**EFFECT OF MOISTURE CONTENT ON THE MORPHOLOGY OF LONGITUDINAL FRACTURE IN EUCALYPTUS MACULATA**

by

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**Summary**

The longitudinal surfaces of *Eucalyptus maculata* wood samples fractured either artificially (splitting) or naturally (drying stresses) at a range of moisture contents, were examined under a scanning electron microscope. In those samples above fibre saturation point, a relatively clean surface was produced, since the cells either separated in the outer regions of the wall with minimal fibrillation (fibres, some ray parenchyma), or the fracture path travelled abruptly through the wall exposing the lumen (vertical parenchyma, vessels, some ray cells). Below fibre saturation, particularly as the air dry condition was approached, a fibrous, splinterly surface resulted, due mainly to fibrillation and delamination of the secondary walls in fibres and ray parenchyma.

**Key words: Eucalyptus, moisture content, fracture, wood anatomy, cell wall structure, microscopy.**

**Introduction**

Knowledge of the morphology of fracture in wood is important not only in explaining the development of shake and the mechanical properties of timber (DeBaise et al., 1966; McGinness et al., 1974, 1976), but also in enhancing understanding of the chemistry and ultrastructural arrangement of the secondary xylem cell walls (Wardrop, 1951; Wardrop & Addo-Ashong, 1965) and the properties of mechanical and semi-mechanical pulps (Lagergren et al., 1957; Koran, 1967, 1968). Many earlier studies concentrated on the effect of temperature on the pattern of fracture. With increasing temperature, e.g. 0–200°C, there is an increasing proportion of clean 'intrawall failure' (continuously within the cellular double wall as compared with 'transwall failure' which exposes the lumen), and decreasing delamination and fibrillation of the wall structure (Koran, 1967, 1968; Ohsawa & Yonedo, 1978; Woodward, 1980). Some observations (Wardrop, 1951; DeBaise et al., 1966; Cousins, 1974) point to a parallel effect of wood moisture content as it increases to fibre saturation point (c. 28%), but this topic remains largely unexplored. Thus, as part of a broader program of investigation of ring shake in *Eucalyptus* species (e.g. Wilkes, 1986), the effect of wood moisture content on fracture morphology is examined here for *E. maculata* Hook. (spotted gum). This species has a hard, dense, strong timber of considerable commercial importance.

**Material and Methods**

Examination of fracture surfaces, using a scanning electron microscope, was completed in two phases.

1. **Natural shakes.** – Fifty railway sleepers (ties), 90 x 175 x 2400 mm, were air dried in an exposed position for five months in summer. Of these, 10 which displayed both ring (tangential) and ray (radial) shakes at either end were selected. The larger fractures extended more than 200 mm axially, and typically, 30–80 mm in the transverse direction. Most of the separations were assumed to have resulted from drying stresses. Occasional shakes, detected in the very early stages of drying, apparently originated in the living tree or as a result of felling stresses, and were not assessed here.

A cross section, 25 mm deep, was cut 50–75 mm from one end of each sleeper where separation was evident in both the radial and circumferential directions. The central regions of these shakes were distinguished from their outer [tangential (ring shake) or radial (ray shake)] extremities. The shakes enlarged slowly during drying, and thus in the central (older) areas, fracture occurred in wood at a higher moisture level than in the outer (fresher) areas; geometric determinations on selected samples indicated that the relevant moisture contents were c. 30–50% and c. 8–15% respectively. The fracture surfaces (5 x 5 mm) of a minimum of six blocks (two 'old', two 'fresh', two 'intermediate'), from both a ring and a ray shake in

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each of the 10 cross sections, were coated with 20 nm of gold and examined under a Cambridge Steroscan electron microscope. At any position, at least one sample block was cut from each of the complementary faces.

2. Failures induced artificially. — Two blocks, 5 x 5 x 5 mm, were cut from larger samples of clear, green (moisture content c. 60–80%) heartwood tissue of the 10 selected sleepers. At room temperature (20°C), a knife was used to split one block in the radial, and the other in the tangential direction. Following air drying, the newly exposed faces were coated and examined.

The morphology of fracture was assessed at three levels:

a. The consistency of the plane of separation.
Fracture surfaces were examined at low magnification (20–25 x) to determine the frequency and extent of changes in the plane of failure at the gross cellular level.

b. The type of separation at the individual cell level. The frequency of intrawall and transwall failure in each cell type was noted.

c. The course of the separation in cell wall substance. The amount of delamination and fibrillation in the wall structure was recorded. In the case of intrawall failure, the location of the separation in the cellular double wall, and the frequency at which the fracture crossed individual lamellae within each layer of the secondary wall, was determined.

Results

The morphology of the naturally occurring and artificial fractures was essentially similar; ‘old’ and ‘fresh’ surfaces of the shakes formed during drying closely resembled those produced by splitting the green and air dry specimens respectively. Additionally, the pattern of fracture in each of the vertical cell types was similar on the radial and tangential faces, and it is only for the ray cells that the direction of separation need be defined.

Low magnification views of tangential-longitudinal surfaces resulting from failure at the high (> fibre saturation) and low (air dry) moisture conditions are shown in Figures 1 and 2 respectively. The surface produced at the higher moisture level is much cleaner than that developed in the drier wood, a difference largely attributable to a contrasting pattern of fracture within fibres. Above fibre saturation, such cells separated by relatively clean intrawall failure in the outer regions of the cell wall (Fig. 3), while a complex mixture of intrawall and transwall failure occurred in the drier tissues (Fig. 4). The clean intrawall separation usually formed in the outer (S₁) layer of the secondary wall (Fig. 5), as suggested by the microfibrillar angles of 40–70° on the exposed surface; less commonly it occurred in the compound middle lamella. The path of fracture sometimes jumped across lamellae of the S₁, and even from the layers P( primary)-S₁ of one cell to those of an adjoining element. At lower moisture contents, fibres failed within, between and across all wall layers, resulting in extensive delamination and fibrillation (Fig. 6). Separation between the layers S₁ and S₂ was particularly common.

A contrast in the pattern of fracture of the ray parenchyma at high and low moisture contents also contributed to the difference in the overall appearance of the tangential surfaces produced. In the moister wood, ray parenchyma either broke cleanly, or pulled away exposing the end wall of an adjacent cell (Fig. 3). In the latter situation, a cell protruded from one complementary face while a cavity was produced in the other. At low moisture contents, ray cells neither pulled away (Fig. 4), nor fractured cleanly (Fig. 6). The helical orientation of fibrils was often exposed. This behaviour of the ray parenchyma was confirmed on observation of the radial faces. Where separation occurred in timber which was green or in the early stages of drying, both intrawall and transwall failure were common (Figs. 7, 8). The former occurred at the compound middle lamella, giving a smooth surface to the exposed parenchyma (Fig. 7), while the transwall failure was normally clean (Fig. 8). However, in the drier wood, ray cells fractured within and across the secondary wall layers, producing a spiralling, fibrillated surface with the microfibrils orientated at a large angle to the longitudinal axis of the cell (Fig. 9).

Failure in vessels and vertical parenchyma was less affected by wood moisture levels. Transwall failure consistently predominated, although some clean intrawall separation at, or near, the compound middle lamella, was apparent where fracture occurred at high moisture contents (Fig. 1). The transwall failure was of two types: diametral splitting [vessels (Figs. 1 & 2), some parenchyma (Fig. 10)], or a shattering of the cell wall [some parenchyma (Fig. 11)]. In both cases the fracture was clean, with little evidence of delamination or fibrillation. It was commonly difficult to detect any fibrillar structure in the wall (Fig. 11).

The blocks taken from the intermediate positions on the natural shake surfaces were intermediate in appearance between those from the high and low moisture content positions. However, as the wood dried, the change in the pattern of fracture apparently occurred more quickly in fibres than in ray parenchyma, i.e., at certain intermediate moisture levels, separa-
Fig. 1. Clean tangential-longitudinal surface (TLS) resulting from artificial fracture of green wood. The vessels show both intrawall failure (small arrow) and transwall failure (large arrow). — Fig. 2. Splintery TLS resulting from artificial fracture of an air dry sample from the same timber shown in Figure 1. — Fig. 3. Relatively clean intrawall failure in fibres (small arrow) and certain of the ray parenchyma cells (large arrow). Other ray cells show abrupt transwall failure. The fracture occurred naturally in the early stages of drying. — Fig. 4. Surface of the same shake shown in Figure 3, but at a marginal position. Considerable fibrillation (small arrow) and delamination (large arrow) is evident. — Scale bar: Figs. 1 & 2: 100 μm; Figs. 3 & 4: 30 μm.

Discussion
The predominance of clean intrawall failure in the outer wall regions of the fibrous elements of spotted gum separating at moisture contents above fibre saturation parallels other observations on shake in living trees (Meyer & Leney, 1968; McGinnes et al., 1974, 1976). In fibres, the change from a fibrillated to a clean break with increasing moisture levels (< fibre saturation) is similar to the reported effect of increasing temperature (Lagergren et al., 1957; Woodward, 1980). Possibly the trend results from a
Fig. 5. Fibres showing minimal damage where failure has occurred naturally in the early stages of drying. Arrows show positions where the fracture path has 'stepped' across lamellae of the secondary wall. Ray parenchyma cells have broken relatively cleanly. — Fig. 6. Complex combination of transwall and intrawall failure in fibres where separation has occurred in the later stages of drying. Ray parenchyma cells have not broken cleanly. — Fig. 7. Radial longitudinal surface (RLS) produced near the point of initiation of a drying shake. In ray parenchyma, intrawall separation at the compound middle lamella is clean (arrows). — Fig. 8. Transwall separation in ray parenchyma artificially fractured in the green condition. Fibrillation is not apparent and delamination (arrow) is minimal. The cells contain polyphenolic matter. — Scale bar: Figs. 5, 6 & 8: 10 μm; Fig. 7: 30 μm.

softening (plasticising) of the lignin (encrusting) and/or hemicellulose (matrix) materials in the outer wall layers of low density. Water molecules frequently occupy hydrogen bonding sites in wood which might otherwise be involved in the interbonding of wall constituents (Wardrop & Addo-Ashong, 1965). Lignin has fewer of the sorption sites than hemicellulose (Panshin & De Zeeuw, 1980), which is consistent with the fracture of fibres and tracheids at high moisture contents in the layer S₁ (Fig. 5; Koran, 1967, 1968; Cousins, 1974; Woodward, 1980) where the concentration of the hemicelluloses is higher, and that of lignin lower, than in the middle lamella (Panshin & De Zeeuw, 1980). The intrawall failure in ray parenchyma was at the middle lamella (Fig. 7), perhaps reflecting quantitative (Wardrop & Addo-Ashong, 1965),
Fig. 9. RLS produced when air dry wood was split. Separation has occurred at various positions within the secondary wall of the parenchyma, and in one area, the lumina containing polyphenolic matter are exposed (transwall failure). — Fig. 10. Tangential failure through a region of axial parenchyma in the green condition. There is little evidence of delamination or fibrillation in these elements which have split diametrically. — Fig. 11. Region of axial parenchyma fractured in the radial direction when green. The cells have shattered, but fibrillation is minimal. Ray parenchyma (bottom) have behaved similarly. — Fig. 12. RLS showing differential behaviour of fibres and ray parenchyma where separation has occurred at an intermediate moisture content. The fibres have fractured in the secondary wall (predominantly S₁), while many of the ray parenchyma continue to show clean intrawall failure in the middle lamella region (arrow). — Scale bar: Figs. 9 & 10: 20 μm; Figs. 11 & 12: 50 μm.

or even qualitative, variation in lignin/cellulose deposition between cell types in spotted gum.

While in this study the exact moisture content at a particular point of fracture was not always known, it appears that fracture morphology is affected by variations in wood moisture content only below fibre saturation point; the surfaces of samples split green (moisture c. 60–80%) were indistinguishable from those of the older areas of the natural shakes (moisture at failure c. 30–50%). This accords with the belief that it is only the bound water in the cell wall which affects the physical properties of wood such as strength (Panshin & De Zeeuw, 1980).

The prevalence of transwall failure in vessels and axial parenchyma probably reflects the low Runkel ratio (double wall thickness/lumen
diameter) of these cell types [<0.1, <0.2 respectively (Wilkes, 1986)]. Intrawall failure in these cases would involve the fracture of a much greater area of wall substance. Nevertheless, within actual wood substance, separation between wall layers/ lamella (intrawall path) presumably requires less energy per unit area fractured than does breakage across the layers (transwall path).

The limited studies of the wall structure of vessels and parenchyma suggest it to be quite variable. Wardrop (1964) notes that in some woods, the secondary wall of parenchyma consists of three layers, superficially resembling those of fibres and tracheids. However, in other species the layering is often complex, particularly when cells are sclerosed (Wardrop & Dadswell, 1952; Wardrop, 1964; Chafe & Chauret, 1974). While such complexity is not a feature of Eucalyptus (Wardrop, 1964), the present results suggest a difference in secondary wall arrangement and composition between fibres and non-fibrous cell types in spotted gum, e.g. a distinctive fibrillar structure was not apparent in vertical parenchyma when fractured either green (Figs. 10, 11) or air dry. The differing patterns of fracture in fibres and ray parenchyma at the intermediate moisture contents (Fig. 12), despite certain similarities in the patterns at the upper and lower ends of the moisture range tested, also suggests variation in cell wall composition between cell types. Both average fibrillar angle and lignin content are often greater in parenchyma cells than fibres (Wardrop & Addo-Ashong, 1965; Wardrop, 1964). Differences in cell wall chemistry and ultrastructure between vertical and ray parenchyma cells are also evident in this work, e.g. fibrillation was minimal in the axial (as compared with ray) elements fractured air dry.

In addition to wood moisture content and temperature, factors such as the type of stress (compression, tension, shear), the direction of stress, and strain rate can appreciably influence fracture morphology (Wardrop & Addo-Ashong, 1965; DeBaise et al., 1966; Cousins, 1974). The marked similarities between the natural and artificial fracture surfaces in spotted gum may indicate that this species is less sensitive to certain of these factors than are some other woods.

Conclusions

As the moisture content of Eucalyptus maculata timber decreases from fibre saturation to the air dry condition, fracture along the grain involves decreasing amounts of clean intrawall or transwall failure, and increasing delamination and fibrillation of the wall structure of fibres and ray parenchyma. This effect, which was not common in vertical parenchyma and vessels where clean transwall separation always predominated, is probably attributable to an increase in hydrogen bonding between macromolecules.

References


