TREE GROWTH STRESSES

I. GROWTH STRESS EVALUATION

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Summary

Experimental methods for the determination of natural longitudinal stresses in trees are described and the data are used in the development of a mathematical expression for the stress distribution.

Transverse stresses naturally existing within the tree are similarly investigated and the results analysed mathematically.

Another significant class of stresses is shown to result directly from the felling or cross-cutting of a tree.

I. Introduction

Many difficult problems arise in efficient timber utilization. Not the least of these concern the development of shakes on felling or on subsequent cross-cutting of trees, the tendency of flitches to spring and twist† when sawn from logs and the development of "brittle heart" (Dadswell and Langlands 1934) or similarly degraded wood tissue. Although at least some of these phenomena point to the existence of stresses of considerable magnitude within the tree at the time of felling, little effort appears to have been made to reach an understanding of the forces involved.

Martley (1928) sought to explain observed longitudinal strains (changes in length) in terms of the weight of the tree. Koehler (1933) advanced a number of hypotheses as to the causes of shakes and checks in standing trees. However, Jacobs (1938) was the first to make measurements of strains. Although his experiments were concerned chiefly with strains existing in a direction parallel to the height of the tree, he gave some consideration to changes of dimension in a transverse plane.

Martley (loc. cit.) noted a tendency towards a selective alteration in length of a plank cut through the centre of a log. The change occurred immediately after cross-cutting and produced curvature of the face of the plank. Adjustments were such that the maximum length of the plank occurred in the position corresponding to the pith, suggesting that in this area the wood had expanded longitudinally on sawing from the tree. Evidently the release of internal stresses was responsible. In an effort to explain this behaviour, Martley made calculations of the compressions which might result from the weight

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† For definition of terms see Coun. Sci. Industr. Res. Aust., Div. For. Products Trade Circ. No. 15, 1933.

of the tree. He showed that these stresses were unlikely to rise much above a value of the order of magnitude of 300 lb./sq. in. in symmetrical trees, and that a value appreciably lower was more probable. He deduced that such stresses were unlikely to account for the measurable changes in length which had been observed.

Measurements made by Jacobs showed the existence of a longitudinal strain gradient across any radius varying from extension at the periphery to compression towards the pith. The stress equivalent of these strains, when considered in relation to the known strength properties of the timber, suggested to him that some special method of absorption of the applied forces might exist in the zone towards the pith of the tree. He reasoned (1945) that longitudinal tension continuously applied at the periphery could give rise to the observed strain distribution. The strains measured are equivalent to stresses of several thousand lb./sq. in. and are much higher in value than could occur as a result of the weight of the tree. In addition, he pointed out that the existence in pendant eucalypt branches of a stress distribution similar to that of an erect tree is not in accordance with the tree weight hypothesis of the origin of observed strains.

Investigating transverse strains, Jacobs (1939, 1945) showed the existence of peripheral compressions in the circumferential direction. However, in this field his observations were largely qualitative.

Jacob's data on longitudinal strains have been developed and the relationship to transverse strains shown. In addition, a more comprehensive approach to transverse strain evaluation has been attempted.

II. Longitudinal Stress Evaluation—Experimental Procedure and Results

Because the methods of investigation adopted by Jacobs may render interpretation difficult, an experiment was planned to obtain spot confirmation of the magnitudes and directions of strains measured by him; and to study the possible effect of felling and cross-cutting in disturbing the natural distribution of longitudinal strain in a tree.

Green logs of mountain ash (*Eucalyptus regnans* F.v.M.) were chosen. The first of these was 26 ft. long and approximately 23 in. diam. at mid-length. Others were 18 ft. long and from 15 to 24 in. diam. Dial gauges calibrated to read changes in length to the nearest 1/10,000 in. were used for strain measurements.

A parallel-sided slot approximately 2½ in. wide and 18 in. long was cut from the bark into the pith of the log, at about the centre of its length. On the sides of the slot, spikes were driven tangentially to the growth rings, and along lines parallel to the length of the tree, in such manner as to act as reference lengths for the strain gauges. Generally, these reference lengths were approximately 3¾ in. The gauges were supported in position on two main lines—one near the periphery, and one towards the pith.

After initial readings of the gauges had been recorded, the log was cross-cut at positions successively closer to the slot. After each cross-cut, the gauge readings were noted, and thus the changes in reference lengths determined. An impression of the arrangement of gauges and the method of procedure may be obtained from Plate 1 and Figure 1. Figure 2 sets out some results of strain measurements in the form of two typical strain relief curves.

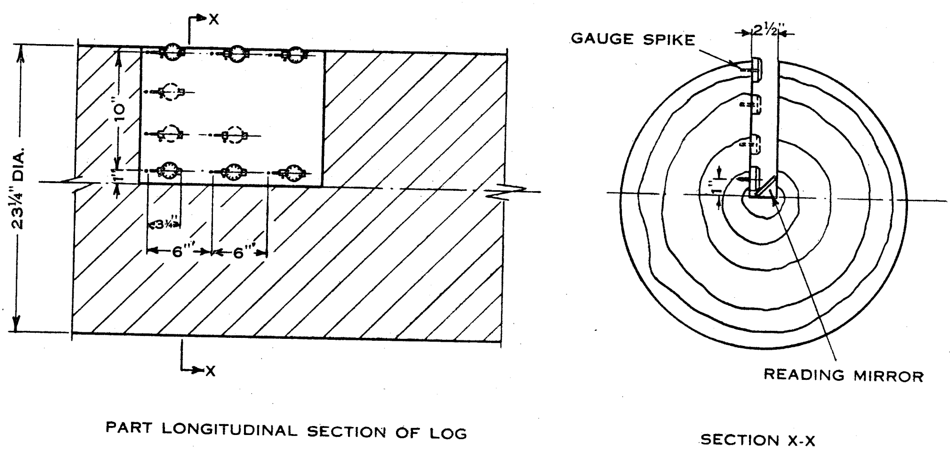


Fig. 1.—Sketch of arrangement of dial gauges for longitudinal stress measurements in trees.

It is not proposed to analyse all aspects of the results at this stage. However, applying the principles of elasticity, it will be appreciated that the removal of longitudinal restraint, which occurs as a result of cross-cutting, allows the relief of the primary longitudinal strains (and their equivalent stresses) in the immediate vicinity of the cut. Obviously, however, there must theoretically be some position remote from the face at which the longitudinal strain is undisturbed. The curves obtained from this experiment indicate that in this instance, significant change of strain did not occur at points distant more than approximately 3 ft. from the cross-cut face.

In addition to the experiment described above, specimens were cut from the log along the wall of the slot and immediately behind each row of gauges. On loading these in a compression testing machine, it was possible to determine the stress equivalent of strains measured by the dial gauges.

Near the periphery, the gauges recorded a shortening over the reference length, as cross-cutting proceeded. This was indicative of a state of tension at this position in an undisturbed tree. The total shortening, up to the stage when the cross-cut was within approximately 1 in. of the end of the first reference length, indicated an equivalent stress somewhat greater than 1,000 lb./sq. in. This is of similar order of magnitude to the figure of 1,200 lb./sq. in. determined by Jacobs on alpine ash (*Eucalyptus gigantea* Hook. f.) and other species.

Near the pith, the gauges indicated a lengthening over the reference distance as cross-cutting proceeded. This was indicative of a state of compression at this position in an undisturbed tree. The equivalent compressive stress was approximately 2,000 lb./sq. in.

The experiment was repeated on two other logs of mountain ash, one approximately 24 in. diam. and the other approximately 15 in. diam. at the gauging section. In each case similar stress distributions were found, though the tensile values were of the order of 2,000 lb./sq. in., and the compressive stress values nearer 3,000 lb./sq. in. In no case was strain detected in a zone distant approximately one-third of the radius of the log from its periphery.

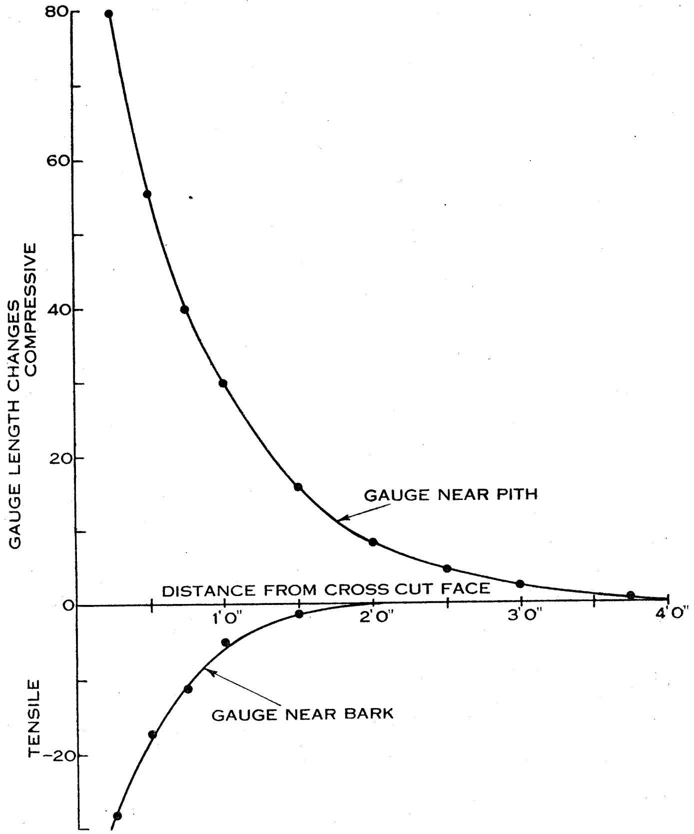


Fig. 2.—Elastic longitudinal strain recovery in trees. Length changes were measured in inches x 10^{-4}; gauge length was approximately 3¾ in.; and maximum change of length at failure approximately 100 x 10^{-4} in.

The compressive stress value of 2,000 to 3,000 lb./sq. in. is considerably below the theoretical amount of approximately 11,000 lb./sq. in. (minimum) on the central 2 in. diam. core, computed for a tree 24 in. diam. and on the hypothesis of longitudinal strain proposed by Jacobs (1945). However, the latter value is in excess of the maximum strength of the wood even on the basis of short duration or standard test loading, and therefore could not be expected. On the other hand, Jacobs's results on residual strains (1939) in positions towards the centre of the tree reveal similar "low" values. His measurements indicated that the large theoretical strains were not fully recoverable from wood near the centre of trees, and he attributed the cause to long-duration loading. It is interesting to note that in the experiments described here, matched specimens taken from the edge of the slot, and re-subjected to the same strain as had been recovered from them, proved to be strained beyond the elastic limit on the basis of a standard, short-duration test, i.e. they were subject to plastic strain in their natural condition within the tree.

Generally then, these experiments supported the existence of strain patterns identical in type with those indicated by Jacobs's work. Further, the magnitudes of strain measured at various positions within the logs were generally similar to those deduced by Jacobs from the curvature of small strips of wood taken from various positions within the tree.

As pointed out earlier, one of the main purposes of the experiments detailed was to obtain data on the relief of longitudinal strain in the region of a cross-cut face. Jacobs took no account of this phenomenon; however, detailed consideration of the likely effects in the experimental routine followed by him suggest that the errors are not significant in the results used to calculate longitudinal stress development. For this reason, advantage will be taken of his results in subsequent sections of this paper.

III. Mathematical Consideration of Longitudinal Stresses

Jacobs (1945) reported that the growing sheath of cells in erect stems of alpine ash develops a longitudinal tension which appears to be approximately constant in all diameter classes. Its measured strain of 0.0008 represents an equivalent tension of 1,200 lb./sq. in. Similar strains were measured on trees of other species. He stated that this continuously recurring tension has the effect of imposing a progressive longitudinal compression on the core, the amount imposed by each new sheath of cells (if assumed of unit thickness) being represented by the equation

$$\triangle y = \frac{0.00364}{x^{0.925}},$$

where $\triangle y$ = the longitudinal compressive strain induced in the entire area of core within the sheath of cells considered, by a unit thickness (radially) of the sheath, and

x = the diameter of the tree or of the growing sheath of cells in inches.

This is equivalent to

$$du = \frac{0.001916}{r^{0.925}}\, dr,$$

where r = the radius of the growing sheath of cells in inches, and

du = the longitudinal compressive strain induced in the core by a sheath of thickness dr (radially).

In addition, Jacobs (1945) published the curve of progressive longitudinal compression of the core of a tree. This may be obtained by integration of the expression above, whence

$$y_1 = -0.02555\ (r_0^{0.075} - r_1^{0.075}),$$

where the negative sign indicates compressive strain,

r_0 represents the outside radius of the tree (inches),

r_1 represents the radius of core used as a datum of strain calculations, that is, the radius at the point for which a valuation of the strain is required (inches),

y_1 represents the compressive strain imposed on the core at radius r_1 by the sheaths external to it.

This equation may be used to determine the compressive strain imposed at any radius r_1 by successive sheaths of cells external to it, as the tree grows from radius r_1 to radius r_0. However, as each sheath of cells initially develops a tensile strain t_0, the first increments of compressive strain are counterbalanced, and the total residual compressive strain on any sheath is that determined from the equation above, less the equivalent of t_0. It can be shown, therefore, that the longitudinal strain theoretically existing in a sheath of cells at any radius r_1 is given by the equation

$$y_1 = -0.02555\ (r_0^{0.075} - r_1^{0.075}) + t_0\,. \quad . \quad . \quad . \quad (1)$$

Because of the phenomenon of plastic relaxation of stress, the full theoretical strain, though possibly applied to a particular group of cells considered, will never be elastically recoverable from it. Such relaxation must tend to be greater in the more highly stressed parts of the tree than elsewhere. This is partly on account of the higher stress and partly because of the longer duration of load on the older wood in this area. The effect of the relaxation is to absorb some of the strain energy in a form which does not allow immediate elastic recovery. As a consequence, immediately recoverable longitudinal strain will be less than that shown in equation (**1**). Nevertheless, the equation serves as a useful basis of strain analysis.

Though the compressive strain imposed on the core by each sheath of cells varies inversely with the radius of the sheath, the total effect appears to be uniformly distributed over the core. Thus successive sheaths of growing cells cause a progressively higher value of compressive strain to be developed in the region towards the pith. Consequently, as the diameter of the tree increases, the strain ultimately reaches such a value that the limit of purely elastic strain is passed (Jacobs 1945). From this point plastic flow commences and some permanent and irreversible adjustment occurs in the fundamental structure of the wood. In this regard it should be realized that some plastic flow may occur in wood at relatively low stresses (much less than the usual value of elastic limit based on short duration tests in a testing machine). The seriousness of this “flow” would depend upon the duration of loading as well as the intensity of stress.

Although alpine ash was the only species investigated in detail by Jacobs, specimens from a considerable number of other pored species were measured. Without exception these showed strain gradients similar in nature to that of alpine ash.

IV. Stresses in a Transverse Direction

Frequently, particularly in pored species, checks or shakes develop from the pith outwards, immediately after cross-cutting both green and relatively dry logs. These shakes cannot be explained as drying checks, but are obviously manifestations of stresses within the living tree. Despite their significance in timber utilization, no satisfactory explanation of the phenomenon is available.

Koehler (1933) considered some of the explanations which have been suggested. He attributed the shakes and cracks to stresses operating at right angles to the grain, that is, in a transverse plane. He observed that, for many species, if a disc is cut from a green tree trunk the outside portion is in circumferential compression. He reasoned that such peripheral compression is associated with radial tension, and that this combination could be responsible for the opening up of heart shakes.

Jacobs (1939) made qualitative and quantitative demonstrations of the existence of a continuous strain gradient across the transverse section of a disc cut from a green log. From one set of experiments he concluded that a general state of circumferential compression in a direction tangential to the growth rings existed throughout the disc. Later experiments (1945) suggested to him that the central zones of the discs were in a state of tension.

Because of this anomaly, which appears to have been caused by interactions of radial and tangentially directed strains, new experiments have been carried out. The primary purpose of these was to obtain information on stresses causing the development of shakes in the ends of logs. The object was to demonstrate the nature and measure the value of both circumferential or ring stresses, and those directed along the radius of a transverse section of a tree.

With this in mind, it was considered desirable to establish primarily that any circumferential and radial stresses investigated by means of sections cut from a log were truly representative of similar stresses present in the standing tree. In addition, further experiments have been carried out to show the direct effect of longitudinal strains at any point within a log in producing corresponding transverse strains and also the effect of release of longitudinal strain energy at a cross-cut face in producing transverse strains across that face.

(a) *Experimental Procedure and Results*

(i) *Reliability of Laboratory Measurements.*—For the purpose of establishing whether strains determined from laboratory measurements on discs cut from logs were truly representative of conditions in the growing tree, an experiment was conducted on trees of mountain ash and messmate stringybark (*Eucalyptus obliqua* L'Herit.). Part of this experiment was carried out on living trees in the forest. The trees were subsequently felled and investigated both in the forest and in the laboratory. In the forest, the experimental procedure was to select two trees of each species having diameters within the capacity of gauges available (13½ in.). A short length of bark was removed carefully from the full periphery, at several positions. Heights of the gauge positions were approximately 18 in. and 3 ft. above the proposed level of the felling cut. Right-sections were drawn around the tree at the positions chosen, and hemispherical-headed nails were driven in at the ends of two diameters at right angles.

Measuring apparatus consisted of a dial gauge set in one end of a stiff, adjustable frame. A hollowed-out seat for the large, hemispherical-headed nails was provided at the end of the frame opposite to the gauge. With the fixed seat held in position over one nail and the gauge contacting the head of the diametrically opposite nail, as in Plate 2, Figure 1, it was possible to make comparative measurements of each diameter to the nearest 1/1000 in.

After measuring diameters with the tree standing, the tree was felled and again measured. No change in diameter of the gauging positions was observed. Logs, each 7 ft. long and including the gauging positions, were cut from the trees. After re-measurement had established no diameter change, they were transported to the laboratory and measured a day after felling. Still no change was detectable. Finally, discs containing the reference points were removed from the logs, using a technique to be described in detail later.

In these experiments no significant change of diameter occurred as a result of felling or any of the subsequent operations, except in one instance, in which a felling check passed through the gauge section. As any change in transverse stresses between the location in the growing tree and in the log at the laboratory would tend to show as variations in diameter measurements, it was concluded that no significant change occurred, and that laboratory measurements on these logs provided a fair method of assessing transverse stresses in the undisturbed tree.

(ii) *Radial Strain Experiment.*—Discs were cut from a green log of *E. regnans*. These were approximately 27 in. in diameter and 2 in. thick, with parallel, right-section faces. Faces were dressed smooth. A "V" was drawn on the face, with the apex at the pith, and the open end approximately 4 in. wide. A similar "V" was drawn to the side of the first. Specially prepared ¾ in. long copper nails were set in radial lines approximately ½ in. inside the "V" lines, and 2 in. apart in the radial direction. These nails were driven firmly into pre-drilled holes. Their heads carried finely etched, crossed lines. The arrangement is shown in Plate 3. A measuring microscope with graduations of approximately 1/25,000 in. was used for distance measurements.

After preparation of the disc, measurements were taken between each pair of nails. The wedge-shaped sections were then cut from the disc as in Plate 3 (*b*). It was considered that the distances between nails, before and after freeing the wedges from the restraint of the disc, represented the strained and the unstrained lengths respectively of the wood between. To check that radial strain was as completely released as possible, one wedge was further divided as shown in Plate 3 (*c*). Care was exercised during the whole experiment in an endeavour to keep the moisture content of the wood constant.

Adjacent side-matched specimens of wood, taken from the disc and parallel to the direction of radial strain, were tested separately in tension and compression. From these tests, the stress equivalents of measured radial strains were determined.

The distance between nails on radial lines became less as the restraint was removed. This indicated a state of radial tension in the original disc. There was no significant effect of the subdivision of the wedge. Actual differences in measured spacings before and after restraint removal are shown in Table 1. The gauge length was 2 ± 0.02 in. The stress equivalent of the average strain measured was approximately 150 lb./sq. in. radial tension.

TABLE 1

RADIAL STRAIN IN TREE

(*E. regnans*, 27 in. diam.)

Marker Pairs	Reduction in Marker Spacing, Before and After Stress Relief (in. x 1/1000)					Average Radial Tensile Strain
	Row A	Row B	Row C	Row D	Average	
1-2	2.2	3.9	2.0	2.7	2.7	0.0013
2-3	3.0	3.3	1.7	2.2	2.7	0.0013
3-4	2.6	2.5	2.5	2.0	2.4	0.0012
4-5	3.1	2.4	3.1	2.6	2.8	0.0014
5-6	2.2	2.8	3.0	1.7	2.4	0.0012
6-7	1.0	1.3	1.5	0.8	1.2	0.0006

(iii) *Circumferential Strain Experiment.*—In this experiment, trees ranging in diameter from 5 in. to 13 in. were investigated. Laboratory tests were made on logs 7 ft. long. These were kept green and at approximately constant temperature and moisture content during test.

Species investigated included *Eucalyptus regnans* F.v.M.—3 logs; *Eucalyptus obliqua* L'Herit.—2 logs; *Eucalyptus sieberiana* F.v.M.—1 log; *Eucalyptus australiana* Baker and Smith—1 log; *Acacia dealbata* Link—1 log; *Acacia melanoxylon* R.Br.—1 log; and *Pinus radiata* D. Don—2 logs. Measuring frames were of the type shown in Plate 2, Figure 1, and calibrated to measure differences of 1/1000 in. Three specimen discs were cut from each log—one at the centre of the length, and the others at approximately a quarter of the length from the ends. A special technique was required to ensure that major heart shakes did not develop within the discs on cross-cutting, as these would render subsequent measurements valueless. A comparison of discs cut with, and without, the adopted technique is shown in Plate 2, Figure 2—M_4 and M_5 showing the minor shakes associated with the technique, and M_3 showing the normal shakes for the specimen (other specimens developed even larger shakes). A description of the technique and its significance will be given later in this paper.

The procedure of the experiment consisted in setting hemispherical-headed nails around a right-section of the log, and at opposite ends of two diameters at right angles. A disc containing these nails, and approximately 1¼ in. thick, was cut, and the diameters across pairs of nails measured accurately with the special comparator gauges. A hole was drilled about 1½ in. from the periphery, and a saw cut made approximately along the line of the growth rings so that the outer annulus could be removed from the core as in Plate 2, Figure 2. In every instance the annulus expanded, showing that the wood composing it had been under a state of circumferential compression in the disc. The changes in diameter were measured, and results are set out in Table 2.

A load-strain curve was determined from an experiment on matched specimens of mountain ash (*E. regnans*). This indicated that the mean measured strain in the annulus was equivalent to a ring compressive stress of approximately 300 lb./sq. in.

It is of interest to note that Jacobs (1945) quoted a comparable figure of 360 lb./sq. in. for *E. gigantea*. When allowance is made for the variability of the material, the species, and also the width of the annulus, the agreement is close.

(iv) *Direct Effect of Longitudinal Forces in a Transverse Plane.*—Measurements on trees of *E. regnans* and *E. obliqua* indicate that transverse stresses are not significantly altered in conversion of trees to logs. Further, it may be deduced that longitudinal stress arising from the weight of the tree has no significant effect in a transverse plane.

Though no longitudinal stresses can exist at the cross-cut face, experiments have shown their existence within the log. The problem thus becomes one of relieving the longitudinal stresses at the gauge section in such a manner that no confusing interactions are induced, and of measuring any effect. To help achieve this, the special technique previously mentioned was used to prevent the usual formation of heart shakes.

In this experiment the following species were examined: *E. regnans, E. obliqua, E. sieberiana, E. australiana, A. dealbata, A. melanoyxlon,* and *P. radiata.* Measurements of diameter in the log and on the discs after cutting showed no diameter change, i.e. within the accuracy of measurement (1/1000 in.) no change of strain was measurable, even on the largest diameter log. Thus the effect on the diameter of any variation of strain which may have occurred as a result of the relief of longitudinal stress was less than 1/(1000 x diam.), or less than a diametral (or circumferential) strain of 1/10,000. The equivalent stress would be less than 30 lb./sq. in., approximately, in the transverse plane.

(v) *Effect of the Release of Longitudinal Strain Energy in Producing Transverse Strains.*—The general plan of the experiment has been described in connection with the measurement of longitudinal strains and the arrangement is shown in Figure 1 and in Plate 1. Between the banks of gauges at the periphery (tension zone) and near the pith (compression zone), several other gauges were placed.

TABLE 2

DIAMETRAL STRAINS IN TREES

Species	Log Number	Disc No. 1 Diameter A Approx. Diam. (in.)	Disc No. 1 Diameter A Diam. Change $\left(\frac{\text{in.}}{1000}\right)$	Disc No. 1 Diameter A Strain x10⁴	Disc No. 1 Diameter B Approx. Diam. (in.)	Disc No. 1 Diameter B Diam. Change $\left(\frac{\text{in.}}{1000}\right)$	Disc No. 1 Diameter B Strain x10⁴	Disc No. 2 Diameter A Approx. Diam. (in.)	Disc No. 2 Diameter A Diam. Change $\left(\frac{\text{in.}}{1000}\right)$	Disc No. 2 Diameter A Strain x10⁴	Disc No. 2 Diameter B Approx. Diam. (in.)	Disc No. 2 Diameter B Diam. Change $\left(\frac{\text{in.}}{1000}\right)$	Disc No. 2 Diameter B Strain x10⁴	Disc No. 3 Diameter A Approx. Diam. (in.)	Disc No. 3 Diameter A Diam. Change $\left(\frac{\text{in.}}{1000}\right)$	Disc No. 3 Diameter A Strain x10⁴	Disc No. 3 Diameter B Approx. Diam. (in.)	Disc No. 3 Diameter B Diam. Change $\left(\frac{\text{in.}}{1000}\right)$	Disc No. 3 Diameter B Strain x10⁴	Mean Diametral Strain x10⁴
E. regnans	1*							13¼	9	7	13	7	5							
	2	11½	14	12	12	14	12	12	9	8	13	15	12	11½	19	16	11½	13	11	12
	3	5¾	6	10	6	7	12	6	2	3	6½	6	9	5½	5	9	5¾	2	4	8
E. obliqua	1	10¾	13	12	11¼	13	12	10¾	12	11	11½	12	10	10¼	9	9	11	11	10	11
	2	9	8	9	10	22	22	9½	10	11	9½	9	9	9½	10	10	10½	14	13	12
E. sieberiana	1	8½	8	9	9½	22	23	8½	9	11	10	19	19	8¼	7	9	9¼	19	21	15
E. australiana	1	7¾	8	10	7½	8	11	7¼	11	15	7½	6	8	8	13	16	7¾	8	10	12
A. dealbata	1	5¾	7	12	6	3	5	6¼	5	8	6	4	7	5¾	12	21	6	1	2	9
A. melanoxylon	1	5¾	3	5	6	5	8	6	7	12	6	5	8	5¼	3	6	5½	3	5	7
P. radiata	1	7¾	5	6	7¾	7	9	8	6	8	8½	6	7	7¾	6	8	7½	4	5	7
	2	7¼	5	7	7¼	4	5	7½	8	11	7¾	3	4	7¼	7	10	7¼	7	10	8

* *E. regnans* log No. 1 was cut before a satisfactory technique had been developed. Severe heart shakes caused fracture of the annulus during removal.

For the two main banks of gauges, curves of gauge length changes, in relation to distance from the cross-cuts, are shown in Figure 2. The position of gauges between the two main banks was so chosen as to coincide with the theoretical zero strain position. The theoretical basis of strain calculation was confirmed in each case, in that gauges so located did not show any significant strain changes during the whole process of strain (and stress) relief.

An analysis of the results of this experiment suggests that strain adjustment consequent to stress relief may be mathematically expressed by a function of the nature

$$\log Y = A + Bx + Cx^2,$$

where Y represents the movement parallel to the length of the log, of a point at a particular radial position and originally on a right cross section plane,

x represents the distance of the right cross section considered from the cross-cut face,

A, B, and C are constants.

In reference to the relief of tensile stresses, the constants are capable of determination with much more exactitude than applies to the relief of compressive stresses. This is because the gauge limit spikes in the compression area tend to cross growth rings, and are therefore subject to strain reactions which are not uniform along their lengths. A typical tensile strain relief curve is

$$\log\ (-Y) = 2.80 - 0.11x + 0.0020x^2,$$

where x is in inches and $-Y$ represents a reduction in length measured in inches x 10^{-5}.

The stress equivalent of strains noted may be determined from stress-strain curves for specimens of the material placed in a testing machine. From these, the equivalent residual stress values for the original tree or log may be calculated. The use of strain values and the species mean modulus of elasticity of the timber, determined by standard testing procedure, as an alternative method of stress assessment is unsatisfactory, particularly in the high-intensity compression zone.

The curves show that, at all positions between the cross-cut and the gauging point, length changes of varying degree occur in the wood structure. These changes indicate corresponding variation of stress over the volume of wood considered. In turn, this implies changes in the applied forces and the "work done" or "energy" absorbed within the material. The effect of cross-cutting is to reduce restraint at that section on the internal forces in the log; that is, it allows some of the strain energy originally held within the wood to be released. The experiment also shows that strain energy is released by the various wood elements throughout the length of the log affected, in a regulated and definite manner. The degree of release at various points indicates that this energy is transferred to the cross-cut face.

To date, results from only three logs of mountain ash are available. Although it might be anticipated that similar strain reactions will occur throughout this and other species, the quantitative expression of the results may vary with the species, the size of tree, age, etc. It is proposed to investigate this phenomenon further, but meanwhile, from these limited results some impression of the total volume of strain energy released at the cross-cut face may be obtained, and an approximate calculation of its value made.

That the release of longitudinal strain energy at the cross-cut face is of practical importance may be readily shown by a separate experiment. The cross-cutting technique mentioned earlier will be used to illustrate the point.

During the previous experiment, it was noted that, immediately after each new cross-cut was made, large heart shakes opened up in the newly exposed faces of the log. If the section cut off was a few feet or less in length, the shakes in the new face of that piece were less severe than those in its opposite end, and in the new face of the parent log. Taken in conjunction with the strain energy deductions discussed above, it led to the hypothesis that the development of shakes resulted directly from strain energy movements, and that control of strain energy release may give control of the development of heart shakes.

In this experiment and in many other observations, it was noted that, immediately after cross-cutting, shakes split the log for a distance generally not more than a few inches in the direction of the length except in very severe instances. It was thought that at the plane at which splitting stopped, probably the accumulation of strain energy was less than the critical splitting value for the log. On the basis of this hypothesis, control or measuring sections, a few inches thick in the direction of the length, were marked on a number of logs. The diameters varied from 4 to 13 in., and the positions selected were between 1 and 2 ft. from an existing face (depending upon the tree diameter). Short sections were cut away successively from both ends of the log, retaining the control section approximately central. As discs were removed from the ends, the strain energy from the remainder tended to "flow" to the new ends, causing shakes to develop. However, as the control was approached the shakes developed were smaller, and by the time the control section was isolated, virtually all longitudinal strain energy had been previously released from it and absorbed in cracking reject parts of the log. Consequently, the control sections were almost entirely free of shakes. The detailed result of the application of the special technique to three sections of one log, approximately 8 ft. long and 13 in. diam., is shown in Plate 4. The discs at the end of each line show the severe cracking or development of heart shakes resulting from normal cross-cutting, or non-control of longitudinal strain energy dispersion. The reduced development of shakes in discs towards the central control disc in each line is obvious.

From the description of procedure it will be obvious that only longitudinal strain energy dispersion is different in the different discs, and that this alone must account for the variation in development of shakes. The importance of this effect is therefore considerable. Further, reference to the other experiments described will show that cross-cutting alone does not disturb transverse strains. The technique proposed makes this more positive by ensuring that transverse strains are not relieved as a result of cracking of the disc, and it is the only satisfactory method of preparation of sections for transverse strain measurements.

(*b*) *Discussion of Transverse Strain Experiments*

Under the conditions in which transverse strains have previously been investigated, nominally all the longitudinal stresses have been relieved at the cross-cut face. Thus the reactions in a transverse plane during the relief of longitudinal stress may be proposed as responsible for bringing transverse strains into existence.

If it is supposed that readjustment of cell cross sections on relief of longitudinal stresses is a valid explanation of the development of the measured transverse strains after cross-cutting, then it follows that such transverse strains did not exist in the standing tree. Occasionally, the appearance of heart shakes after large trees have been felled suggests that shakes were present in the standing tree. As the shakes are indicative of a high level of transverse stress, it appears that such stress develops in growing trees, that is, before longitudinal stresses are substantially relieved. In such trees it is difficult to visualize the occurrence of any sudden or substantial relief of longitudinal stress which might account for the development of this transverse stress and consequently the shakes. Therefore, another primary source of transverse strains is indicated.

It may be of value, however, to consider the likely effects of relief of longitudinal stress. Longitudinal compressive stresses can be built up only after the wood structure has reached a mature and elastic condition. Hence, any longitudinal stresses which are ultimately relieved by cross-cutting are equivalent to those which have been built up during growth, less any which have been relieved by plastic adjustment in the cell walls. Thus the general effect of a reduction of longitudinal stress to zero would appear to be a corresponding removal of transverse strains.

Here, however, the problem has been over-simplified, in that the longitudinal stresses are developed as the tree grows, and the consequent reactions tend to produce ever higher intensities towards the pith. Therefore, towards the periphery of the tree, new cells are subject to relatively small longitudinal stresses and relatively small induced cross-sectional strain when the central part of the tree is comparatively highly strained in the transverse direction, as a result of the greater longitudinal stress. Thus, considering the transverse plane only and assuming transverse restraint still exists, the conditions under which the peripheral cells are free from longitudinal strain would not coincide with those for an unstrained state in cells towards the pith. It is clear then that apparent total relief of longitudinal strain in a disc representing the full cross section of the tree will not remove all transverse strain resulting from such primary longitudinal strain.

Tests made on specimen trees of *E. regnans, E. obliqua, E. sieberiana, E. australiana, A. melanoxylon, A. dealbata,* and *P. radiata* appear to indicate that, for these species, no substantial change in the over-all cross section of the tree occurs as a result of felling, or cross-cutting right up to the face of the section measured. As controlled cross-cutting does not affect transverse strains, it may be deduced that the relief of longitudinal strains by this means does not produce any change in tree diameter—a result which might have been anticipated on consideration of the Poisson ratio effect. For stability, the total longitudinal tensile and compressive forces acting over any cross section of a tree must be balanced, and therefore the gain in area of cross section of cells as a result of relief of tensile forces would balance the reduction in area of cross section of cells as a result of relief of compressive forces. Despite this lack of significant change in area of a disc on relief of longitudinal strain, and under the actual conditions of transverse restraint, the result may still be compatible with the supposed development of transverse strains; but such strains must be appreciably less in value than those present under actual growth conditions. Therefore, it must be considered whether these residuals are sufficient to account for the noted expansion of an outer annulus separated from the core of a disc.

For example, if a tree of mountain ash is considered, and the total original longitudinal stress is of an average value of 2000 lb./sq. in. over the annulus (this is probably more severe than any practical case), and it is assumed that the elastic moduli for the material are 2,000,000 and 70,000 lb./sq. in. in the longitudinal and circumferential directions respectively, and that the corresponding Poisson's ratio is equal to 0.45, then:

$$\text{maximum longitudinal strain} = \frac{2{,}000}{2{,}000{,}000} = \frac{1}{1{,}000},$$

$$\text{resulting transverse strain} = 0.45 \times \frac{1}{1{,}000},$$

$$\text{equivalent stress} = \frac{0.45}{1{,}000} \times 70{,}000 = 31.5 \text{ lb./sq. in.}$$

Thus the maximum transverse stress which might arise from longitudinal stress in the wood considered would be little more than 30 lb./sq. in. It will be noted that this stress equivalent is approximately one-tenth only of measured peripheral stresses in discs, and as the actual stress from the longitudinal stress residual, rather than the original total stress, is probably much smaller still, its effect is not likely to be significant. Thus there must be some other primary cause of the development of transverse stress.

In addition to the adjustment in cell cross section discussed above, there is another transverse straining effect of the relief of longitudinal stresses. The process of strain development with growth produces a condition of differential longitudinal strain across any diameter. Then if the tree is cross-cut, all longitudinal strain is relieved at the cross-cut face. Also, partial relief occurs at positions beyond the face. This relief requires each cell to adjust its length (as well as cross section) in accordance with the strain previously existing in it. Thus the most highly strained central fibres elongate a greater amount than cells towards the periphery. Cells near the periphery, which are in tension, reduce their length. The effect of the length reaction is to convert an originally flat cross-cut to a dome shape. This is confirmed by the measurement of the longitudinal length adjustments resulting from cross-cutting. It has been demonstrated, too, that this process of transverse strain generation may produce strains of a value sufficient to cause heart shakes.

V. Mathematical Evaluation of Transverse Strains

For simplicity, the total transverse stress distribution on any cross section can be taken as made up of:

(*a*) Transverse stress distribution arising from primary circumferential stresses in the growing sheath of cells.

(*b*) Secondary transverse stresses which develop from changes in cell cross sections induced by primary stresses existing in a longitudinal direction.

(*c*) Secondary transverse stresses resulting from the change in length of cells at, and near, a cross-cut face.

It should be clear that the first class of stresses are assumed present in the growing tree, and are primarily independent of cross-cutting. The second class also will be present in a growing tree, but would tend to be relieved by cross-cutting. The third group of stresses can arise only when there is opportunity for substantial longitudinal stress reduction. Though some degree of cross-sectional adjustment may occur in a standing tree as a result of partial inelastic reaction to longitudinal stress, such as plastic action or possibly structural failure of individual fibres, perhaps the most important practical case arises with relief of the residual longitudinal stress on cross-cutting. However, because of the balanced nature of the longitudinal stresses across every cross section, and because of the resistance to differential movement between fibres, no substantial effect of fibre length reaction can occur except near the cross-cut face.

(*a*) *Transverse Stresses Arising from Primary Circumferential Stresses*

As a result of qualitative experiments on a considerable number of trees and a variety of species, Jacobs (1945) has shown the existence of circumferential strain of appreciable magnitude. On the basis of these experiments, he has suggested the hypothesis that this strain arises in the growing sheath of cells and is continuously renewed at the same value in each new sheath of cells—a phenomenon similar in principle to that which appears to apply to longitudinal strains. This hypothesis is supported by the results shown in Table 2. It is proposed to develop an expression which will represent the transverse stress at any point in a cross section as a result of such primary circumferential strain and its related stress.

Jacobs's experimental work on longitudinal strains leads to the conclusion that each increment of strain at the periphery impresses an approximately uniform strain reaction upon the core. If this is so for primary longitudinal strains, it appears very likely that a similar law would regulate the effect of primary transverse strains. This assumption will be made as a basis for calculation of a theoretical strain distribution.

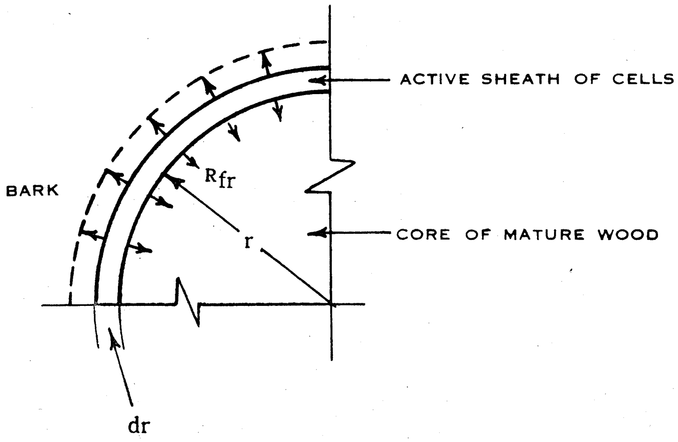


Fig. 3.—Portion of the cross section of a tree trunk.

In Figure 3, it is supposed that the sheath of cells of thickness dr and radius r is the "stress active" portion of the tree, producing circumferential and radial stresses. Through some agency not yet established, this sheath shows a tendency to expand circumferentially, and consequently in diameter. Such expansion is resisted by the attached central core, or enveloped portion of the tree, and to some degree by the bark. The effect of this restraint on free movement must be to produce compression in the active sheath, and at the same time radial tension in the core.

If a radial stress R_{fr} is imposed on the core at radius r, and causes equilibrium of the whole transverse section, then this stress is balanced at the annulus-core interface. Also, if the annulus, or sheath of cells, is regarded as a thin cylinder, then

$$\text{circumferential stress in the active sheath} = \frac{\text{radial stress} \times 2 \times \text{radius}}{2 \times \text{thickness of annulus}}$$

$$= \frac{-R_{fr} \times r}{dr}. \qquad \ldots \quad (2)$$

The negative sign indicates a compressive stress.

On the assumption that primary strains arising at the periphery impose a uniform strain on the core, then the radial strains must be equal at all points along a diameter. This hypothesis is supported by the measurements of radial strain shown in Table 1. With the exception of one measurement taken near the pith, which was possibly affected by a small check, strains were substantially equal at all points.

Now if C represents the strain (or change in length per unit length) in the circumference at any radius r,

the unstrained length of the circumference $= 2\,\pi\,r$,
the change in length of the circumference $= 2\,\pi\,r\,C$,
hence the strain on the radius $= C$.

Thus at any radius, the radial strain is equal to the circumferential strain. Consequently, on the hypothesis assumed above, circumferential strains, as well as radial strains, must be equal at all points along the core diameter.

Now from the theory of elasticity, the relationship between stress and strain is such that

$$\text{radial strain} = \frac{\text{radial stress}}{\text{Young's modulus for strain in a radial direction } (= E_R)},$$

and circumferential strain =

$$\frac{\text{circumferential stress}}{\text{Young's modulus for strain in a tangential direction } (= E_T)}.$$

Hence, as circumferential and radial strains are equal,

$$\begin{aligned} \text{imposed circumferential stress} &= \text{radial stress} \times \frac{E_T}{E_R} \\ &= R_{fr} \times \frac{E_T}{E_R}, \qquad \ldots \quad (3) \end{aligned}$$

and is constant along the diameter.

Comparing equations (**2**) and (**3**), if the circumferential compressive stress in the active sheath is represented by the quantity

$$-\frac{R_{fr} \times r}{dr},$$

then a tensile stress of value

$$+\,R_{fr} \times \frac{E_T}{E_R}$$

is impressed at all points along the diameter of the core, and in a tangential direction. Similar increments of stress imposed by each successive sheath of cells on the peripheral side are added to the stress primarily existing in the particular sheath, when it represented the periphery of the tree. Thus it is seen that if each new sheath of cells generates an initial compressive stress, each succeeding sheath imposes a tensile stress on the first. Consequently, the tendency is to reduce the intensity of the original compression, and ultimately to convert it to a tensile stress.

If the circumferential stress in the peripheral sheath of cells has the value $-S$ and it is assumed, on the basis of the experiments described, that a stress of the same value is generated in each succeeding sheath, independently of the diameter of the tree at the time, then from equation (**2**),

$$-S = -\frac{R_{fr} \times r}{dr},$$

$$\text{or } R_{fr} = \frac{S dr}{r} \quad \ldots\ldots\ldots \quad (\mathbf{2a})$$

Substituting this value of R_{fr} in equation (**3**), it may be seen that the radial stress on each stress active sheath of radial thickness dr imposes on the enclosed wood a uniform circumferential tensile stress

$$= \frac{E_T}{E_R} \times \frac{Sdr}{r} .$$

The effect, as the diameter increases from radius b to radius a, is to impose across the core of radius b a circumferential tensile stress

$$= \int_b^a \frac{E_T}{E_R} \cdot \frac{S}{r}\, dr ,$$

$$= S \frac{E_T}{E_R} (\log_e a - \log_e b) ,$$

$$= 2.3S \frac{E_T}{E_R} (\log_{10} a - \log_{10} b). \quad . \quad . \quad . \quad . \quad (4)$$

When the sheath of cells at radius b was originally laid down, it was subjected to an initial compressive stress of value S. Hence at radius b the net tensile stress finally developed in a sheath of cells

$$= 2.3S \frac{E_T}{E_R} (\log_{10} a - \log_{10} b) - S. \quad . \quad . \quad . \quad . \quad (5)$$

This expression gives the ring stress at any radius b in the cross section of a tree of diameter $2a$. The stress is directly attributable to an initial, and continuously recurring, circumferential compressive stress in the peripheral sheath of cells.

(*b*) *Secondary Transverse Stresses which Result from Changes of Cell Cross Sections Induced by Primary Longitudinal Strains*

A primary longitudinal strain in a tree will produce strains in two directions at right angles—circumferential and radial. Because of the approximately circular form of the tree cross section, and the nature of the longitudinal strain distribution, these strain effects interact.

For simplicity, the general effect of circumferential and radial strains induced by the longitudinal strain in any particular sheath of cells within the tree cross section will be considered separately. Later, the effects of all such sheaths will be combined to obtain the full strain pattern in a transverse section across the tree. A circumferential strain produces a change in the circumference of the sheath equal to the sum of the changes in width in this direction of all the individual cells. A corresponding change in diameter must occur.

Any such sheath of cells, however, is not an independent entity, being attached to other similar sheaths of cells towards both pith and periphery. Thus the rigidity of all other cells restrains the free adjustment of position of the sheath to accommodate the direct tangential effects of longitudinal strain. Consequently, the circumferential strain in the sheath is less than that of an independent sheath.

The difference between "potential" and actual strain in the sheath is balanced by the imposition of radial forces on the core and the outer annulus. In turn, the radial forces upon the core will produce ring stresses as well as radial stresses therein. Also, the forces applied to the annulus will have an effect in the two directions.

Similarly, strains which have a direct component in the radial direction will not have freedom of adjustment. Consequently the residual radial component strain will be less than in a free sheath of cells, and additional strains will be imposed on the outer annulus and the core.

So far discussion has been confined to the manner of production of transverse strains arising from the longitudinal strain in one sheath of cells only. In any case of practical significance, there are many thousands of such sheaths, all producing their complex distribution of strain, and therefore all interacting with one another. Further, this complex system exists quite independently of any system of primary transverse strains, such as that envisaged as arising in the peripheral sheath of cells. Because of the complexity of this problem for a longitudinal strain pattern which is variable across the transverse section, a detailed mathematical solution has not been attempted herein. It is possible, nevertheless, to obtain an impression of the limits of the effect of longitudinal strain in a transverse direction.

Jacobs (1945) has shown that the maximum strain which is recoverable from the core of a tree is equivalent to a stress of approximately 2000 to 3000 lb./sq. in. This is supported by experiments described herein. Adopting the values of elastic constants already used, an approximate calculation may be made as follows:

$$\text{longitudinal strain} = \frac{3{,}000}{2{,}000{,}000} = \frac{1.5}{1000},$$

$$\text{resulting transverse strain} = 0.45 \times \frac{1.5}{1000} = \frac{0.67}{1000},$$

$$\text{equivalent ring stress} = \frac{0.67}{1000} \times 70{,}000$$

$$= 47 \text{ lb./sq. in.}$$

Therefore, if the full cross section were uniformly compressed with the maximum elastic, longitudinal strain existing in the tree, the maximum ring tension developed would be approximately 50 lb./sq. in. Actually, the highest intensity longitudinal strains exist near the centre of the tree, and the effect of the lower-strained outer area must be to reduce the corresponding maximum ring stress on the core, possibly to a value of the order of 30 lb./sq. in. (tension).

Such an equivalent stress might be possible in a growing tree, or remote from a cross-cut face. At a cross-cut face, the longitudinal stress is fully relieved. However, because the peripheral cells are differentiated and matured at a time when the core is already highly strained, subsequent removal of all longitudinal strain effect on cell cross sections over the full transverse section of the tree is not possible. A likely effect in the transverse plane would be a reduction of the tensile strain in the core, with a possible slight increase of the peripheral circumferential compression. If then, the final transverse effect is a maximum residual ring stress of the order of 20 lb./sq. in. in a cross-cut disc, it is small compared with peripheral, circumferential compressions of the order of 300 lb./sq. in. Such compressions have been measured in experiments described herein and by Jacobs (1945). Further, it has been shown theoretically that peripheral compressions of the magnitude of those measured would tend to induce ring tensions much greater than appear to result from primary longitudinal strains.

(c) *Secondary Transverse Strains Resulting from a Change in Length of Cells at, and near, a Cross-cut Face.*

It has been illustrated experimentally that, if a log is cross-cut, the primary longitudinal strain is fully released at the face, and partially released for some significant distance beyond it. It is likely that the length over which significant release of strain occurs depends on the species, the diameter of the tree, the value of the "undisturbed" strain at the cross-cut section considered, and the mechanical properties of the wood in the particular specimen.

Simultaneously with the longitudinal strain variation, there is a corresponding length adjustment in the fibres or wood cells. Movement occurs in the direction of the cross-cut face, and the total deflection of any point on the face is the sum of the separate and varying length adjustments over successive cells beyond the face. This deflection is proportional to the area under a curve plotted to show the relation between longitudinal strain relief and distance from the cross-cut face (Fig. 2). Thus, the area under the curve represents a certain volume of "strain energy" released at the cross-cut face, and at a certain radial distance from the pith.

Because of the variation of longitudinal strain over the cross section of a tree, the adjustments of cell length distort an originally flat face into a "dome" shape. As the length of a curved surface is greater than that of a straight line joining its ends, some strain is induced when such a surface is developed from an originally flat one subject to boundary restraint. In the particular example under consideration, radial and circumferential strains are induced on the cross-cut face. Incidentally, it follows that similar strains, of gradually decreasing amount, are induced at all sections across the tree beyond the cross-cut face, up to the limit of length over which primary longitudinal strain is partially relieved.

It is now possible to derive an approximate mathematical expression of the forces involved. Equation (**1**) developed from Jacobs's work will be adopted to represent the longitudinal strain at any point in a tree cross section. If e_y represents this strain at any radius r in a standing tree, then

$$e_y = -0.02555 \ (r_0^{0.075} - r^{0.075}) + t_0.$$

Referring to the cross-cut log illustrated in Figure 4, if l represents the distance beyond the cross-cut face over which some release of strain occurs, the total longitudinal displacement of any point beyond the plane of the original face will be some function of l, say $f(l)$, multiplied by the strain at the particular radial distance from the pith. Thus, if y represents the longitudinal distortion at the face and at distance r from the pith,

$$y = f(l)\ [-0.02555\ (r_0^{0.075} - r^{0.075}) + t_0]. \quad . \quad . \quad . \quad (6)$$

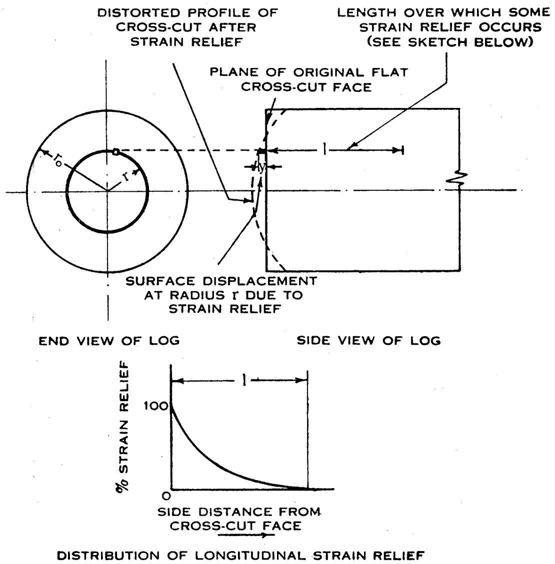


Fig. 4.—Longitudinal strain distortion of a cross-cut face.

This equation represents the movement of a point on the curved surface developed from the originally flat cross-cut surface. The slope of this surface at a particular position on a radial plane is represented by dy/dr. If, to simplify the illustration, $f(l)$ is treated as independent of r, then

$$\frac{dy}{dr} = \frac{0.001916\ f(l)}{r^{0.925}}.$$

Also, the radial strain (due to curvature) at any point on the distorted cross-cut face

$$= \frac{\text{length of the curved face} - \text{its original (flat) length}}{\text{original length}}$$

$$= \frac{ds - dr}{dr},$$

when infinitely small lengths are considered. But

$$\frac{ds}{dr} = \pm\sqrt{1 + \left(\frac{dy}{dr}\right)^2}$$

$$= \pm \sqrt{1 + \left[\frac{0.001916}{r^{0.925}} f(l)\right]^2}$$

$$= \pm \sqrt{1 + \frac{0.00000367}{r^{1.85}} [f(l)]^2}.$$

If the radial strain at radius r is denoted by e_r,

$$e_r = \frac{ds - dr}{dr}$$

$$= \sqrt{1 + \frac{0.00000367}{r^{1.85}} [f(l)]^2} - 1. \qquad \ldots\ldots \quad (7)$$

Thus, in any particular case in which $f(l)$ is known, it is possible to determine the strain distribution on the log cross-cut face, arising from strain energy release. On this simplified basis, and using data from the experiments described, it may be deduced that strains having an equivalent radial tension value of the order of several thousand lb./sq. in. tend to be developed near the pith of trees of some species. The strain may fall away rapidly, however, and reach values of no practical significance beyond the central few inches of tree diameter.

The nature of failure in heart shakes – a failure due to excessive ring stresses towards the centre of the tree – indicates that ring stresses are usually more critical than radial stresses. It can be shown that the ring stress intensity arising from the strain energy effect does not decrease as rapidly as the radial stress with increasing distance from the pith. Theoretically, these stresses may be calculated from the radial strain.

Under the conditions in which the release of longitudinal strain energy causes distortion of a cross-cut face, the total change of length along any radius of length r from the pith

$$= \int e_r dr,$$

and the mean strain

$$= \frac{l}{r}\int e_r dr.$$

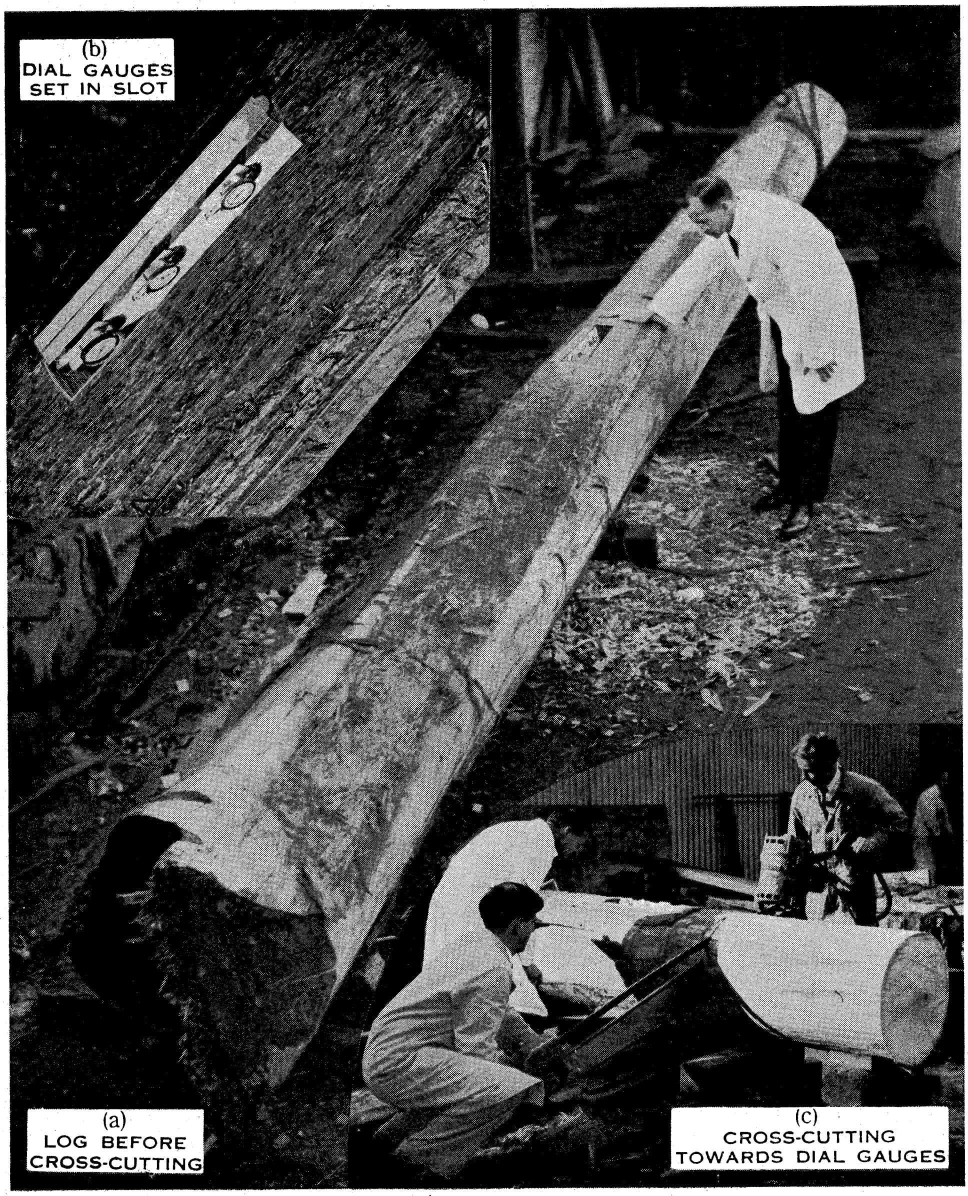
But the circumferential strain at radius r is equal to the mean radial strain. Hence,

$$\text{ring stress at radius } r = \frac{E_T}{r}\int e_r dr.$$

Or substituting the value of e_r from equation (7),

$$\text{ring stress at radius } r = \frac{E_T}{r}\int\left\{1 + \frac{0.00000367}{r^{1.85}}[f(l)]^2\right\}^{\frac{1}{2}} dr - E_T.$$

Even with the approximations already adopted, a solution of this expression is complex. Substitution of more precise values for $f(l)$ and its relation to r would complicate the calculations further. At this stage, results available are insufficient to justify evaluation or presentation of the more exact analysis.



Longitudinal strain measurements.

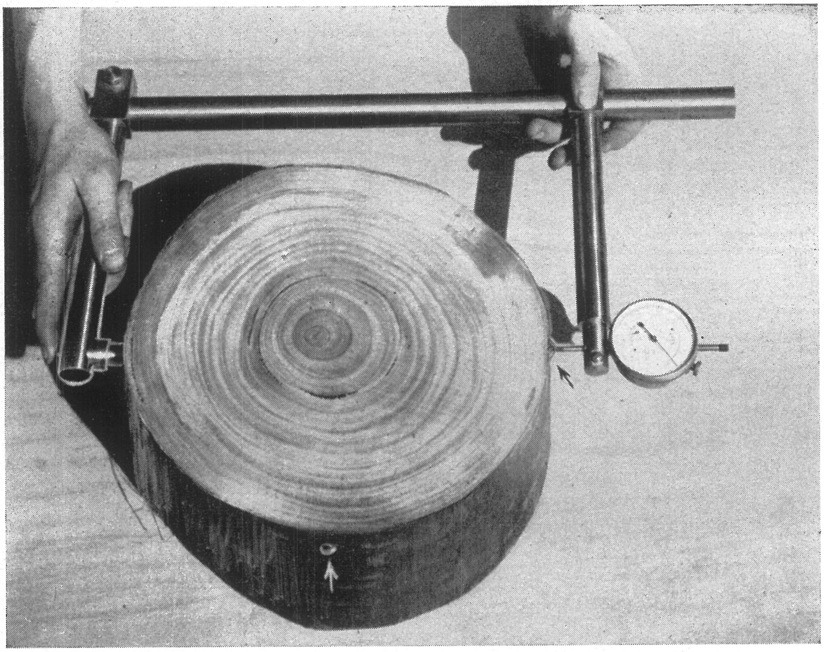


Fig. 1.—Measurement of transverse strain. Diameter gauge on tree section. Note reference nail under dial gauge and at lower centre.

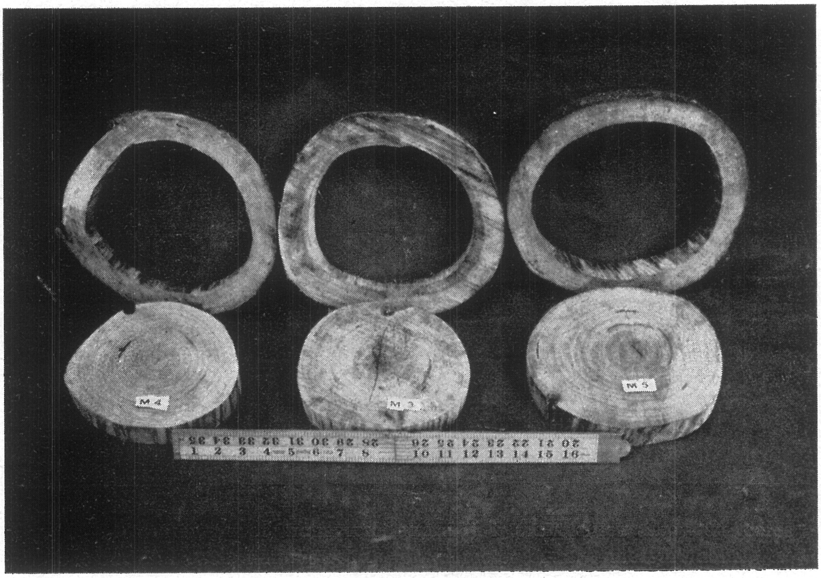
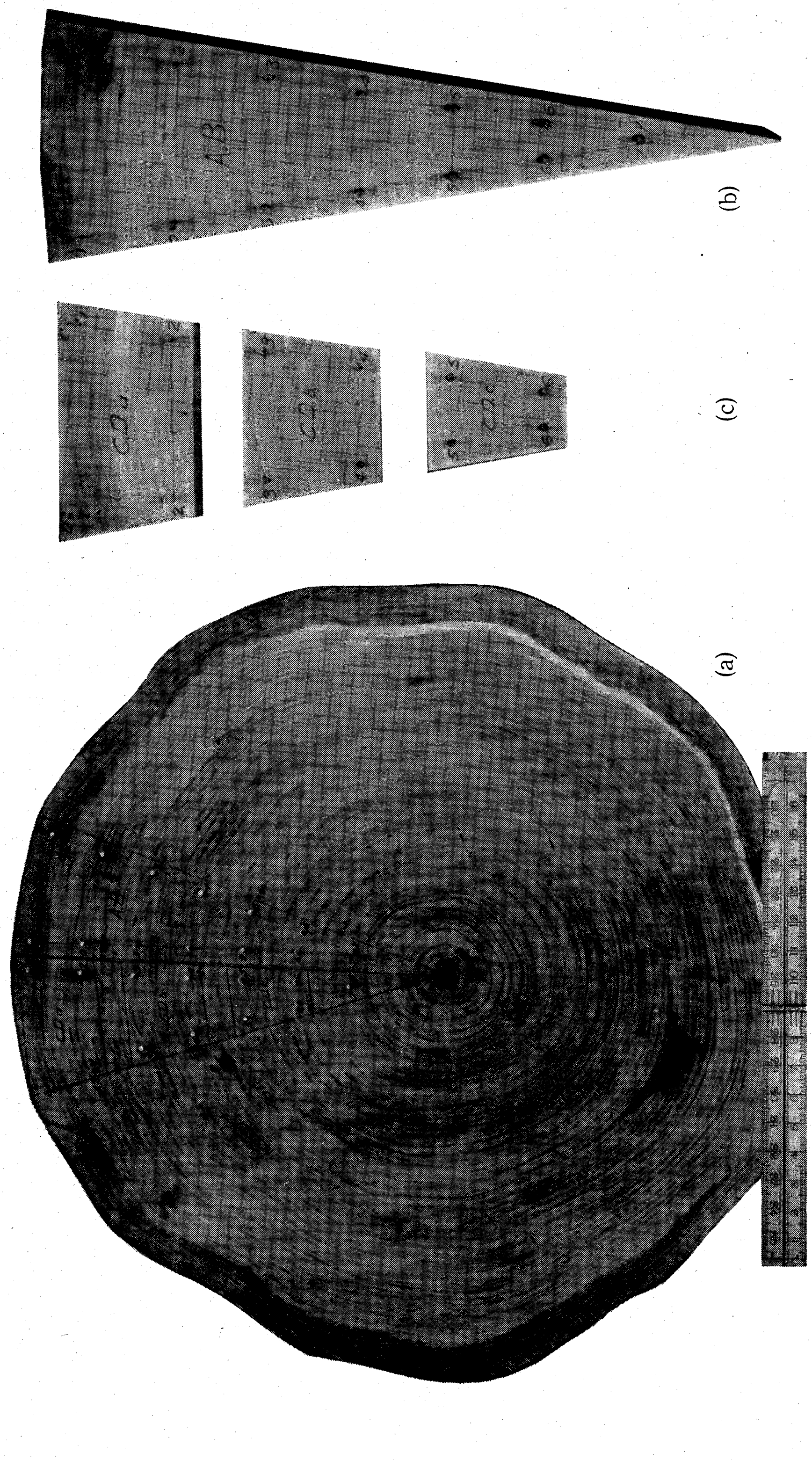


Fig. 2.—Measurement of transverse strain. Typical discs, showing cores cut out and each annulus ready for diameter change measurement.

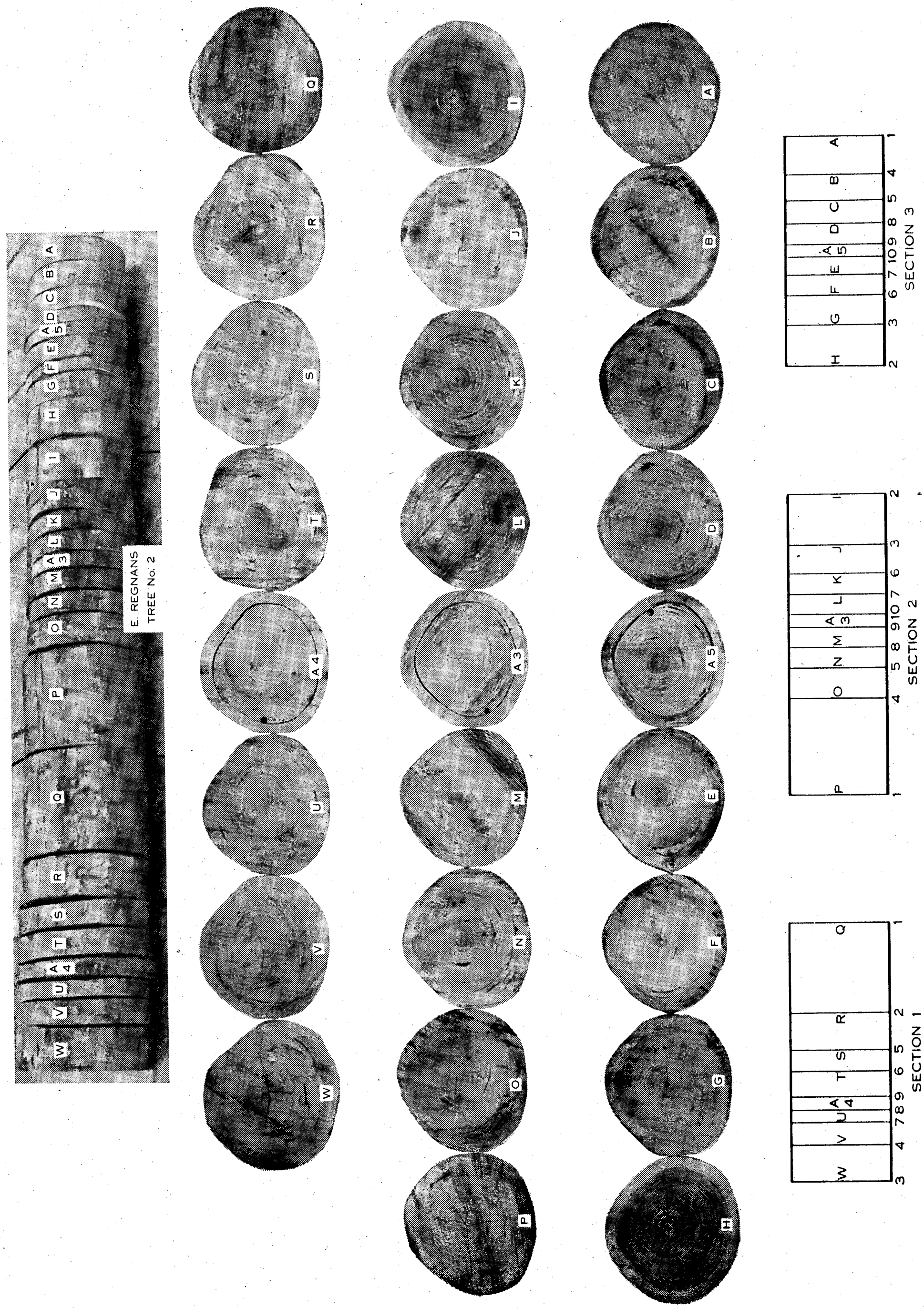


(a) MARKED DISC

(c) WEDGE SUBDIVIDED

(b) WEDGE CUT FROM DISCS

Radial strain measurement.



Effect of variation in strain energy release on heart shake development in *Eucalyptus regnans*. Numbers on sections represent the order in which cross-cuts were made. Letters are adjacent to faces of discs shown.

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