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A STUDY OF THE ORIGIN OF LONGITUDINAL GROWTH STRESSES IN TREE STEMS*

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FOREWORD

In the wood newly formed by diametric growth of tree stems are developed strains due to this growth and stresses corresponding to them. The stresses accumulate year after year and, as a result, axial, radial and circumferential stresses are fairly regularly distributed in the tree stem.

This report deals with the mechanism of the generation of the longitudinal growth strains and stresses in tree stems based on the results of tests on the distribution of longitudinal growth strains made after M. R. JACOBS' method (5, 6) and on the measurements of fibril angles in the middle layers of the secondary walls of wood fibres (softwood tracheids and libriform wood fibres and fibre-tracheids of hardwoods) which seemed to be related to the generation of growth stresses.

TEST RESULTS

Results of Tests on Distribution of Longitudinal Growth Stresses in the Cross-Section of Tree Stems

Mature Part of Upright, Straight Tree Stems (13, 14).–Sugi (*Cryptomeria japonica* D. Don.) and hinoki (*Chamaecyparis obtusa* Sieb. et Zucc.) (softwood species), and arakashi (*Quercus glauca* Thunb.) (hardwood species), were selected as the test species. Tests were made on logs of 2 m length from each species. Examples of the distribution of longitudinal growth strains for each species are shown in Figure 1. In every case, there are tensile strains and stresses distributed in the newly-formed wood.

Part of Tree Stem Including Reaction Wood (13, 14).–The species used in the test were hinoki (softwood species) and shiinoki (*Shiia sieboldi* Makino) (hardwood species), and logs of 2 m length were used in the test. The cross-section of the stem of hinoki was elliptical with major and minor axes 42 and 34 cm, respectively, and with the pith at the centre. Compression wood was distinctly observed on the diametrically opposite sides of the pith along the major axis. The distribution of longitudinal strains along the major axis was measured. The cross-section of the shiinoki stem was of an eccentric shape with major and minor radii 15 and 7 cm, respectively, and there was distinct tension wood on the major radius side. The test results are shown in Figure 2. As seen in the Figure, there were longitudinal compressive strains and stresses in the newly-formed reaction wood of hinoki, while there were longi-

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tudinal tensile strains and stresses in the newly-formed reaction wood of shiinoki.

Fig. 1. Distribution of growth strains in SUGI-, HINOKI-and ARAKASHI-log.

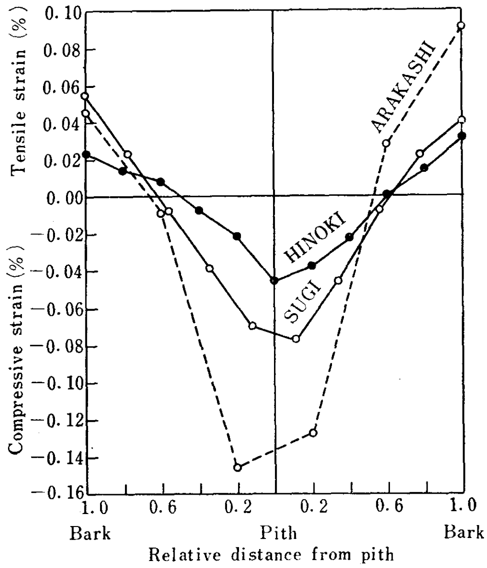
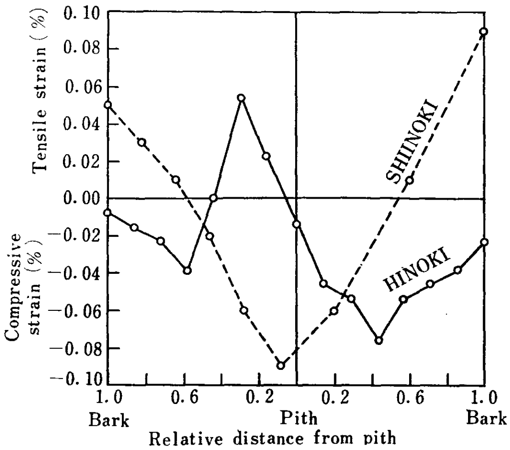


Fig. 2. Distribution of growth strains in HINOKI-log including compression wood and SHIINOKI-log including tention wood.



Young Part of Upright, Straight Stems (15, 17).-Tests were made with sugi (softwood species) and poplar (*Populus angulata* Michx.) (hardwood species). Logs of 1.5 m length and of 3 and 5 annual rings, from each species, were used. Figure 3 and Figure 5 show the distribution of longitudinal growth strains in the logs of sugi of 5 annual rings and 3 annual rings, respectively. Figure 4 and Figure 6 show the distribution of longitudinal growth strains in the logs of poplar of 5 rings and 3 rings, respectively. In the logs of 5 annual rings of both the species, there were longitudinal tensile strains in the newly-formed wood. In the very young stems of 3 annual rings, however, there were longitudinal tensile strains in all the four test logs of poplar, while there were longitudinal compressive strains in four of the seven test logs of sugi and longitudinal tensile strains in the remaining three.

Results of Tests on Variation of Fibril Angles in the Middle Layers of Secondary Walls of Fibre Walls in the Cross-Section of Tree Stems (15, 16)

Tests were made with sugi, poplar and shiinoki. With each species, cross-sectional disks cut at the height of 2 m above the ground from upright, straight tree stems, were used as test material. The numbers of annual rings in the disks were 50 in sugi, 15 in poplar, and 23 in shiinoki. The measurement of fibril angles was made by the method involving the formation of iodine crystals in the inter-fibrillar spaces (4).

With sugi, the variation of fibril angles in one annual ring was at its maximum in the early wood at the initial part of the annual ring and decreased towards the late wood

Fig. 3. Distribution of growth strains in SUGI-logs of 5 annual rings.

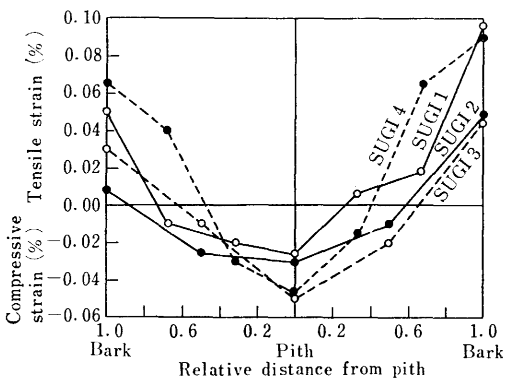


Fig. 4. Distribution of growth strains in POPLAR-logs of 5 annual rings.

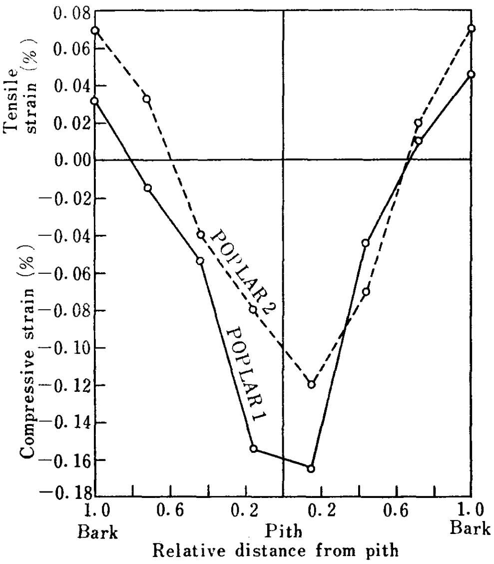


Fig. 5. Distribution of growth strains in SUGI-logs of 3 annual rings.

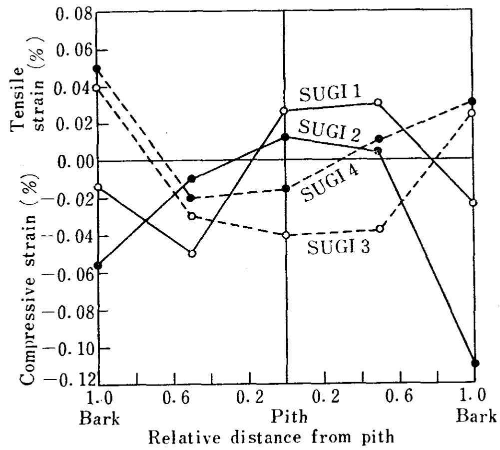
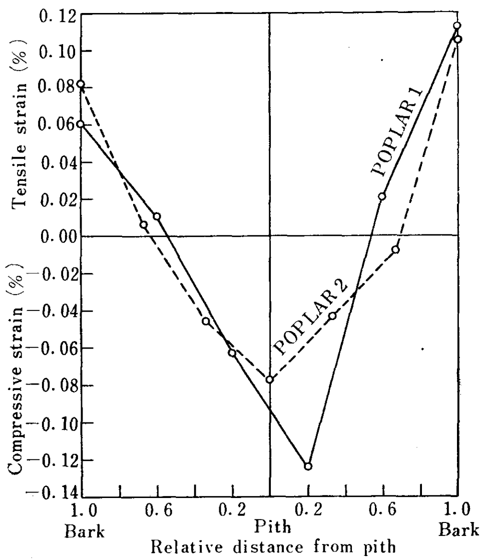


Fig. 6. Distribution of growth strains in POPLAR-logs of 3 annual rings.



at the terminal part, as shown in Figure 7. With both poplar and shiinoki, however, there was no significant tendency for fibril angles to decrease from the early wood towards the late wood as seen in Figure 8.

As for the variation of fibril angles with tree age in the cross-section of the tree stem, in the case of sugi the angle was at its maximum for both the early wood

Fig. 7. Variation of fibril angles in an annual ring of SUGI-stem.

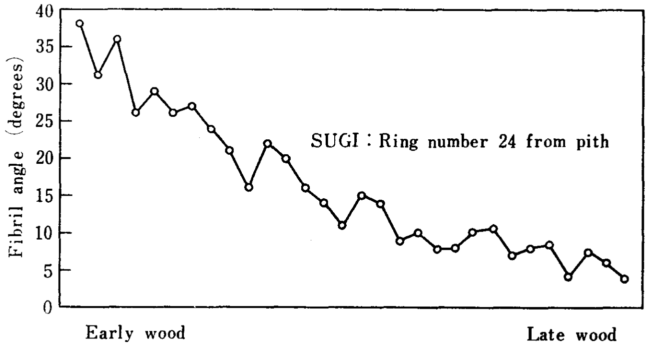
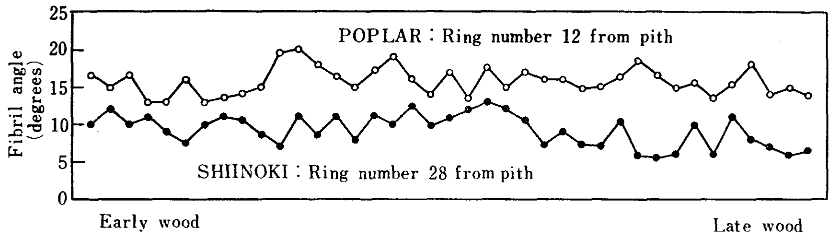


Fig. 8. Variation of fibril angles in an annual ring of POPLAR- and SHIINOKI-stem.



and the late wood at the wood next to the pith, and there was no significant difference between the early wood and the late wood, as shown in Figure 9. However, the fibril angle decreased towards the outer annual rings gently with the early wood and sharply with the late wood, and the mean value of the two decreased rapidly with tree age from the pith to about 20 years and then reached a more or less constant value. With poplar and shiinoki, there was practically no significant difference between the fibril angles of the early wood and the late wood, and the angle was large in the wood close to the pith and decreased towards the outer annual rings very gradually as compared with the case of sugi. In these cases also, the fibril angle tended to get more or less constant at about 15 years, as shown in Figuer 10.

In the test results, the maximum fibril angle of sugi was about 35° in the wood next to the pith, both with the early wood and the late wood, and the stable fibril angle was about 30° with the early wood and about 10° with the late wood. The average value of stable fibril angles of the early wood and the late wood was about 20°. With poplar the maximum fibril angle was about 20°, the stable angle being 13°. With shiinoki the maximum angle was about 17° and the stable angle about 10°. Thus the maximum fibril angle in the wood next to the pith of sugi was as large as 35° and was very large as compared with those of poplar and shiinoki which were approximately 20°. The stable fibril angle of sugi was about 20° on the average of the early wood and the late wood, and was large as compared with those of poplar

Fig. 9. Variation of fibril angles from pith to bark in SUGI-stem.

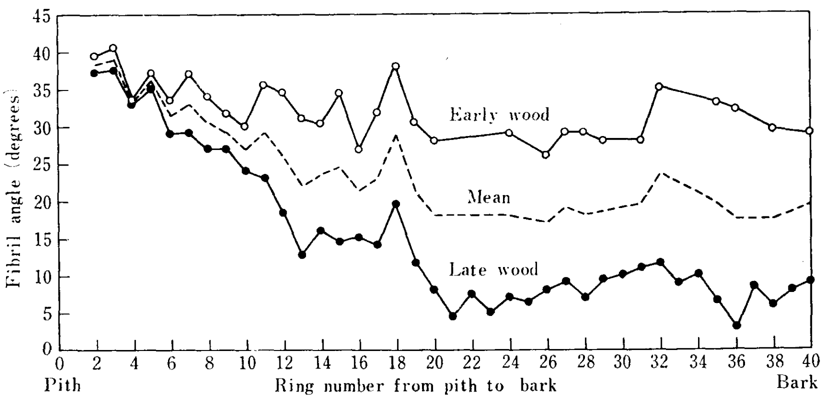
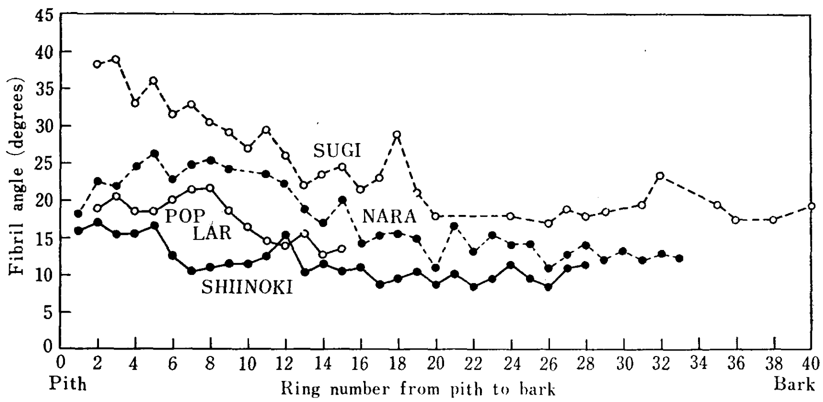


Fig. 10. Variation of fibril angles from pith to bark in POPLAR- and SHIINOKI-stem.



and shiinoki which were about 10°.

DISCUSSION

Referring to the prevailing theories on the generation of growth stresses (2, 3, 5, 6, 7, 10, 11) and based on the foregoing test results, the author considers the mechanism of the generation of the longitudinal growth strains and stresses in the tree stem as follows.

The tracheids of softwood and the libriform wood fibres and the fibre-tracheids of hardwood are the fundamental elements of wood, and the structure of their cell walls has strong influences on the character of wood. When these cell walls are lignified, lignin is laid down and polymerized in the inter-microfibrillar spaces and the wall generally swells irreversibly. In this case, the middle layer, the thickest layer of the secondary wall, tends to swell in the axial and the radial directions of fibre in accordance with the magnitude of the fibril angles. Since the fibril angles of the middle layer are generally small, the swelling rate in the radial direction is greater than that in the axial direction. As this swelling in the radial inward direction is hindered by the inner layer of the secondary wall, it is mostly directed outwards. However, since the tracheid of the compression wood lacks the inner layer of the secondary wall, a part of the swelling of the middle layer is directed inwards, and consequently the outward swelling of the middle layer is considered to be relatively small. The outward swelling of the middle layer puts pressure on the thin outer layer of the secondary wall and the primary wall from the inside, and the pressure causes the outer layer and the primary wall to swell outwards, the fibres thus tending to increase in diameter. When pressed from the inside, tension is caused in the microfibrils of the outer layer and the primary wall, to resist this pressure. At the same time, the outer layer and the primary wall tend to contract in the axial direction in accordance with the magnitude of swelling in the radial direction. Consequently, the fibres are deformed in the radial direction until the outward swelling of the middle layer and the resisting action of the outer layer and the primary wall reach a balance, and in the axial direction until the axial elongation of the middle layer is balanced with the axial contraction of the outer layer and the primary wall induced by the outward swelling of these caused by the radial swelling of the middle layer.

Therefore, whether the fibres are shortened (shortening type) or elongated (elongation type) by lignification is considered to be related to the magnitude of the fibril angle of the middle layer of the secondary wall. When the fibril angle is smaller than a certain value, the fibres undergo the shortening deformation and when it is larger than the value, the fibres undergo the elongating deformation. Generally, it is presumed that the smaller the fibril angle, the stronger the shortening tendency, and the larger the fibril angle, the stronger the elongating tendency.

The fibres in the newly-formed wood of upright, straight mature stems of softwood and hardwood trees are of the shortening type, because the fibril angles of the middle layers of the secondary walls of the cells are relatively small. The tracheids of the compression wood of softwood trees have large fibril angles and lack the inner layer of the secondary wall, as is well known, and consequently they are of the elongation type. The gelatinous fibres of the tension wood of hardwood trees are supposed to be of an extreme shortening type, and the mechanism of the shortening cannot be explained by the fibril angle alone. Rather, it is presumed that the shortening is caused by the behaviour of the very thick inner layer of the secondary wall (12). As the fibril angles of the tracheids of the newly-formed wood in the very young part of the upright, straight stems of softwood trees are considerably large in both the early wood and late wood, the tracheids may, in some cases, be of the elongation type. The fibres in the newly-formed wood in the very young part of the upright, straight stems of hardwood trees have relatively small fibril angles, and they are all considered to be of shortening type.

In the case where the fibres of the newly-formed wood are of the shortening type, the newly-formed wood tends to contract in the direction of stem axis. However, as the old wood inside the stem hinders this deformation, longitudinal tensile strains and stresses are caused in the newly-formed wood of the stem. On the other hand, in the case where the fibres of the newly-formed wood are of the elongation type, the newly-formed wood tends to elongate in the axial direction, and since the old wood inside the stem hinders this deformation, longitudinal compressive strains and stresses are caused in the newly-formed wood.

In short, it is presumed that the lignification of the cell walls of the wood-constituting fibres and the fibril angles of the middle layer of the secondary wall play an important role in the generation of the longitudinal growth stresses in all parts of the newly-formed wood, excepting the part of the tension wood in the tree stem.

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