a view of radial surface of the tangential specimen and Fig. 7b is a view of tangential surface of the radial specimen which was broken by the radial stress at 20℃. It is obvious that the fracture type varies with the stress angle.

3.4 The effect of temperature on the proportion of the transwall failure

As is observed in Fig. 5, the proportion of the transwall failure is affected both by the stress angle and temperature. The effect of temperature is attributable to the difference of the properties of the components which form the cell wall and intercellular layer. Each component indicates different behaviour at various temperature against the external force.[5] Korán investigated the effect of the temperature on morphology of the separated surface using Black spruce,[3] and Hayashi et al. also studied it using Lawson cypress and Buna.[4] And they stated that the drop in the percentage of cells broken by transwall failure as temperature increased was apparently due to the softening of the hemicellulose and lignin. In this study on Ramin and Red meranti wood the effect of temperature shows almost the same trend as their result. But there is a difference between radial and tangential directions. The effect of temperature is obvious in the specimen of radial direction, however it becomes obscure with approaching to the tangential directions. It seems that the fracture in the tangential plane of the radial specimen is affected by the softening of intercellular layer.

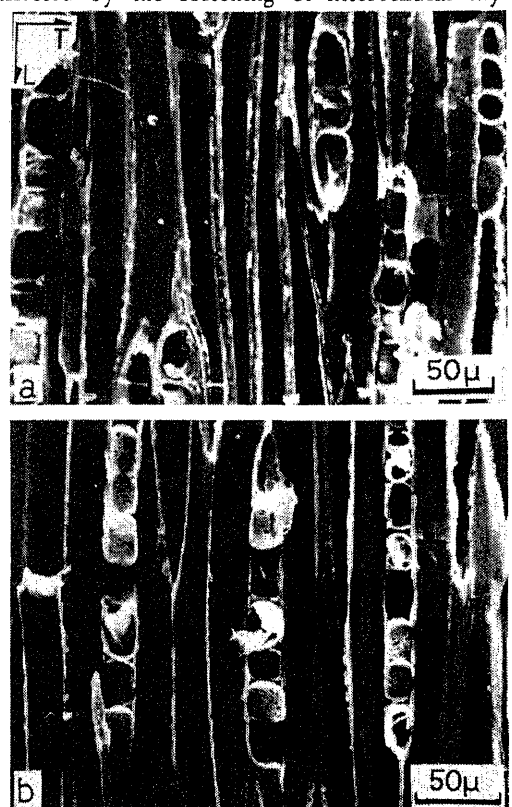


Fig. 8. Fracture surface in tangential plane of Ramin wood.
(a) At 20℃ and (b) at 80℃.

And as the fracture in the radial plane tends to occur within the double cell wall even at the lower temperature, it can be considered that the influence of the softening of lignin and hemicellulose does not appear in the tangential specimen.

Photographs of tangential surface of the radial specimen separated by radial stress are shown in Fig. 8, (a) and (b) indicate the fractured surface of tension side of Ramin wood at temperature 20 and 80°C respectively. Although cells are broken by transwall failure at 20°C, the fracture develops along the intercellular layer at 80℃. Fig. 8b also shows that ray tissues are separated by intrawall failure at higher temperature.

4. CONCLUSION

From the appearance of the fracture path, the shapes of the fracture were divided into three groups. And it corresponded to the maximum deflection. The maximum deflection of the specimen which indicated the zigzag fracture path was larger than that which indicated the straight fracture path.

The proportion of the transwall failure showed the same trend as the strength values in change of stress angle. Especially in Ramin wood, the dispersion of the proportion corresponded to the dispersion of the strength values.

In the radial direction the proportion of the transwall failure was higher than in the tangential direction. And it decreased with increasing temperature within the range of temperature of this study, but its difference caused by temperature decreased with approaching to the tangential direction.

It was found that at higher temperature ray tissues were also separated by intrawall failure.

It can be considered that the difference of the strength values between radial and tangential directions is chiefly caused by not only the strength of the ray tissues but also the arrangement of the cells.

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