Growth stress, its measurement and effects

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Summary

This paper provides a brief, general background to growth stress, its undesired effects on sawlog utilization, and the methods that have been developed to counter these effects. The paper also describes three major methods used at present for growth strain measurement on tree or log surfaces, and discusses the need for an improved understanding of these methods.

Key Words: growth stress, growth strain, sawlog, wood quality

Introduction

Eucalypts are now widely planted throughout the world in response to the needs of increasing populations and pressing needs for environment protection, and because of their high productivity on marginal sites and their ability to produce a range of useful forest products (Midgley and Pinyopusarerk 1995). The total world area of eucalypt plantation is estimated at 13.6 million ha with very large plantings in India (4.8 million ha), Brazil (2.9 million ha) (Flynn and Shield 1999), and China (about 2 million ha[1]).

In most countries where large areas of eucalypts have been planted, the primary use has been for wood chips, firewood, mining timber, shelter-belts, etc. Higher-value uses such as furniture and internal decoration are very limited due to unsatisfactory quality of the raw material, and/or the lack of knowledge and experience in handling growth stresses during sawlog processing and later timber-drying. Except as a good source of wood chips and firewood, plantation eucalypts are viewed overall as a low-quality wood resource.

There has been a growing interest in obtaining higher-value products from eucalypt plantations. The motivating factors are the vast areas of plantations, the decline in hardwood pulpwood prices, better financial prospects from higher-value products, environmental concern over the deleterious impacts of short-rotation management, emerging conversion and processing technologies, and the potential to substitute eucalypt products for tropical hardwoods (Flynn and Shield 1999). Also, the development of higher-value uses for plantation wood provides additional local employment, makes wood products affordable to people of low-income, eases demands on natural forests, and helps reduce reliance on timber imports.

One of the key factors limiting higher-value use of young eucalypts as sawlogs is high growth stress. Growth stress management would have both a national and global economic significance. Knowledge and experience obtained from new research on growth stresses have potential worldwide benefits.

Australia is striving to quickly expand its eucalypt plantations, but some of the choice species are known to develop high growth stresses (e.g. *Eucalyptus globulus*, *E. grandis, E. saligna, E. maculata)*. At present, there is no eucalypt breeding program in Australia for reducing growth stress because little is known about threshold levels of growth stress, effective silviculture practices, and genetic correlations between reduced growth stress and other wood properties. Although significant knowledge and experience of growth stress have been accumulated in the scientific community and in the sawmilling industry (particularly in the Australian states of Victoria and Tasmania), there is still much room for improvement.

This paper outlines the most common undesired effects of growth stresses on sawlog utilization and the methods that have been developed to counter these effects. We also describe three major methods used for surface growth strain measurement, and discuss the need for better understanding of these methods and the need for increased measuring speed.

Growth stresses

Growth stresses are self-generated in the cambium during cell maturation and are present in all tree species (Jacobs 1938; Kubler 1987). Strains, as a consequence of relief of growth stresses, are called growth strains. Stress is measured as the force per unit area. Objects under stress will change their dimensions and shape. The dimensional change per unit original length is the strain (tensile or compressive). With a given modulus of elasticity (MOE) and within the proportional limit of elasticity, a greater strain results from a higher stress. Growth stresses are usually impossible to measure directly, whereas growth strains are readily measured. By measuring the strain, the stress corresponding to that strain can be calculated. Growth stress remains a very difficult property to determine and must be approached indirectly, by measuring growth strain, or even more indirectly by measuring other wood properties for hopeful correlation and prediction. Whilst the terms growth stress and growth strain are not interchangeable, careless use of them without clear distinction has been seen.

Growth stresses are commonly resolved in the longitudinal, tangential and radial directions, following the natural geometry of the trees. There are two leading theories that attempt to explain how growth stresses are generated. The 'lignin swelling' theory proposed that growth stresses arise during the lignification process of maturation of newly formed cells.

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[1] One million ha are planted primarily for landscape improvement and as windbreaks (personal comunication Luo Jianju, China Eucalypt Research Centre).

Poymerization of lignin causes contraction or swelling of cells in lateral directions and simultaneous elongation or shortening of fibres or tracheids in their axial direction (Munch 1938; Boyd 1972, 1985) depending on the microfibril angles in these cells (Boyd 19739, 19736). The 'cellulose tension' theory states that growth stresses are generated as a consequence of the contraction of microfibrils in the newly formed cells while their continuing crystallization is inhibited by the deposition of lignin (Bamber 1979, 1987).

It seems that neither theory is applicable in all circumstances. In hardwood species that form tension wood, highest growth stresses are usually associated with that tissue (Trenard and Gueneau 1975; Bamber 1979; Okuyama *et al.* 1994). In other hardwood species including some eucalypts, however, high growth stresses have been found in wood showing no characteristics of tension wood (F.S. Malan pers. omm. Nicholcon *et al.* 1975) the wood had smaller microfibril angles, a higher degree of cellulose crystallinity, and a higher α-cellulose content (Okuyama *et al.* 1994). South Africa's experience with breeding low growth-stress trees is that as average growth stress is reduced, the lignin content of the trees increases (F.S. Malan *per. comm.*). It is thought that a number of factors, rather than only one, could contribute to the level of growth stresses generated; microfibril angle, cellulose and lignin contents, and cellulose crystallinity all are candidates. Regardless of the mechanism, the consequence is that dimensional changes of the cells in longitudinal and lateral directions are restrained by already-lignified neighbouring cells, which in turn gives rise to the formation of longitudinal and lateral growth stresses in the maturing cells.

Severe growth stresses do not generally occur in conifers, but can be quite excessive in many hardwoods (Bootle 1983; Kubler 1987). Eucalypt species, as noted, are particularly prone to high growth stress (Jacobs 1938; Nicholson 1973b; Malan and Toon 1980; Kubler 1987).

The continuous formation of growth stresses during tree growth results in an uneven and continuously changing distribution of stresses across tree stems. Classical models of growth strain distribution are given by Boyd (1950a) and Kubler (1959a, 1959b). When logs are sawn longitudinally, these stresses are partially released and the gradient of longitudinal residual stresses causes sawing inaccuracy, spring in quarter-sawn boards, and bow in back-sawn boards. A detailed description is given below. Proper log processing strategies, sawing equipment and subsequent drying can successfully minimize the above problems; otherwise considerable sawing expense and waste can occur.

Evidence from earlier research shows that levels of longitudinal growth stress vary not only between and within species (Jacobs 1938; Waugh 1972; Nicholson *et al.* 1975; Malan and Toon 1980; Hillis 1984; Kubler 1987; Malan 1995; Aggarwal *et al.* 1997, 1998; Okuyama 1997; Wahyudi *et al.* 1999; Maree and Malan 2000; Yang and Fife 2000), but are also highly responsive to growth conditions (Ferrand 1982; Kubler 1987, 1988; Wilkins and Kitahara 1991). Some species of eucalypts contain higher levels of growth stresses than many other hardwood species (Kubler 1987) and, based on recent measurements, *E. globulus* can be added to the list (Yang and Fife 2000). Growth strain measurements which demonstrate the variation between species and between trees have been tabulated by Kubler (1987). However, some of these growth strain values cannot be directly compared due to different measurement methods. To tree growers, an important issue is to find and breed from species and trees with low growth stress and to apply tree management strategies that help reduce, or at least do not promote, the development of high growth stress.

Undesirable effect on sawlog utilization

Loss of sawlog recovery due to log end-splitting

When a log is cross-cut, the longitudinal growth stress at the freshly cut end is released and transformed into secondary radial and tangential tensile stresses at the cut end. This results in a considerable increase in the tangential stress near the pith (Boyd 1950b; Kubler and Chen 1974). When the tangential stress exceeds the tangential tensile strength of the wood, splits develop on the log end, originating from the pith (Fig. 1). Given the magnitude of growth stresses, log end-splitting can be made worse by careless tree felling, incorrect stem cross-cutting and rough log handling. Or, it can be withheld or lessened to a certain extent if the wood has interlocked grain. Log end-splits 20 mm wide and 1000 mm in length along the grain are not unusual. From time to time, a log is seen to split along its entire length (Fig. 2). End-splits usually reach their worst in the first week following cross-cutting, then slowly become wider and longer with time. Sawlog recovery may suffer heavily from log end-splits. Splitting-related losses in South African sawmills were reported to exceed 10% (Maree and Malan 2000).

Figure 1. Log end splits due to the release of growth stresses following the crosscut (*Eucalyptus spp.*)

Figure 2. A near-full-length log splitting due to the release of growth stresses following the crosscut (*Eucalyptus spp.*)

Sawn board thickness inaccuracies

When a log is cut, both the board being removed and the remaining flitch will move or distort as they attain a new state of stress equilibrium. As the flitch remaining on the carriage curves away from the straight saw-line, the next board being cut will be below the nominal thickness at the ends of the board and above the thickness at its centre if appropriate sawing equipment is not used to manage this problem.

Sawn board distortion due to stress re-balance

Sawn boards distort upon being sawn from logs, as a consequence of the re-balancing of residual growth stresses in the boards (Fig. 3). Quarter-sawn boards spring and back-sawn boards bow. Bow can be corrected without re-sizing the boards, but excessive spring can only be removed through re-sizing. The higher the growth stresses and the smaller the tree stems, the larger the board distortion will be. Experience shows that log diameter should be not less than 50 cm for both quarter- and back-sawn production, and back-sawing is recommended for smaller eucalypt logs.

Figure 3. Distortion of sawn boards due to the growth strain differential (*Eucalyptus spp.*)

Loss of productivity

To re-size quarter-sawn boards that have excessive spring, and to re-size sawn boards to correct thickness inaccuracies at a later stage, is to add one more step of processing, thus reducing productivity.

Constraints on log break-down and sawing patterns

The sawyer usually aligns the first log-break-down cut parallel to the major end-split on the log end. He also follows a certain sawing pattern and log turning sequence in order to minimize sawn board distortion and sizing inaccuracies. In other words, the sawyer has to make a compromise between the location of the major log end-split and the ideal log orientation. The log cannot always be oriented and turned in the way that is best for minimizing the impact of other external and internal defects on grade recovery.

Drying degrade due to tension wood

Growth stresses are generated by some modification in newly formed wood cells. Highest growth stresses are usually found during the formation of tension wood. Trees that show high growth stresses are suspected to have more tension wood, or at least have wood that is different from less-stressed wood (Nicholson *et al.* 1975). A number of eucalypt species are prone to collapse-checking during drying. The presence of tension wood makes the collapse-checking worse (Dadswell *et al.* 1958). Sawn boards from highly stressed trees have been observed to collapse more severely than normal material (Nicholson *et al.* 1972). The presence of collapse-checking in seasoned wood has limited effect on structural sawn products but, depending on the severity of the checking, it may exclude the use of the seasoned wood for higher-value appearance products.

Weak material in core wood zone caused by brittleheart

Brittleheart starts to form during tree growth when the compression stress induced by growth stresses towards the tree centre exceeds a certain percentage of the compression strength of the wood. Its severity and radial extent are positively associated with the magnitude of growth stresses and the tree diameter. Brittleheart has low strength properties, in particular impact strength, and fails with a brash fracture (Dadswell and Lanlands 1938). It was found that the bending strength of brittleheart of Tasmanian regrowth *E. obliqua* was only about 67% of the clear material; on the other hand, its bending MOE was far less affected, being approximately 97% of that of the clear material (Yang 2000). The incidence of brittleheart has also been reported in Zambia-grown *E. grandis* (Hillis *et al.* 1975) and South-Africa-grown *E. grandis* (F.S. Malan *pers. comm.*). Fortunately, brittleheart seems to be a minor problem for small-size trees, which are becoming the major supply in the log market.

Heart checks in standing trees

Heart checks result from excessive tangential strain. They usually develop only in large-diameter trees (e.g. >100 cm in diameter) in which excessive tangential strains have developed (Kubler 1987). Again, as with brittleheart, heart checks seem to be a minor problem for small-size trees.

Greater effects on conversion of small logs

According to Kubler's longitudinal growth strain distribution model (1959b), with a given growth strain at the log periphery, the smaller the log, the greater the growth-strain gradient across the radius. Sawn boards from a small log will display greater distortion (either bow or spring or both) than sawn boards of the same thickness from a large log with the same peripheral growth strain. There has been a common perception that fast-grown plantation eucalypts have higher peripheral growth strains than regrowth or old growth, because sawn board distortion and severe log end-splitting are often observed in logs from short-rotation plantations. However, substantial data are needed to support this speculation. The more likely explanation is that since plantation trees are commonly harvested at a far younger age, the logs are usually small in diameter and therefore have a steeper strain gradient. A detailed review of this aspect has been given by Chafe (1979b). Also, plantation trees, as well as possessing greater amounts of weaker juvenile wood, may have weaker strength properties as a result of the trees being selected and managed for growth rate only. Therefore, log end-splits are due not only to high stress gradients but also to lower resistance to fracture.

Methods that counter the effects

Various efforts have been made in recent decades to minimize the adverse effects of growth stresses on log utilization. They include:

Tree girdling or defoliating trees with chemicals

Tree girdling refers to the cutting of a kerf around a standing tree at some height above where the felling cut is anticipated (Kubler 1987). Log girdling involves the cutting of circumferential kerfs prior to crosscutting, one kerf at each side of where the crosscut will be cut (Barnacle and Gottstein 1968). This method has been found to be reasonably successful and has the advantage of being easily achieved with a chainsaw in the field. Defoliating trees (Waugh 1972) sets back tree growth and releases growth stresses in standing trees to a certain extent.

Appropriate procedures and techniques for harvesting and log handling

Logs can develop severe end-splits or even full-length splits when subjected to a large impact during felling. Care during harvesting and log handling could minimize this impact and hence minimize damage.

Appropriate techniques for log cross-cutting

The way the log is supported during crossing-cutting, and the steps taken in completing the cross-cut can minimize both splitting at the cross-cut and tear along the log length.

Log grooving

Log grooving refers to cutting a circular groove at the log end, between the periphery and the center of the log. The effectiveness of a groove varies with the width, depth and radius of the groove, as finite element computing illustrates (Kubler and Chen 1975). Similar to the kerfing method, grooving itself will result in a certain loss of log volume. Its application eventually depends on the financial return when all factors are put into the equation such as the saved and lost log volume, with and without grooving, and the labor costs.

Oblique cuts (or slant cross-cutting of logs)

The three-dimensional, theoretical aspects have been examined by the finite element method (FEM) (Tantichaiboriboon and Cook 1976), the semi-analytic FEM method (Bandyopadhyay 1978), and the classical analytic method (Byrnes 1974). A summary of the above researchers' work is given by Archer (1987). New contributions to this area of research have been made by Mattheck and Walther (1992), with promising results for European beech. Oblique cuts have been applied in very few countries, e.g. Brazil. The technique needs further experimental evaluation, and its economic impact must be assessed.

Reducing log length

The distortion in a sawn board is highly dependent on the length of the board. If the log length is halved, the distortion will be reduced by a factor of four. However, shorter log lengths may affect the marketing of the timber and the productivity of the mill.

Log storage under water spray

Nicholson (1973a) found that water-spray storage reduced residual mean growth stresses by approximately 20% when logs were stored for a period of 300 days. The release of residual stresses in logs helps in later sawing. This method also has the advantage of ensuring a constant supply of logs to the mill in areas where winter logging may be impossible. Storing logs under water spray has been a common practice for many years in many eucalypt sawmills in south-eastern Australia.

Strapping or fasteners applied to log ends

This method involves the stretching of steel bands around the stem close to where cross-cutting is to take place (Kubler 1987), or hammering S or C shaped irons into the crosscut surface to prevent or reduce log end-splitting. These methods may not effectively prevent end-splitting in large, highly-stressed logs. Even if they do, most of the residual stresses may still exist in the logs if these methods are not used in conjunction with other stress-releasing treatments such as steaming. Metal straps and fasteners are much stronger than plastic ones, but they have to be removed prior to sawing. The log ends may very likely split soon after the strap or fastener is removed, thus defeating the original purpose.

Heating logs prior to processing

It has been a common practice in the veneer industry to heat logs in water (hydrothermal treatment) to soften dense wood prior to peeling or slicing. Recent work has used hot smoke to similar effect (Okuyama *et al.* 1987). The higher the moisture content, the lower is the softening temperature required and the greater is the absolute softening achieved (Fengel and Wegener 1984). However, the cost of this treatment can be justified only for high-value logs. Also, associated disadvantages such as excessive shrinkage because of probable increased collapse need to be well understood and considered.

Burying in manure

Concentrated ammonia has been used extensively in furniture making for bending solid wood elements because of its highly effective plasticizing effect (Kubler 1987). By burying fresh eucalypt logs in animal manure, longitudinal growth stresses were reduced by one third in five months and two thirds in seven months (Giordano and Curro 1973). Combined elevated temperatures (around 60°C), stable moist conditions and, in particular, ammonia vapour were thought to be responsible. However, this practice is not practical for large numbers of sawlogs.

Suitable sawing equipment

Appropriately designed sawing equipment (e.g. line-bar carriage, hob-feed sizing accessories, twin-blade system) will be able to process highly-stressed logs and minimize the variation in thickness of sawn products.

Appropriate sawing strategies

These strategies refer to log orientation for the first saw cut, sequence of turning the flitches, the sizes of sawn products to be cut, back-sawing strategies in particular for small logs, etc. Such strategies can effectively reduce the amount of sawn board distortion and other sawing defects.

Breeding and stand management

Genetics and silviculture definitely affect the level of growth strains (Waugh 1972; Kubler 1988; Wilkins and Kitahara 1991b; Malan 1995). Schacht *et al.* (1998, cited in Garcia 1999) found log end-splitting of *E. urophylla* had a high heritability of 0.89, and a similar value has been found by Garcia (1999) for *E. grandis*. In South Africa, log end-splitting of *E. grandis* was characterized by enormous between-tree variation, even among trees growing under uniform conditions. Consequently, growth stress has been assumed to be under genetic control, and the absence or low level of log end-splitting has been an important criterion in the tree breeding program in South Africa (Malan 1995).

An overview of present measurement methods

A number of methods for growth strain measurements on the tree surface (with bark removed) have been developed since this field of research originated in the 1930s. Only a few, however, differ from each other in the way the stresses are released, and hence in the amount of longitudinal strain that is measured. The other methods are basically variations of these methods. Growth stress remains a very difficult property to determine and must be approached indirectly, by measuring growth strain, or even more indirectly by measuring other wood properties for hopeful correlation and prediction.

Three major methods

The three methods widely used at present to measure growth strains on tree or log surface are the Nicholson method (1971), the CIRAD-Forêt method (the French method) (Gerard *et al.* 1995), and the strain gauge method (Aggarwal *et al.* 1997b; Okuyama 1997). They all cause a certain amount of damage to the bark and cambium. This is because cuts or holes must be made to the wood to allow the wood to move so that strains can be detected. The injuries may affect tree growth, and fungi may infect the trees through the injury. The techniques may therefore conflict with the need to retain trees for later measurement and breeding.

The Nicholson method (1971)

The Nicholson method was developed in two versions: the 'primary' and 'simplified' procedures. The 'primary' procedure has been the traditional method used at CSIRO and in some overseas countries. With the Nicholson 'primary' procedure, two steel studs are glued to the surface of a tree stem, or a log, which has had its bark removed. The studs are about 50 mm apart and aligned parallel to the wood grain. The linear distance between the studs is measured before and after a wood segment is removed from the tree or log. The segment is 19 x 90 mm and approximately 10 mm thick, and contains the two studs centrally. Because of the gradient of longitudinal growth strain along the tree radius (Kubler 1959b), the wood segment may develop a curvature upon its removal. The elimination of this ‘secondary’ curvature is accomplished by using a special apparatus to bend the wood segment in an opposite direction and restore its original conformation, as in the tree. Following the curvature adjustment, the distance between the studs represents the linear measurement after strain release. Strain is calculated from the difference between the before- and after-removal measurements.

With the 'simplified' procedure, only two horizontal cuts are made in the tree, one above and one below the metal studs, with linear measurements made before and after the cuts. Nicholson did not quote the time saved by omitting the two vertical cuts and removal of the sample from the tree, but from our current field experience we estimate it to be approximately 15%. A close relationship between the 'primary' and the 'simplified' procedures was found (Nicholson 1971) from 99 growth strain measurements on 7 large logs (diameter >76 cm). This 'simplified' procedure was recommended for use on large logs only (diameter >76 cm) in order not to lose too much accuracy (Nicholson 1971).

The advantages of the Nicholson 'simplified' procedure, in addition to time saved by sample retention, are that no curvature adjustment is required (a possible further 5% of the time saved), it causes far less injury to the cambium and leaves no void in the tree. The disadvantage is that the results are less accurate because of incomplete release of growth stresses. Whilst Nicholson recommended the 'simplified' procedure for large trees/logs, he did not report whether the 'simplified' procedure had been trialled on small logs.

The French method

This method has gone through various models and reached its present state of development over about twenty years, as is reflected by the continuing upgrading of the tool kit. The newest model is described by Gerard *et al.* (1995). It is primarily used in France but has been gaining popularity worldwide. The method is based on measurement of the distance between two reference points before and after a hole equidistant from these two points is drilled. Firstly, a piece of bark (around 200 mm long and 100 mm wide) is removed from a standing tree to reveal the cambium. Using a guide that helps vertical alignment, two notched pins are punched into the wood, and a tiny indentation is made at the same time at the mid-distance between the two pins. A steel measurement frame that is fixed with a dial gauge is then hung on the upper pin, with its spring feeler touching the lower pin. The distance between the two pins is measured before and after a hole of approximately 20 mm in diameter and 30 mm deep is drilled radially where the small indentation was made.

The most recent upgrading of the tool kit was to replace the metal measurement frame with a less cumbersome design to improve its ease of use (H. Bailleres, CIRAD-Forêt *pers. comm.*).

The strain gauge method

The strain gauge method seems to have been the dominant method used in Japan (Okuyama 1997). Various local versions have also been developed and used in other countries such as Australia (Wilkins and Kitahara 1991a, 1991b) and India (Aggarwal *et al.* 1997a, 1997b, 1998). Basically, a flexible, waterproof, resistance strain gauge that has a polyamide base is pasted on a freshly exposed wood surface of a tree or log. The growth stresses are released by kerfing or boring the wood around the strain gauge, above and below the gauge for longitudinal strain, and on both sides of the strain gauge for tangential strain. The longitudinal and tangential strains can be measured immediately. It is possible to carry out the measurements close together with little interference between the measurements (Okuyama 1997; P.K. Aggarwal *pers. comm.*).

Comments on the three methods

Measurements by each of the methods result in different strain measurements because of the way the stresses are released to facilitate dimensional changes for strain determination. With the Nicholson method, strain is determined from the change in length of a wood segment after it is removed from the surface of the tree. Since the outer zone of an eucalypt tree is usually under tension, the wood segment will contract along the grain upon its removal. Such contraction is independent from the rest of the tree because the segment is totally removed from the tree, although the segment still contains some elastic residual stress (Nicholson *et al.* 1973). With the French method, the two reference points move apart when a hole is drilled between them. The longitudinal strain so determined is likely to be greater than the real strains (Mariaux and Vitalis-Brun 1983, cited in Kubler 1987) due to the difference in stress redistribution. Compared with the French method, the strain gauge method has greater similarity to the Nicholson method as cuts or holes are made above and below the strain gauge to partially release the stresses between the cuts or holes. The longitudinal strain determined by this method is likely to be smaller than that by the Nicholson method because of incomplete release of the stresses. So far, quantitative differences between these three methods are not known. Because of this, strain data collected using different methods cannot be compared directly.

A comparison of the Nicholson and the French methods had been carried out at CIRAD-Forêt, primarily using a mathematical approach (H. Bailleres, *pers. comm.*). However, none of the results has been published.

Other direct or indirect methods

Predicting growth strain from MOE

It has been suggested recently that a stress wave technique or an ultrasonic method might possibly predict the level of growth strains, based on the relationship between the speed of stress waves, or sound through the wood, and the density and modulus of elasticity of the wood. A number of researchers have found that a stress wave technique or ultrasonic method, in particular the resonance flexure (stress wave) technique, can be used to predict MOE with high precision (Haines *et al.* 1996; Haines and Leban 1997). Since MOE is highly dependant on cell wall characteristics, and growth stresses are generated during the development of cell wall characteristics, wood of high growth strain might have an 'abnormally high' MOE.

One characteristic of the stress wave and ultrasonic methods is that they predict the average MOE of a tree or log, or a board. However, the prospect of utilizing these methods to predict growth strains remains doubtful for several reasons. First the relationship between the level of growth stresses and MOE seems inconsistent (Nicholson *et al.* 1975; Chafe 1990:) at least for small wood specimens. Second, since wood properties are highly variable in the radial direction, the average MOE of a tree or log probably could not relate reliably to the MOE at the tree or log surface where growth strain is usually measured.

Predicting strain from other measurements

Other attempts have been made to predict the level of growth strains or stresses by measuring certain properties, for example, wood hardness and density (Chafe 1979a, 1990; Muneri *et al.* 1999), and change in increment core dimensions (Polge and Thiercelin 1979; Wilkins and Bamber 1986). However, the use of hardness or density alone as a predictor does not appear to be promising because of poor or inconsistent correlations.

The basic idea of the increment core method is to establish relationships between longitudinal growth stress and changes in tangential and longitudinal directions of increment cores after their removal from the trees; and then, upon finding a significant relationship, using this relationship to predict longitudinal growth strains. Polge and Thiercelin (1979) had found significant and negative between- and within-tree relationships in beech trees (*Fagus sylvatica*) between longitudinal growth strains and average tangential diameters of increment cores (5 mm in diameter and 25 mm in length). They used a quite sophisticated laboratory device that had an accuracy of +/- 1 mm and enabled continuous measurements of core diameters with the help of a stepping motor. The core specimens could be accurately positioned with reference to their grain orientation by using the reticle of an eyepiece.

According to Polge and Thiercelin (1979), the relationships could be adversely affected by, in order of significance, the condition of the borer, the precision of the measurement device, and the alignment of the core specimens during measurement (Polge and Thiercelin 1979). Other factors could also affect core specimen diameters such as shrinkage, and reduction of diameter with time as a consequence of further stress release (Wilkins and Bamber 1986). A 48-hour waiting period has been suggested for core diameters to stabilize, before any measurements are taken (Wilkins and Bamber 1986). It is apparent that a good understanding of the errors and effective control is essential in order to gain user confidence in the increment core method. If this method works, it will have a number of added advantages: the technique is simple to apply in the field, the same increment cores collected for growth strain measurements can be used in other wood property studies (density, microfibril angle, cell dimensions, etc.), and it causes the least injury to the tree.

Is faster measurement possible, and what are the options?

All three main methods of growth strain measurement have been considered by some users as inefficient and cumbersome. A frequently asked question from foresters is ‘Is there a method for fast measurement or estimation of growth strains in a large number of trees’? To answer this question, we must ask a few other questions as well. What is the definition of a fast method? What is the acceptable cost to make a method faster? And how much accuracy can be sacrificed for speed? Depending on the purpose of growth strain measurements, there appear to be two different answers.

For the purposes of tree breeding, evaluation of forest resource and stand management, a major task is to rank or make comparisons between species, populations, genotypes, silvicultural treatments, etc. In these cases, each single measurement does not have to be precise, as long as the accuracy is high enough to reveal the presence or absence of significant differences. As such, the ability to carry out a large number of measurements on a large number of trees is very important. It is therefore adequate to develop a faster, but less accurate, more user-friendly, and less destructive method or measurement procedure.

With reference to wood science research and sawing simulation work, precise measurements of growth strains are essential. Unfortunately, as with some other wood properties, growth strain is unlikely to be measured precisely, quickly and economically, unless there is a strong user demand to propel new research and development in order to significantly improve the present methods.

Growth strain may be predicted from the measurements of other wood properties (such as density, microfibril angle, cellulose and lignin content, cellulose crystallinity) but the results are always less accurate than direct measurements. In addition to the time and expense of developing a relationship, it is likely to be species dependent, hence one relationship may have to be established for each species or a group of species.

The application of the Nicholson 'simplified' procedure to smaller logs is certainly worthy of further investigation. Work needs to be done to determine the effect of tree size, kerf depth and the interaction between the two, on the precision of this procedure. The increment core method could also be re-visited, provided standardization in instrumentation and procedure can be achieved, as well as the determination of significant relationships between less and more accurate methods (e.g. the Nicholson 'primary' procedure). The real challenge, however, is to ensure that a simple and standard process is developed, based on a reliable and inexpensive device. Otherwise this method will not find many users.

The need for improved understanding of measurement methods

The lack of systematic assessment of the presently used methods means that quantitative relationships between the methods are unknown, as are comparative advantages or disadvantages for different uses.

The Conference Communique of the 2000 IUFRO conference on ‘The Future of Eucalypts for Wood Production’ held in Launceston, Australia has recommended the following for future research:

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 better understanding of growth stress determination and the development of faster measurement methods will benefit research and forest resource management. As the quality of eucalypt plantations is improved, so to is their potential for higher-value end-use.

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