

Measurement methods for longitudinal surface strain in trees: a review

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Summary

There are three common methods for measuring surface strain as a consequence of stress release in trees: (a) the Nicholson technique, (b) the CIRAD-Forêt method, and (c) by strain gauges. This article describes how each method works, the extent of its uses, why measurements are not directly comparable between methods, the source of known and potential errors, and the advantages and disadvantages of each method based on our own experience. Each method has unique advantages and disadvantages. The Nicholson method is able to determine the average longitudinal strain within a volume of wood and the 'simplified' version of the procedure is suitable for a large number of field measurements without causing severe damage to the cambium. The CIRAD-Forêt method does not measure strain but it gives a good estimate of the longitudinal surface strain and suits routine field measurements. The strain gauge method measures the surface strain (in longitudinal or tangential directions) directly and more accurately than the other two methods, and particularly suits fundamental research. The major disadvantage of the Nicholson and CIRAD-Forêt methods is the amount of cambium injury caused by debarking, which limits their use on small trees. Also, the Nicholson 'primary' procedure is error prone. The major disadvantage of the strain gauge method is the ongoing costs as strain gauges are not cheap and may not be reusable. This paper also gives a brief account of other, less widely used methods.

Keywords: wood properties, growth stress, strain, techniques, methodology, strain gauges, reviews, *Eucalyptus*

Introduction

Mechanism of growth stress

A main function of growth stresses is to reorient the tree stem and crown to a more favourable position (Kubler 1988). Growth stresses result from self-generated forces during the differentiation and maturation of new cells (Jacobs 1938; Boyd 1972, 1985; Bamber 1979, 1987; Kubler 1987; Yamamoto and Okuyama 1988; Okuyama *et al.* 1990, 1994, 1998; Yamamoto *et al.* 1992; Sugiyama *et al.* 1993; Yamamoto 1998). In the cambium, when a new wood cell is initiated, the development of its cell wall layers takes several days or weeks to complete. This development is the so-called 'maturation' period in which complex biochemical

reactions occur, i.e. the active construction of a cellulose network and the deposition of lignin and hemicellulose. Each of these chemical components contributes uniquely to the properties and behaviour of wood. In hardwood species and to a lesser extent softwood species, the direct physical consequence of the maturation is a longitudinal shortening and a tangential swelling of the new wood cell. However, maturing cells cannot shorten completely as they are joined to older, already lignified cells. Hence they are held in a state of tensile stress, released when a cross-grain cut is made in the wood.

The wood cells at the surface of a hardwood tree are generally held in tension. However, as the cambium produces new wood cells, the wood cells inside the trunk are slowly compressed until they are held in compression of increasing severity toward the centre of the trunk (Fig. 1). This gradient of mechanical stress in standing trees constitutes a self-balanced pre-stressed field, whereby the outer part of the tree trunk is held in tension and the inner part in compression.

Stress is defined as the force per unit area. Objects subjected to stress will change their dimensions and shape. The dimensional

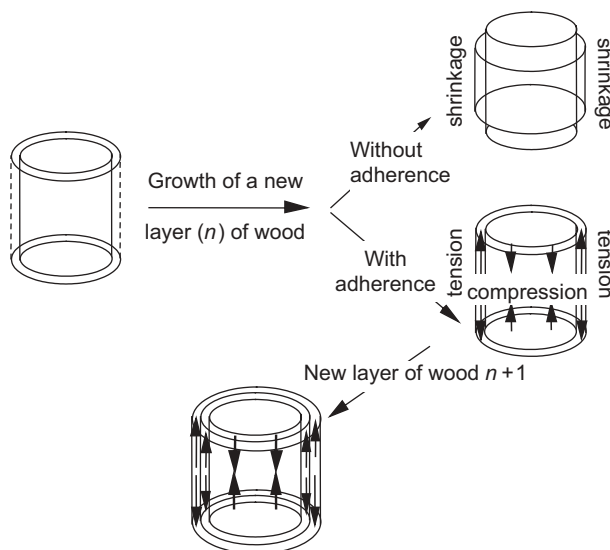


Figure 1. Accumulation process of longitudinal stresses in trees (after Baillères 1994)

change per unit of original length is the strain (tensile or compressive). Within the proportional limit of elasticity, stress is equal to strain multiplied by Young's modulus, a measure of the rigidity of the material. Growth stresses are usually impossible to measure directly, whereas the strains are comparatively easy to assess. As the stress near the tree surface is within the proportional limit of elasticity, it can be calculated from the measurement of the strain and Young's modulus.

Statement of problems

Eucalypts are now widely planted throughout the world because of their high productivity on marginal sites and their suitability for a wide range of forest products, and the growing demand for environmental protection of native forests. Consequently, there has been a growing interest in obtaining higher-value products from eucalypt plantations. The motivating factors include a decreasing supply of hardwoods from south-east Asia, a decline in hardwood pulpwood prices, better financial prospects from higher-value products, environmental concern over the deleterious impact of short-rotation management, emerging conversion and processing technologies, and the potential to substitute eucalypt products for tropical hardwoods (Flynn and Shield 1999; Donnelly *et al.* 2003).

A key factor limiting the use of young plantation eucalypts as sawlogs and veneer logs is high stresses inside the logs. Internal longitudinal stresses in hardwoods are the primary cause of shake in standing trees, heart checks in felled logs, distortion of sawn timber in the form of bow, crook and twist as it is sawn from the log, and compression failure (brittleheart) in standing timber (Dadswell and Langlands 1934, 1938; Jacobs 1938, 1939, 1945; Archer 1986; Kubler 1987; Malan and Gerischer 1987; Mattheck and Kubler 1995). Green sawn timber is often not straight when the internal stresses are released during sawing (Jacobs 1938, 1939, 1945; Boyd 1950a,b; Kubler 1987; Malan and Gerischer 1987; Malan 1995; Waugh 1998, 2000; Muneri *et al.* 1999; Yang *et al.* 2002). The magnitude of problems associated with internal longitudinal stress in log conversion and recovery is variable, but can be severe, and may still not be fully appreciated by foresters, wood technologists and industrial producers.

Longitudinal growth stress has generated continuous scientific interest since the 1930s, primarily because of its impact on log processing and recovery. Many publications document these effects and discuss various methods to minimize their negative impact (Dadswell and Langlands 1934, 1938; Jacobs 1938, 1939, 1945; Boyd 1950a; Dinwoodie 1966; Skolmen 1967; Barnacle and Gottstein 1968; Nicholson 1973; Waugh 1977, 1998, 2000; Chafe 1979; Priest *et al.* 1982; Hillis 1984; Archer 1986; Padmanabhan *et al.* 1986; Kubler 1987; Okuyama *et al.* 1987; Gérard 1994; Malan 1995; Waugh *et al.* 1996; Yang *et al.* 1996, 2002; Tejada *et al.* 1997; Laghdir 2000; EU project FAIR CT98-9579 2001; Nogi *et al.* 2001; Yang 2001; Yang and Waugh 2001; Yang and Pongracic 2004). A variety of different methods has been developed to evaluate stem surface strains and determine stresses; their details have been given by Archer (1986), Kubler (1987) and Mattheck and Kubler (1995).

Growth stresses vary considerably between trees and in response to growth conditions (Wilkins and Kitahara 1991b; Baillères 1994; Gérard 1994; EU project FAIR CT98-9579 2001; Yang *et al.* 2001), indicating that their magnitude may be managed through tree breeding and silvicultural programs.

Growth strain evaluation

An ideal measurement of strain in trees requires a specimen to be completely removed from the adjoining wood to allow for maximum stress relief (Jacobs 1938; Boyd 1950a; Nicholson 1971; Guéneau and Kikata 1973; Sales 1985, 1989). The change in length of this specimen divided by its original length is the average released strain. The stress within this specimen prior to its removal from the adjoining wood is calculated as the product of the released strain and Young's modulus of the wood specimen.

Knowledge of the distribution of stress inside logs has a high practical value to the sawmilling industry as it is essential in efforts to improve current log processing techniques. However, measurement of internal strain requires tree felling and is highly laborious. Fortunately, an approximate relationship between internal strain distribution and growth strain at the tree periphery (Kubler 1959) enables internal strain distribution to be estimated from surface strain. Because of this, and also because foresters and the industry are interested in simple, fast and non-destructive methods, researchers and foresters usually measure only the strain in a small volume of wood next to the tree surface (Nicholson 1971; Kikata 1972; Guéneau 1973, cited in Archer 1986; Guéneau and Kikata 1973; Krilov, unpublished, cited in Wilkins 1991; Archer 1978; Polge and Thiercelin 1979; Mariaux 1982, cited in Baillères 1994; Mariaux and Vitalis-Brun 1983, cited in Kubler 1987; Fournier *et al.* 1994, cited in Baillères 1994). These methods have been improved or modified (Guéneau and Saurat 1974, cited in Chafe 1979; Saurat and Guéneau 1976; Yang and Hunter 2000) and are discussed in review articles by Chafe (1979), Archer (1986), Kubler (1987), Wilkins (1991), Baillères (1994) and Sassus (1998).

The surface strain measurement methods can be broadly classified into three types: specimen removal or the Nicholson method (Nicholson 1971), the one-hole method (Archer 1978; Mariaux 1982, cited in Baillères 1994; Sassus 1998; also named the CIRAD-Forêt method), and the two-hole or two-kerf method (Kikata 1972; also named the strain-gauge method). (The increment core method by Polge and Thiercelin (1979) is discussed separately in this paper.) Because these methods work differently, the measurements could differ significantly. As a systematic assessment of the differences between methods has been lacking, quantitative relationships between the methods, as well as their comparative advantages and disadvantages, remain little known as far as published literature is concerned.

The purpose of this paper is to provide a detailed account of the various methods and identify their advantages and disadvantages. Only longitudinal stress and strain are covered because of their impact on log end-splitting and distortion of sawn boards.

Description of methods and extent of their usage

The Nicholson method

The Nicholson method was adapted from an engineering approach and published in detail in 1971 (Nicholson 1971). It has been the method used at CSIRO. No modifications to the procedure have been made, despite a recent attempt to examine the validity of bypassing the step of curvature adjustment (Yang and Hunter 2000). The Nicholson method has two versions: the 'primary' and 'simplified' procedures.

Nicholson 'primary' procedure

With the Nicholson 'primary' procedure (Fig. 2), two steel pins are glued to the fresh wood surface of the tree stem or log, nominally 50 mm apart and aligned parallel to the wood grain. The distance between the pins is measured to a resolution of 0.001 mm using a mechanical dial gauge (Huggenberger Tensotast) before and after the wood segment is removed. The segment centrally contains the two pins and its nominal dimensions are 10 mm x 19 mm x 90 mm (radial x tangential x longitudinal). Because of the gradient of longitudinal stress in the radial direction (Kubler 1959), the wood segment may develop a curvature upon removal. The elimination of this 'secondary' curvature is accomplished, in theory, by using a special apparatus to bend the wood segment and restore it to its original in-tree state. Following the curvature adjustment, the distance measured between the pins incorporates the average movement of the segment after stress release. Strain is calculated from the difference between the before- and after-removal distances. All measurements after the removal of the segment should be completed within five minutes to ensure the measurement is largely of elastic strain. It has been shown (Nicholson *et al.* 1973) that some residual stress can persist in small pieces of green wood after their complete removal from the

trees, and that the residual stress alternates in layers of tension and compression that may or may not coincide with the density pattern.

Advantages of the Nicholson 'primary' procedure are that:

- it allows for the release of most internal stresses in the wood segment when the segment is completely removed from the tree;
- it enables the direct determination of average longitudinal strain in the wood segment;
- it has a very low running cost since the pins are re-usable and have a long life, and the glue is inexpensive;
- the tool kit is quite affordable, costing less than US\$3000. It is also easy to carry around in the forests.
- it allows for the evaluation of sequential changes in strain, when the stress field is disturbed by drilling or grooving at nearby areas.

Disadvantages of the Nicholson 'primary' procedure are that:

- proper removal of the segment is a challenging job and requires well-designed and efficient tools. Chisels and saws, the commonly used tools, are either inefficient or result in unnecessary damage to the tree.
- it is difficult to precisely control the segment thickness during removal and to physically correct it afterwards;
- it injures the cambium, because a window of bark, approximately 50 mm x 130 mm (tangential x longitudinal), needs to be removed; such injury can be quite traumatic for small trees (<150 mm DBHOB);
- the way the gauge contacts the pins may differ between the first and the second measurements of distance, hence introducing measurement errors;
- the curvature-adjustment step takes about 20% of the whole measurement time.

Based on Kubler's distribution of internal longitudinal stress (1959), Yang and Hunter (2000) investigated under what circumstances the curvature adjustment might be disregarded within certain error. For a given magnitude of longitudinal surface strain, they established mathematically the tree/log radius at which the curvature adjustment may be neglected with a specified limit of error in the strain. Their study indicated that for practical circumstances, it may not be necessary to account for curvature if the tree radius under bark was greater than 100 mm. However, this result does not apply for trees with large amounts of reaction wood near the measurement location.

Nicholson 'simplified' procedure

With the 'simplified' procedure, only two horizontal cuts are made in the tree, one above and one below the metal pins in the same spatial configuration as in the 'primary' procedure, and no wood segment is removed. The distance between the pins is measured before and after the cuts. Nicholson (1971) found a close relationship between the 'primary' and the 'simplified' procedures based on 99 released strain measurements made on seven large logs (diameter >76 cm). He recommended the 'simplified' procedure for large logs only (diameter >76 cm) in order not to sacrifice accuracy. He did not explicitly report whether the 'simplified' procedure had been

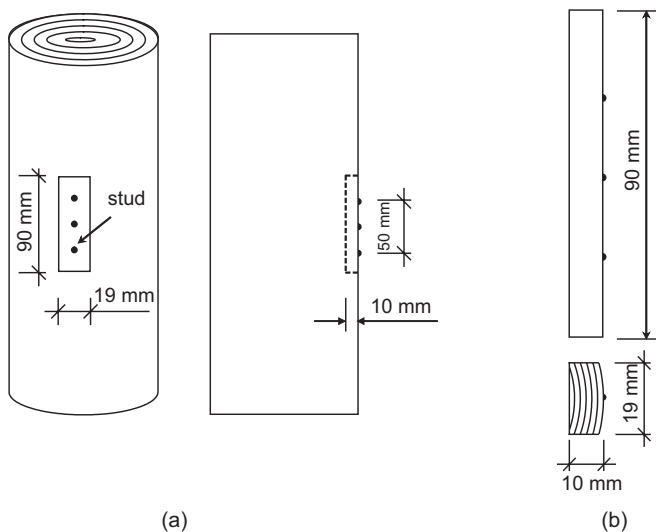


Figure 2. (a) The front and side view of a wood segment to be removed from the surface of a tree or log as specified in the Nicholson 'primary' procedure (1971); (b) The side and top view of the wood segment after being removed from the tree or log

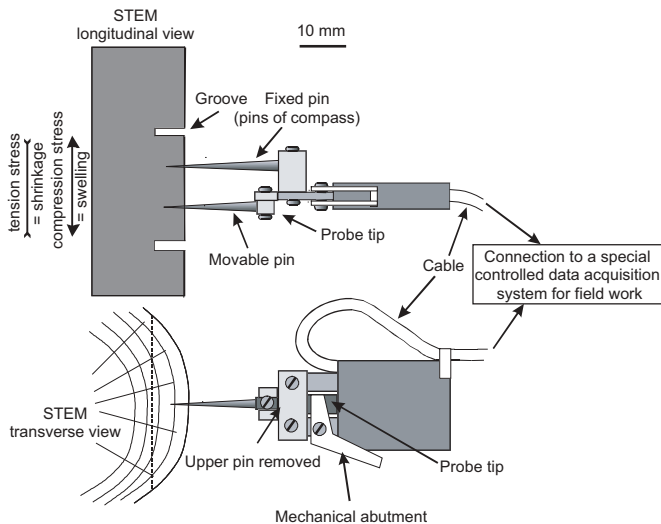


Figure 3. Measurement of longitudinal strain near the tree surface with a classical extensometer (manufacturer HBM, type DD1). The total longitudinal stress is relieved by sawing two grooves above and below the sensor. The longitudinal strain is detected and displayed in microstrain ($\mu\text{m m}^{-1}$) (after Baillères 1994).

investigated on small logs, nor mention the time saved by using this procedure. However, from our field experience, we estimate the time saving to be about 35%.

Advantages of the Nicholson ‘simplified’ procedure are:

- a saving of up to 15% in time by not removing a wood segment;
- that no curvature adjustment is required, and hence there is a possible further time saving of up to 20%;
- that error in the measured strain due to variation in thickness between removed segments is minimized;
- less injury to the cambium because a smaller window of bark needs to be removed and fewer cuts are needed.

Disadvantages of the Nicholson ‘simplified’ procedure are that:

- the measured strain is less accurate because of incomplete release of the internal stresses;
- it has been tested for large trees/logs only; methods for young trees are currently more important.

A two-groove method similar to the Nicholson ‘simplified’ method has been investigated at CIRAD-Forêt (Baillères *et al.* 1994, 1995, 1996; Fournier *et al.* 1994). The longitudinal stress was relieved by making a groove above and below the sensor (Fig. 3). The distance between the two pins was 13.5 mm, the recommended distance between each pin and the nearest groove was 5 mm, and the groove depth was 10 mm. The longitudinal displacement was measured by using a classical extensometric sensor (manufacturer HBM type DD1). This method is, in principle, the same as the Nicholson ‘simplified’ method. However, differences in results between the two methods have not been reported.

One-hole method (CIRAD-Forêt method)

Archer (1978) first documented the application of a one-hole method (Fig. 4) during a study on *Pinus caribaea*. With this

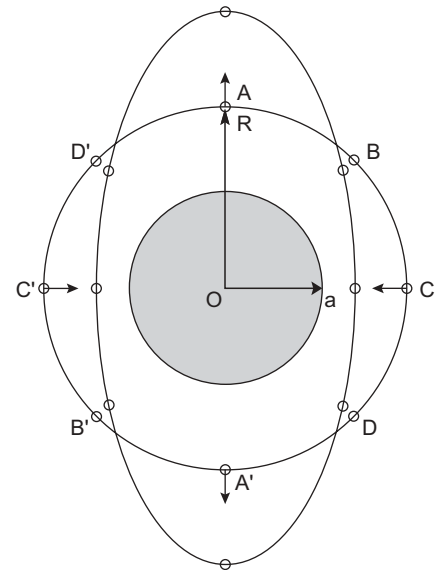


Figure 4. The configuration of the one-hole method of Archer (1978, 1986).

method, an area of bark was removed to expose the fresh wood surface. Four pairs of marker points were then placed on the circumference of a reference circle, 50 mm in diameter, marked on the fresh wood surface. The two points in a pair were positioned opposite each other and all the points were equally spaced. Using a dial gauge (Huggenberger Tensostat), the distance between each pair of points was measured to a resolution of 0.001 mm. A hole of one inch (25.4 mm) diameter was then drilled in the middle of the reference circle to a depth of about 20–25 mm. Archer’s experience was that extra drilling depth did not cause appreciable movement of the reference points. The distance between each pair of points was measured after drilling. The changes in the distances and the least-squares fit of a set of equations suited for a long cylindrical hole in an elastic medium were then used to calculate the stresses in longitudinal and tangential directions, and shear stress (Archer 1986). These stress values were then used to calculate the theoretical displacement of each pair of reference points following the same set of equations. Archer (1986) specifically pointed out that whilst the surface reference displacement (the changes in distance between a pair of reference points) may be used to indicate the levels of residual strains, the displacement can be quite different depending on the location of the reference points. For example, under similar stresses and with similar longitudinal Young’s modulus, the longitudinal displacement is negative (the distance between the reference points became shorter) when a wood segment containing the reference points is removed from the tree, but it is positive and more than twice as large when a stress-release hole is drilled between the reference points (Archer 1986).

Another one-hole method with spatial configurations different from that of Archer (1978) was developed in France by Mariaux (1982, cited in Baillères 1994 and Baillères *et al.* 1994) and later modified by Mariaux and Vitalis-Brun (1983, cited in Kubler 1987). Spatial configuration refers to initial hole diameter, initial distance between reference points, and drilling depth. Because

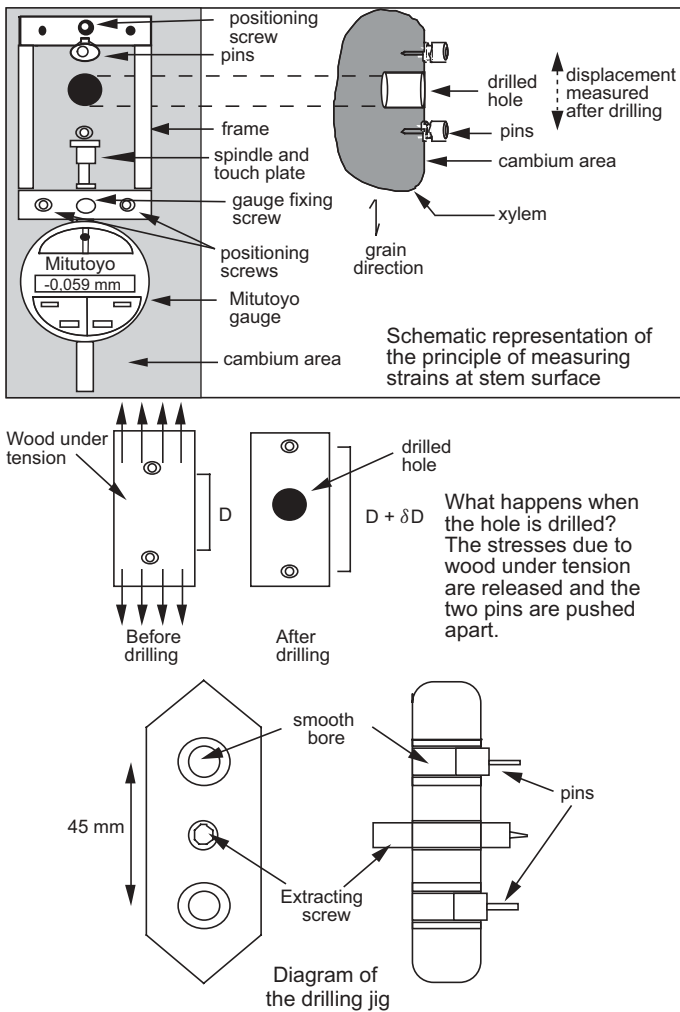


Figure 5. The front and side view of the CIRAD-Forêt strain measurement device in use (after CIRAD-Forêt sensor documentation). The drilling jig is for marking the position of the hole and inserting the pins.

the development work was carried out at CIRAD-Forêt, this method has also been simply called the CIRAD-Forêt method (Fig. 5). It has been used by a number of French researchers and became popular worldwide for its reduced operating complexity and the fact it was commercially available. The most recent improvement on the tool kit has been to replace the metal frame with a less cumbersome design, but this model is not available for purchase yet.

With the CIRAD-Forêt method (Fig. 5), a piece of bark (about 200 mm long and 100 mm wide) is removed from a standing tree to reveal the fresh wood surface. Using a jig that helps vertical alignment, two notched pins are punched into the wood, and a small indentation made at the same time at the mid-distance between the two pins. The nominal distance between the two pins is 45 mm. A steel measurement frame that is connected with a digital dial gauge (0.001 mm resolution) is then hung on the upper pin, with its spring feeler touching the lower pin. The gauge reading is set to zero prior to drilling. A hole of 20 mm in diameter is manually drilled at the small indentation between the pins in the radial direction, to a depth of 20 mm or until the gauge reading stabilizes. The distance between the two pins, or between the top and bottom edges of the hole, increases in the longitudinal direction

if the wood is under tension and *vice versa*. The displacement (δ) between the two pins is displayed by the gauge and recorded. The longitudinal residual strain (α_L) can be estimated using the equation $\alpha_L \cong -\Phi\delta$. Stress can be determined from the strain value and the Young's modulus in longitudinal direction, with

$$\sigma_L \cong -E_L \alpha_L.$$

Φ is a variable that depends on hole diameter, original distance between the two pins, Young's moduli in the longitudinal and tangential directions, shear modulus parallel to the wood grain (G_{LT}), and Poisson coefficient (V_{LT}). The mean Φ values of a number of species, including one hybrid eucalypt from the Congo (*Eucalyptus alba* x *E. grandis*), can be found in Baillères (1994, p. 38). Since it is impractical to obtain a Φ value for each single wood specimen, mean Φ values are used in the calculation of α_L values for different wood specimens from the same tree species. In other words, Φ is treated as a constant, and the estimated strain values α_L vary only with, and are proportional to, the displacement values δ . For this reason, users of the CIRAD-Forêt method usually report only the displacement values δ .

Advantages of the one-hole method are that:

- the tool kit is supplied from a single source, CIRAD-Forêt, as a finished product with documentation. As such, the method is standardized among users, and measured displacement values can be compared directly.
- it has low running cost since the pins are re-usable and have a long life;
- the tool kit is compact, convenient to carry, easy to use in the field, and not dangerous to operate;
- it is quite affordable (2300 euros in 2004);
- it allows for the evaluation of sequential changes in strain, when the stress field is disturbed by drilling or grooving at nearby areas.

Disadvantages of the one-hole method are that:

- it causes more damage to the cambium than the Nicholson 'primary' procedure because of debarking, and the damage is worse for small trees;
- Φ is determined by several wood properties including Young's moduli and shear modulus. Depending on within-tree and between-tree variability within a species, using the mean Φ to calculate released strain α_L may produce significant error. In species that have highly variable Φ , the derived individual longitudinal strain values may be considerably under- or over-estimated.
- the hole size is fixed for trees of all diameters. It is uncertain whether displacement values should be adjusted for tree diameter differences although, given concomitant variation in the stress gradient, this would seem likely.

Strain gauge method (two-hole or two-groove method)

Nagoya University of Japan was the first to use strain gauges in growth stress studies (Kikata 1972, Fig. 6). This research soon gave rise to the two-hole method for estimating surface strains (Guéneau and Kikata 1973; Trénard and Guéneau 1975, cited in Kubler 1987; Saurat and Guéneau 1976; Kikata and Miwa 1977; Wilkins and Kitahara 1991a,b; Aggarwal *et al.* 1997a,b, 1998).

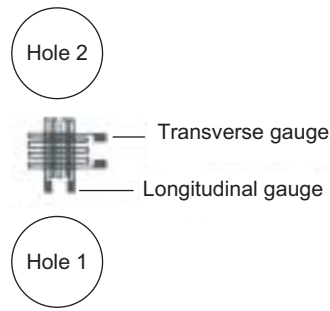


Figure 6. The strain gauge method (after Kikata and Miwa 1977)

With this method, a flexible, waterproof, resistance strain gauge that has a polyamide base is glued onto a freshly exposed wood surface of a tree or log using quick-setting α -cyanoacrylate glue. The surface stresses are released by boring to the necessary depth above and below the gauge for longitudinal strain, and on both sides of the gauge for tangential strain.

It is important to understand that the amount of strain released is affected by several parameters as discussed below. Kikata and Miwa (1977) showed that larger holes (e.g. 30 mm in diameter) not only resulted in greater strain released, but also required deeper drilling before the measurement readings started to stabilize (drilling depth of 20 mm was sufficient for 10 mm holes but not enough for 30 mm holes). Their data also showed that the measured strain was affected by the distance between the hole and the gauge: a shorter distance (e.g. 10 mm) resulted in a much larger strain reading than a longer distance (e.g. 30 mm). A recent study by Aggarwal¹ *et al.* (*pers. comm.* 2000) on the effect of hole size on released strain supported the results of Kikata and Miwa (1977), finding a positive relationship between measured strain and hole size.

The researchers at Nagoya University later replaced the hole-drilling with handsaw-grooving. As the strain values varied with groove depth and position, it was essential to identify optimum depth and position for maximum release of stress. Based on a series of experiments, Yoshida and Okuyama (2002) recommended 5–10 mm as the best groove depth and 3–5 mm as the best distance between a groove and the nearest edge of the strain gauge. This spatial configuration has been used in a number of studies at their university.

Advantages of the strain gauge method are that:

- it is more suitable than the previous two methods for measuring longitudinal strain in a very thin layer of wood and does not involve complex adjustment;
- for tangential strain measurement, no mathematical corrections are needed because strain gauges are glued to the wood surface and their shortening occurs in the circumferential contour of the tree;
- it is less destructive than the previous two methods, because only a small area of bark needs to be removed;

- many strain values can be automatically and simultaneously obtained over time through the use of a data logger and control system, with little human participation.

Disadvantages of the strain gauge method are that:

- it is more expensive to operate since the strain gauges are not cheap (either disposable or reusable ones);
- each measurement represents a smaller volume of wood than the previous two methods, so more measurements might be needed per tree to estimate the average with requisite confidence;
- its high sensitivity means that calm weather is needed. Otherwise, the operators have to waste a lot of time in the field waiting for trees to temporarily stop moving.
- the use of a soldering iron for connecting gauges to wires may prevent the use of this method in forests during hot and dry days, because of fire concern.

The signs of strain values

The signs of strain values for the Nicholson method are: positive for a tensile stress (the pins move closer when the stress is released) and negative for a compressive stress (the pins move apart when the stress is released). The signs for the CIRAD-Forêt displacement values are: positive for a tensile stress (the pins move apart when the stress is released) and negative for a compressive stress (the pins move closer when the stress is released). The signs for the strain gauge (two-hole or two-groove) method are: negative for a tensile stress and positive for a compressive stress. Such inconsistency between methods can cause confusion, even to experienced researchers. It appears necessary that a strictly applied convention should be formulated to ensure consistency between methods.

Known and potential sources of errors

The 'primary' procedure of the Nicholson method provides the maximum release of internal stress in the wood segment. From this point of view, the measured strain is closest to the true average longitudinal residual strain of the segment. However, the precision of measurement can be affected by improper contact between the dial gauge and the pins, or dirt on the pins or inside the feet of the dial gauge. Seemingly small variations ($\pm 5 \mu\text{m}$) readily translate to a $\pm 100 \mu\text{e}$ difference in the strain calculated. Also, the thickness and quality of the removed wood segments depend on wood grain orientation, the condition of the tools, and the skill and conscientiousness of the operator. The quantitative effects of varying thickness and quality of the wood segment on the measured strain have not been determined.

With the one-hole method, potential sources of error include improper debarking (fibres cross-cut near where the pins are to be located), unstable positioning of the framed dial gauge, improper contact between the dial gauge and pins, blunt drill bits, insufficient drilling depth, and impatience waiting for the gauge reading to stabilize on windy days before recording a measurement (this point applies for all methods discussed). To minimize such errors, users need to maintain tools well and carry out work with attention to details. The use of an average Φ also could be a prime source of error when calculating strain

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from individual displacement measurements, as discussed previously.

With the strain gauge method, potential sources of error include insufficient kerf depth, varying distances from the grooves to the gauge between different measurements, blunt saw blade, and improper mounting of the gauge. The quality of strain gauges and condition of the soldered points may also affect measured strain; the error is less than $10 \mu\epsilon$ if the connection is in good condition.

Differences in measurements between methods

With the Nicholson method, strain is determined from the change in length of a wood segment after it is removed from the tree. The movement of the segment is unrestrained, although it still contains some elastic, as well as non-elastic, residual stress (Nicholson *et al.* 1973). Strain measured by this method is the average longitudinal strain of the whole segment. The surface longitudinal strain may be estimated by converting this value; an example can be found in Chafe (1995).

With the one-hole method, the two reference points move apart when a hole is drilled between them if the wood is under tension. The estimated longitudinal surface strain is likely to be greater than the actual residual strain in the wood between the reference points, but the estimated tangential strain is likely to be smaller (Mariaux and Vitalis-Brun 1983, cited in Kubler 1987). This is supported by the experimental results of Yoshida and Okuyama (2002) who found that the measured strain is almost twice as high when two grooves are cut inside the pair of reference pins as when two grooves are cut outside the pins.

The strain gauge method is similar to the Nicholson 'primary' procedure in that the two holes, or grooves, are cut on the outer side of the strain gauge. The difference is that the sampled area is much smaller (e.g. 5 mm x 10 mm) and the sample is still partially attached to the adjacent wood; hence its movement is restricted. As such, the longitudinal strain measured by the strain gauge method might be smaller than that determined by Nicholson's 'primary' procedure. Guéneau (1973, cited in Archer 1986) carried out a laboratory study on large pieces of wood under externally applied parallel-to-grain compressive stress of 10 MPa. The purpose was to investigate how much longitudinal stress was released by drilling two holes of 30 mm diameter on the outer side of a strain gauge. Guéneau (1973) estimated that the two-hole method underestimated the total strain relief by about 15%.

It should be emphasized that for each method, the measured strain or displacement is the overall released strain or displacement of a given volume of wood in one direction, or the collective strain of all individual cells in that direction within that given volume where stress release takes place. Heterogeneity within this wood volume, for example, the presence of reaction wood, could be an important factor accounting for differences between techniques.

Predicting growth strain from changes in increment core diameters

Polge and Thiercelin (1979) suggested that a new strain evaluation method that did far less damage to the cambium, and hence brought less risk of pathological disease, was necessary. Increment cores were viewed as a good option for specimens for two reasons.

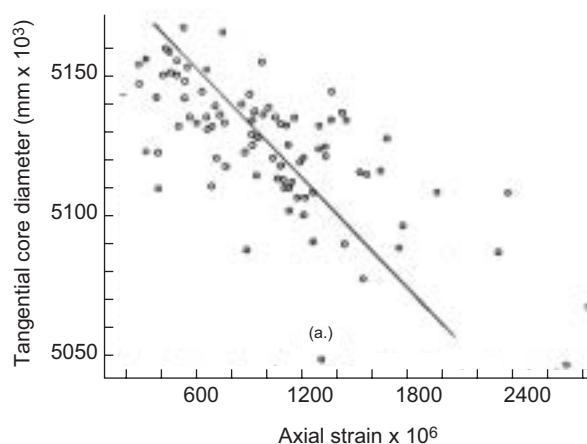


Figure 7. Relationship between longitudinal surface strain and mean tangential diameter of increment cores that were 25 mm long and adjacent to the bark (after Polge and Thiercelin 1979)

Firstly, the changes in increment core diameter may reflect the level of internal stress and its variation along the radius. Secondly, the cores could be used for measuring other wood properties after the primary experiment was completed. These authors measured the longitudinal surface strain using a two-hole method (hole size 30 mm) and collected one increment core of 5 mm diameter above the upper stress-release hole from each of 86 selected beech trees. The longitudinal and tangential core diameters were then measured to ± 0.001 mm resolution at 0.25 mm intervals. Data representing the 25 mm wood segment adjacent to the bark were averaged to yield mean longitudinal and tangential core diameters, and these values were subsequently analysed. A significant relationship was found between the longitudinal strain and mean tangential core diameter ($r = -0.578$), but not between the strain and mean longitudinal core diameter ($r = -0.068$). Polge and Thiercelin (1979) suspected that small among-tree differences in longitudinal core diameters due to high modulus of elasticity and the insufficiently sensitive diameter measuring device were the causes of this poor relationship. The negative relationship between the strain and tangential core diameter (Fig. 7) was explained by the fact that in high-stress trees, the cutting edge of the coring bit became oval-shaped under the combined effect of longitudinal tensile force, tangential compressive force, and the normal cutting forces.

Ferrand (1982a,b, cited in 1982c) used the method of Polge and Thiercelin (1979) in several growth stress studies and observed similar relationships between longitudinal surface strain and tangential core diameter. In beech and poplar, tension wood was found to be the main reason for reduced tangential core diameters. Although the correlation between the released longitudinal strain and core tangential diameter was moderately high ($r = 0.759$, 29 trees, $P < 0.01$), Ferrand (1982c) nevertheless considered that the increment core method would suit studies on provenance differences and silviculture effects where precise strain measurement was not as critical as in wood science studies.

Wilkins and Bamber (1986), while evaluating the method of Polge and Thiercelin (1979), observed that the core diameter changed

with time and set up experiments to investigate the nature of this change. They took 5 mm increment cores from *Eucalyptus pilularis* trees and from large branches of *Pinus radiata*. Using a device similar to that used by Polge and Thiercelin (1979), the longitudinal and tangential core diameters were recorded at intervals of 1.25 mm (up to 100 measurements per core), starting from a point 5 mm from the cambium to avoid the outer distorted segment. Both longitudinal and tangential core diameters decreased with time, most of the reduction occurring during the first hour after sampling. Wilkins and Bamber (1986) considered that the reductions in tangential core diameter were a result of residual stress relaxation rather than moisture loss or from the contact pressure on the cores during measurement. Waiting for 48 h before taking a core diameter measurement was therefore recommended. Wilkins and Bamber (1986) also reported that the rate of diameter reduction was higher in *E. pilularis* than in *P. radiata*, and higher in older trees (40-y-old cf. 15-y-old), the details of which, however, were not given in their paper.

Advantages of this type of method are that:

- an increment core can serve a number of purposes, i.e. it can be used to measure a number of wood properties after the completion of diameter measurements;
- increment cores are easy to take in the field;
- injury to the cambium is negligible, which makes this method very attractive;
- the precision of using core diameter changes to predict strains may be improved by measuring other wood properties and including them as predictor variables.

Disadvantages of this type of method are that:

- a dull coring bit can cause considerable error in measurement. The sharpness of the coring bit decreases as coring proceeds, thus reducing repeatability of results. Small variations may be expected in the diameter of a bit, even in good condition.
- it is difficult to prevent cores twisting during boring, a problem more likely in small-diameter cores, especially when coring is carried out manually;
- an increment corer is affordable, but a sufficiently accurate diameter measuring device is expensive, costing about A\$12 000 to make.

Addendum

We hope this article will be of value to people who are new to growth stress research and strain measurement, and that it can help them choose a suitable method for their purpose while appreciating the limitations of each method and the variability which exists between results of different methods.

Due to a lack of knowledge of methods for measuring growth stress, and a need to understand the quantitative differences between available methods, the Conference Communiqué of the 2000 IUFRO conference on *The Future of Eucalypts for Wood Production* held in Launceston, Australia, recommended:

Collaboration between researchers should continue to be encouraged at an international level along with developing partnerships between researchers and industry to ensure research relevance and application of results ... International research

efforts will be greatly enhanced by the development of standard methodologies, units and common tools, particularly those applicable early in the growing cycle, that allow standard, quick, cost effective and reliable assessment of properties and the most important traits, e.g. non-destructive techniques for measurement of growth strain and stress.

A recently-completed research project at CSIRO Forestry and Forest Products investigated the compatibility of the Nicholson method, the CIRAD-Forêt method and the strain gauge method in segregating trees into various strain classes. Objectives also included searching for less damaging and more efficient methods which either directly measure strain, or predict strain from other wood properties such as microfibril angle (MFA) and cellulose crystallite width (W_{cryst}) as measured by SilviScan-2. The specimens used were from young plantations of *E. globulus* Labill., *E. cloeziana* F.Muell. and *Corymbia variegata* (F.Muell.) K.D.Hill & L.A.S.Johnson grown in Australia. We found significant relationships ($P < 0.01$) between strain (or displacement) measured by these three methods for all three species, and between strain (or displacement) and MFA and W_{cryst} for *E. globulus* (Yang *et al.* 2004). (SilviScan-2 measurements were made only on *E. globulus*.) Our results also showed some potential for using NIRA (near infrared analysis) to predict residual strain, subject to adequate calibration, satisfactory accuracy of the reference methods and proper physical size of wood specimens (Baillères *et al.* 2003; Yang *et al.* 2004).

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