Need for Further Structural Mechanics Study on Radiata Pine Wood Properties

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Abstract

This paper stresses the need for the study of structural mechanics in relation to radiata pine wood properties, through a review of previous and current researches on stems, structural boards and wood cells.

Along the vertical direction, the worst characteristic stiffness and characteristic tensile strength both occurred in the corewood of butt log, which did not match the distribution pattern of low-density wood in the radiata pine corewood. In addition, there was an enlarged conical low-stiffness wood zone rising from the base to about 3 meter of the tree, which also differed from the distribution pattern of the low-density wood. For a structural board, there was a poor relationship between the wood density, local stiffness and tensile strength at the failure point. The knot–related structural factors, such as branch growth angle and structural discontinuity of wood grain, significantly affected the mechanical properties, although knot area ratio alone did not predict the mechanical properties at the failure point in a structural board. At the micro-scale, the previous structure-stiffness models have not well agreed with the experimental data at the small microfibril angles. Further experimental and theoretical investigations are required to explain the influence of cell morphology on the cell mechanical properties.

Introduction

Structural mechanics of biomaterials investigates the relationships between the structural properties and mechanical properties in the living tissues and the resulting biomaterial products. Stiffness and strength are key quality criteria for wood-based biomaterials including standing trees, structural boards and individual wood cells; thus they are the major concerns of structural mechanics (Mark 1967, Preston 1974, Bodig and Jayne 1982, Madsen 1992). Owing to heterogeneity and anisotropy of wood-based biomaterials, stiffness and strength vary with the location of specimen and highly depend on structural factors both at macro- and micro scales. Efforts over recent decades include the following: corewood (the first 10 growth rings from the pith) has been identified as a problem zone in radiata pine trees due to the poor stiffness and strength (Cown 1992, Walker 1998a, 1998b); knots have been considered as the major degrading factor of mechanical properties in structural timber (Kunesh & Johnson, 1972, Tustin & Wilcox 1978, Phillips et al. 1981, Grant et al. 1984, AS 2858: 1986, Pellicane et al. 1987, Barrett & Kellogg 1991, Madsen 1992, Walker 1993, Courchene et al. 1998, Nguedjio 1999); and high average microfibril angle has been acknowledged to be one of the key factors responsible for poor wood stiffness (Cave & Walker 1994, Walker & Butterfield 1995, Cave 1997a, 1997b, Evans & Ilic 2001). However, the mechanism regarding the contribution of structural features to mechanical properties is still far from fully understood. The major needs in wood structural mechanics are discussed in this paper.

Stiffness and Tensile Strength in Radiata Pine Stems

Radiata pine corewood (the first 10 growth rings from the pith) has been well known as struggling to yield structural timber due to the poor wood properties. However, the vertical variations of the characteristic mechanical properties in the radiata pine corewood have not been reported previously in detail. Recently, the lowest characteristic stiffness and characteristic tensile strength were found in the butt corewood zone (Fig. 1). More significant is that, based on machine stress grading and tensile testing, Xu and Walker (in press) identified an enlarged low-stiffness wood zone in the radiata pine butt logs. This low-stiffness wood zone did not overlap with the corewood, or rather, this low-stiffness wood formed a truncated cone from the base of the tree to approximately 3 meters up the stem (Fig. 2). A similar observation was found in Norway spruce (Perstorper 1996), but the volume of the low-stiffness wood cone in Norway spruce was insignificant compared to that in the radiata pine butt log.

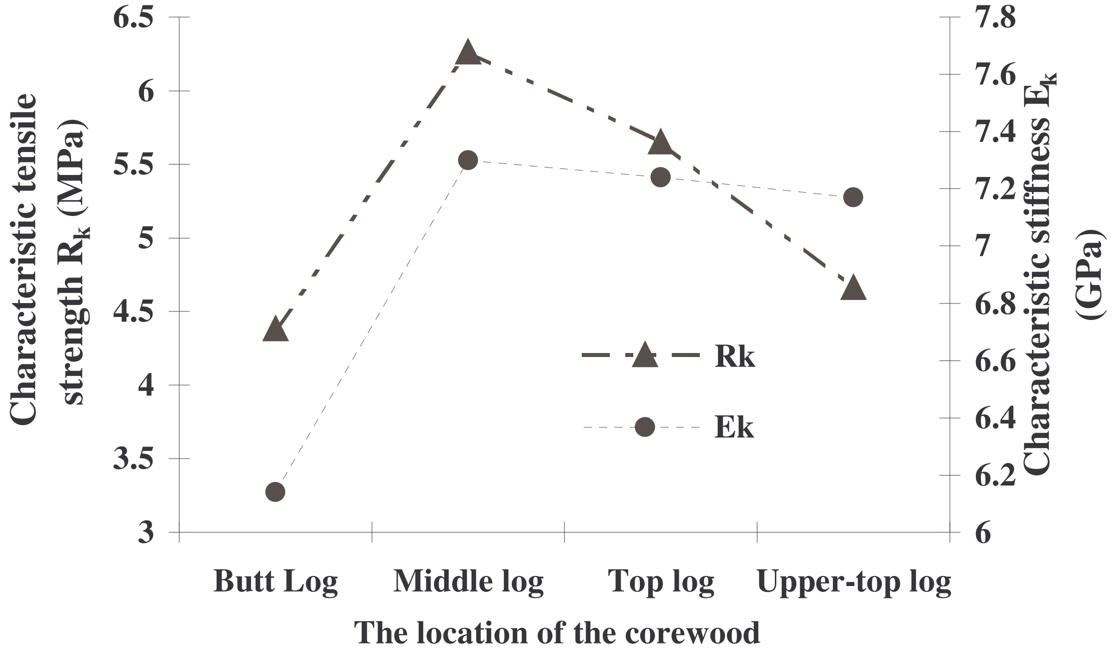

Fig. 1: Variations of characteristic tensile strength R_K and characteristic stiffness E_K in corewood according to log types (Test data obtained from boards located in P1 & P2, see Appendix, Fig. A and Fig. B).

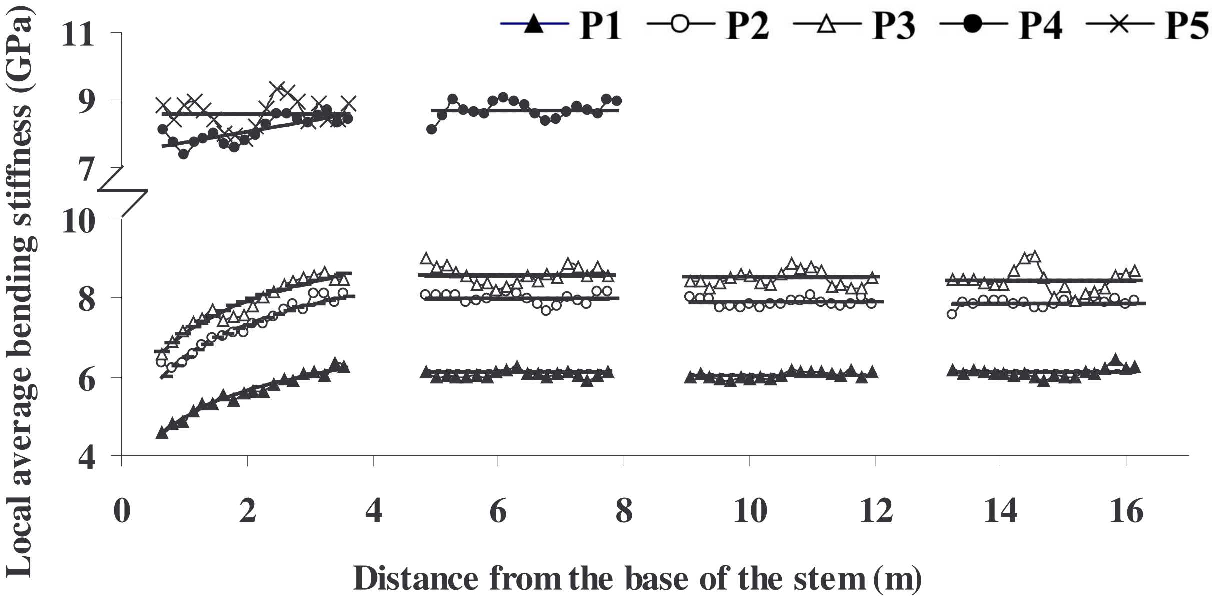

Fig. 2: Variations of average local bending stiffness within 62, 27-year-old, unpruned, radiata pine stems (quote from Xu & Walker, in press). Symbols P1, P2… indicate the locations of boards from the pith to cambium (Appendix, Fig. A and Fig. B). The dimension of every board was 90 x 35 x 4200 mm (width x depth x length).

The features of mechanical properties in the radiata pine butt log attract the attention of wood scientists: what is the explanation of the poorest characteristic mechanical properties in the butt corewood and what is the cause of the enlarged low-stiffness wood zone in the butt log. Obviously, wood density is not the explanation of the poorest characteristic mechanical properties in the butt corewood, since the basic density changed little along the vertical direction in the radiata pine corewood zone (Cown et al., 1991), or even slightly higher in the butt than in other corewood zones for air-dried samples (Tab. 1, Tsehaye et al. 1998). Regarding the cause of the enlarged conical low-stiffness wood zone in the radiata pine butt log, structural factors were suspected to be responsible (Xu & Walker in press, Xu 2003). It is known that higher microfibril angle leads to lower stiffness when density remains constant (Cave & Walker 1994); and the high-microfibril angle wood in the radiata pine butt log shapes similar to the distribution pattern of the low-stiffness wood (Donaldson 1992). However, the cause of this enlarged low-stiffness wood cone in the radiata pine butt log is still far from understood, which necessitates the study of structural mechanics in the radiata pine stems.

	Mean air-dried density (kg/m^3)	St.Dv.	Number of boards
Upper-top logs	442.79	38.69	218
Top logs	440.1	41.04	295
Middle logs	441.8	42.29	339
Butt logs	462.5	46.58	333

Tab. 1: Variations of average air-dried density of corewood according to log types in 62 radiata pine trees (test data obtained from boards located in P1 & P2 , see Appendix, Fig. A and Fig. B).

Stiffness and Tensile Strength In Radiata Pine Structural Boards

Degradation of structural boards due to knots is a major problem in timber processing. Generally there was a lower local longitudinal stiffness around a knot (Xu 2002), and nearly 99% of tensile tested boards failed at a knot zone (Xu et al. 2002).

The effect of knots weakening the stiffness and strength can only be attributed to the structure of the knot-contained zone rather than the wood mass around the knots. The extracted knotwood was denser than clearwood in radiata pine (Kininmonth 1961). However, along the longitudinal direction of a structural board, the local stiffness in the surrounding of knots was much lower than that in clearwood (Xu 2002). Figures 3 and 4 give the relationship between wood density, local failure stiffness and tensile strength. As with the observation of Walford (1981), the wood density around the weakest point of a structural board does not indicate the mechanical properties there.

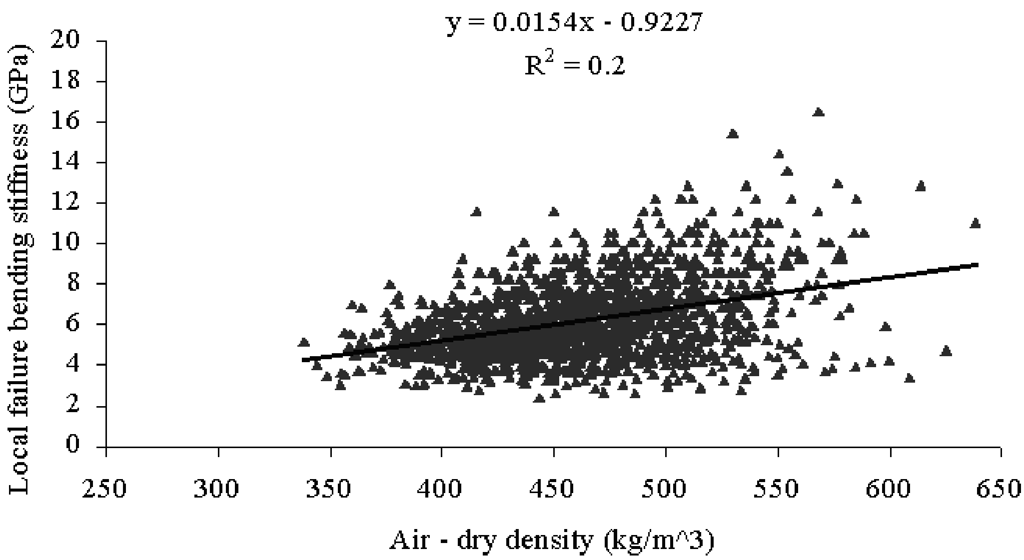

Fig. 3: The correlation between the air-dry density and the local failure stiffness $E_{P,\ fail}$ (data from 1589 boards, and small clearwood samples for density testing were cut from an adjacent zone to the failure point in each board).

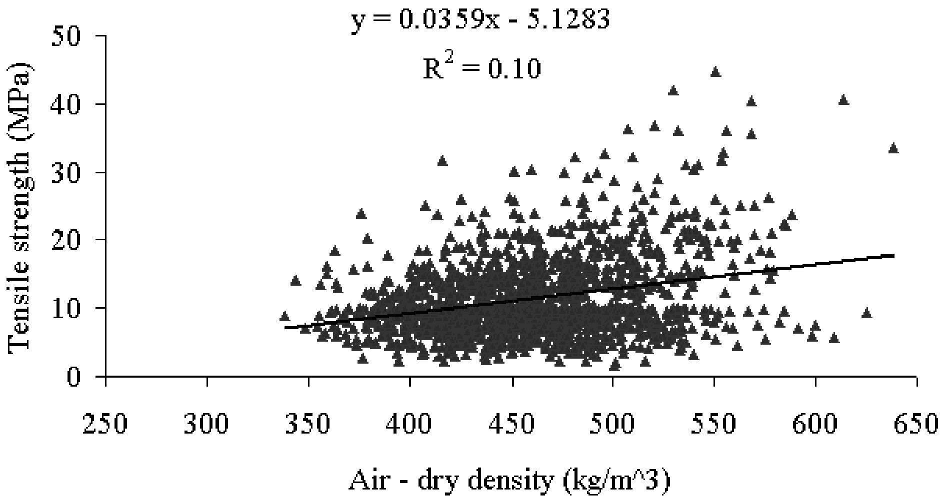

Fig. 4: The correlation between the air-dry density and the tensile strength (data from1589 boards, and small clearwood samples for density testing were cut from an adjacent zone to the failure point in each board).

The influence of structural factors associated with knots on the mechanical properties of structural timber has been a focus of wood scientists since the 1970s. Structural failure associated with knots has been interpreted previously by three hypotheses: i.e stress concentrations, knot area ratio (KAR), and local grain deviation. The stress concentration theory has been generally employed to describe the propagation of failure due to an internal or surface check that may result from drying in the knotty zone (Gordon 1978, Bodig & Jayne 1982, Cramer & Goodman 1983, Tang 1984). The stress concentration theory assumes that: "*In a homogenous specimen uniformly loaded in tension, the path by which stress is transmitted from one end of the specimen to the other can be represented by stress trajectories. In this case the load is borne uniformly throughout the specimen and all parts are equally stressed. However if the specimen contains a crack, or notch, or in the case of timber a knot, the stress trajectories have to find ways round and they tend to crowd the edge of the defect where the local stress can be much higher than the average value. The sharper the crack the greater the stress concentration. Although a round hole is a very blunt crack the stress concentration factor is 3 (at least in the case of metals)*" (Walker 1993). However, there is no experimental validation in previous literatures to show that the crack propagation actually commences from a drying check. The second hypothesis i.e. KAR theory treats a knot as a hole in the board, and the weakening of mechanical properties is from the reduction of the cross section area of board (Green & Zerna 1968, Walker 1993). In order to determine the KAR, the standards (AS 2858: 1986, NZS 3631: 1988) classified the knots as face, margin, edge and arris knots according to the knot location within the board and indicated the calculation methods of KAR. Based on the KAR theory, the maximum KAR in the board has been a major parameter used to judge the grade of structural timber in visual grading systems (AS 2858: 1986, BS 4978: 1988, NZS 3603: 1993). "*However, a single parameter, i.e., KAR alone, does not reliably indicate tensile strength, since there was no strong correlation between tensile strength and the maximum KAR ($R^2 = 0.21$), or tensile strength and the KAR at the actual failure point of the board ($R^2 = 0.19$)*" (Xu et. al. 2002). The third hypothesis, i.e grain deviation theory, considers the wood grain pattern associated with knots as fluid flows around an island, called the flow grain analogy (Goodman & Bodig 1980, Dabholkar 1980, Phillips et al. 1981). On the basis of the flow grain analogy, two-dimensional finite element analysis has been used to predict the stress associated with grain deviation around knots (Phillips et al. 1981, Cramer & Goodman 1983, 1986, Zandbergs & Smith 1988, Pellicane & Franco 1994). Naturally, this is a spatial problem, and inputting highly variable grain geometry into the finite element software requires far more computing power than that the researchers had. These researches therefore were rather superficial, and the validation has never been properly done due to the tricky grain slope variation in knotty region.

Currently, a theoretical model (Xu 2002) is being developed to evaluate the effective local longitudinal stiffness in a "mixed wood" (a combination of knotwood and stem wood) in terms of elastic moduli of all components, volume fractions of all phases and growth angle of knots (angle between branch and stem axes), which explains the reduction of stiffness in the knot-contained zones. In addition, 92% of the knot failure in tension was categorized as two patterns: either boundary-failure or plane-failure (Xu 2001). In boundary failure, the failure surface goes along the interface between knot and stem wood (Fig. 5, 6, 7). In plane-failure, the failure crosses the symmetrical plane of knot and the failure surface contains the pith of the branch (Fig. 8, 9, 10).

Fig. 5: The boundary-failure in a margin knot.

Fig. 6: The boundary-failure in an edge knot.

Fig. 7: The boundary-failure in a through arris knot.

Fig. 8: The plane-failure in a margin knot.

Fig. 9: The plane-failure in an edge knot.

Fig. 10: The plane-failure in a through arris knot.

An encased knot is almost completely separated from the adjacent stem wood because of the bark of the knot (Fig. 5, 6, 7). In this case, the tensile failure propagates along the boundary of the encased knots to form a boundary-failure pattern. An intergrown knot from a living branch may produce both boundary-failure and plane-failure. When the boundary of an intergrown knot is totally inside a surface of the board and there are not severe interior or surface checks in the knot, the failure is prone to follow a boundary-failure pattern. In other cases, an intergrown knot in tension may display a plane-failure pattern. Brittle pith is the weakest site on the symmetrical plane of a knot. An initial failure occurs where the symmetrical plane of a knot coincides with the plane of drying stress concentration (Kininmonth 1961, Liu 1998). Therefore, brittle pith, drying damage and stress concentration on the symmetric plane of a knot may be the causes of plane-failure.

Further structural mechanical analysis is expected to quantitatively clarify where a structural board may break and which pattern of a failure may follow. This knowledge will greatly benefit the improvement of timber visual stress-grading system, thus forest industry.

Stiffness and Strength in Individual Wood Cells

Wood cell wall consists of cellulose microfibrils embedded in a lignin-hemicelluloses matrix with the microfibrils coiled in a helix-like path within the cell wall (Yamamoto & Kojima 2002). The influence of cell structure on cell mechanical properties has been a multidisciplinary research (Treloar 1960, Hearle 1963, Mark 1967, Jaswon et al. 1968, Cave 1968, 1969, Schniewind 1972, Bodig & Goodman 1973, Preston 1974, Bodig and Jayne 1982, Yamamoto & Kojima 2002). It has been reported by many authors that an increase in microfibril angle generally leads to a lower wood stiffness (Cave & Walker 1994, Walker & Butterfield 1995, Cave 1997a, 1997b, Tsehaye et. al. 1998, Navi 1998, Evans & Ilic 2001). **HOWEVER, THE STUDY OF STRUCTURAL MECHANICS AT THE LEVEL IN RELATION TO WOOD CELLS IS STILL IN ITS INFANCY** as addressed below.

First of all, the significance regarding the influence of cell ultrastructure on wood strength has not been emphasized. Secondly, there are some gaps in the study of cell structure-stiffness. The study of cell structure-stiffness includes understanding and quantifying the contributions of various structural factors, such as microfibrils, cellular matrix, microfibrils orientation, and the volume fractions of all phase, to cell stiffness. However, among all cell structural factors, only the mean microfibril angle has been emphasized in recent years. The predictive model of mean cell stiffness in terms of mean microfibril angle (Cave 1968, 1969) has been frequently used in recent years. However, the predicted cell wall stiffness arising from Cave's microfibril elasticity model showed a considerable disparity with his experimental results at lower microfibril angles (Fig. 11). Finally, there are some limitations of techniques for determining the spatial arrangement of microfibrils and the influence of the helix of microfibrils on cell stiffness and cell strength. All these certainly hampered the progress of wood cell structural mechanics.

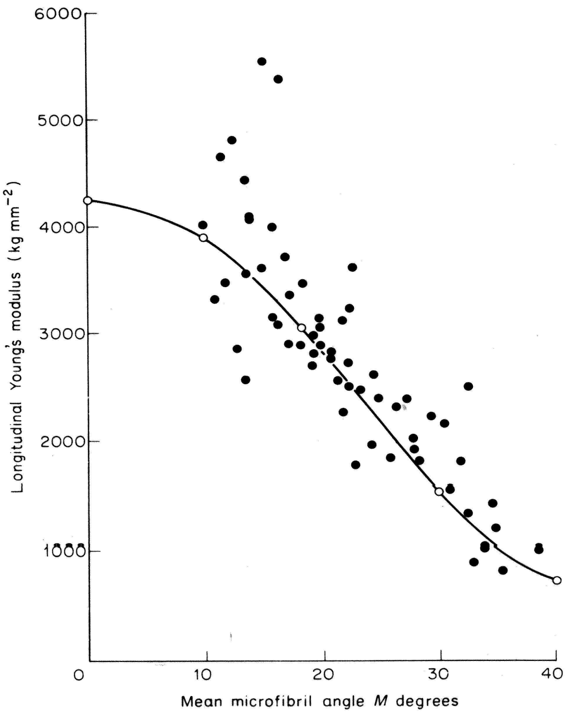

Fig. 11: The predictions and measurements of cell wall stiffness vs. mean microfibril angle (after Cave, 1968). Note: —o—represents the theoretical curve; • represents the experimental data.

Summary

Three topics require immediate attention in wood structural mechanics: the cause of the worst juvenile wood in trees, the weakening of timber mechanical properties due to knots, and the influences of cell morphology on cell stiffness and cell strength.

The butt log is valuable because of its larger size, higher density, and relatively stronger and stiffer outerwood. However, the poorest characteristic mechanical properties in the corewood and an enlarged low-stiffness wood zone may offset the advantages of the outerwood in the butt logs. The problems will be more serious with the rapid increase of juvenile wood proportion due to the reduction of rotation age of radiata pine. A thorough structural mechanics study on the cause of the low-grade structural material will be useful for the genetic selection, modification and breeding program to improve radiata pine wood properties.

Knots significantly weaken the mechanical properties in structural timber. Current research has demonstrated the local stiffness around a knot in terms of growth angle of branch and the volume fraction of knots, which partially explains why the stiffness in denser knotty zones is far lower than that in adjacent clearwood. The quantitative influence of grain deviation on stiffness requires further investigation to formulate a complete theory. KAR alone is poorly correlated to the tensile strength, which reveals that KAR is not the dominant structural factor for the weakening of timber strength around knots. Further investigation involving additional structural factors requires an extensive structural mechanics study, which is useful for improving the timber visual grading system and helpful to code writers.

The wood cells are basic elements of wood-based biomaterials. Determining key ultrastructural factors affecting the cell properties is fundamental for genetic engineering and will create a solid knowledge base to underpin the breeding program and potential genetic modification, and will thereby benefit forest industry.

Acknowledgements

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Appendix

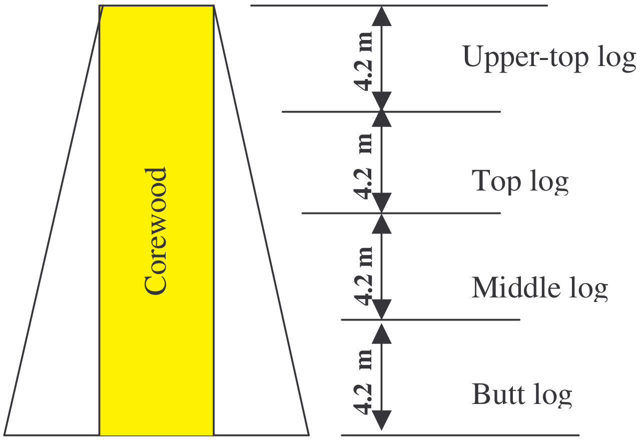

Fig. A: Cutting pattern of stems.

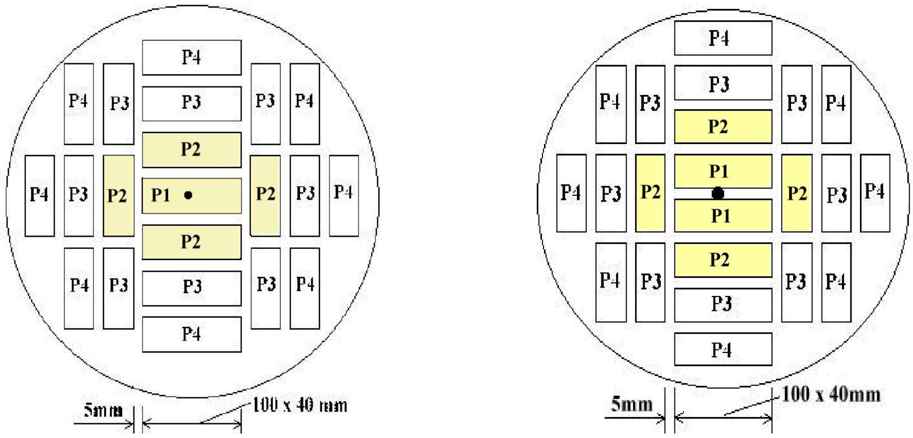

Fig. B: Sawing patterns of logs.