MICROMECHANICS OF PERMANENT DEFORMATION
IN SOFTWOOD

C.Y. Barlow and J. Woodhouse

University of Cambridge, Engineering Department,
Trumpington Street, Cambridge CB2 1PZ, England

ABSTRACT

Permanent deformation of wood by bending is called for in various processes of manufacture. It is sometimes important to know whether the material properties have been significantly modified: for example the effective Young's moduli, the density or the fracture toughness. Any variation in these quantities will depend on the mechanism(s) of permanent deformation at the cellular level. Possible mechanisms are identified for softwood (which has simpler cell structure than hardwood), and the behaviour to be expected from them is investigated using the theory of honeycomb structures. These are then compared with results from small beam specimens of Norway spruce (*Picea abies*) which were bent under constant load around a cylindrical rod, using either ammonia or steam to encourage plastic deformation. Changes in effective Young's modulus were monitored by vibration tests, and microstructural deformation was examined by scanning electron microscopy.

1. INTRODUCTION

In some uses of wood, for example in furniture or boatbuilding, curved shapes are made by plastic deformation of originally flat timber. One particular example has attracted some attention recently: it has been suggested that the arched front and back plates of violins might originally have been made not by carving from the solid, as is now usual, but by bending (Fulton 1992). For this application, it might be of some importance if the vibrational properties of the wood were altered by the permanent deformation, or if residual damage was caused which could increase the risk of macroscopic crack formation during the lifetime of the violin.

The rather simple cellular structure of softwood, together with the fact that violin tops are for preference made from Norway spruce (*Picea abies*), makes this a natural candidate for an initial study. The vast majority of the cells are tracheids, which run axially in the tree (designated the L direction). They are needle-shaped, with length-to-diameter ratios of the order of 15. The tracheids fit together to form an irregular honeycomb in the RT plane (R denoting the radial direction in the growing tree, T the circumferential direction), whose properties are modulated in the radial direction by the annual growth rings. The tracheids are "glued together" by a layer of amorphous material, mainly lignin, called the middle lamella. Spring growth produces large-diameter tracheids with thin walls, but as the growing season comes towards its close the cells become progressively smaller in radial extent and thicker-walled, until growth stops. The following season it resumes, giving an abrupt change of structure to the large, thin-walled spring-

wood cells. The only cells in spruce which do not run axially form the rays. Ray cells are less substantial than tracheids, and are aligned radially, cutting across the honeycomb of tracheids. One ray consists of a stack of about ten cells atop one another in the L direction, only a single cell thick (in the T direction). In Norway spruce, ray cells make up only about 2% of the total.

2. DEFORMATION MECHANISMS

Several different mechanisms of plastic deformation in bending can be envisaged:
  (a) permanent deformation distributed more or less uniformly throughout the sample volume, mirroring the pattern of linear elastic deformation (Gibson and Ashby 1988);
  (b) localised regions of more extreme deformation, with gross buckling of cell walls to form bands in which the predominant pattern might be either shear or collapse mediated by rotation at nodes with little overall shear;
  (c) sliding of layers of cells over one another, perhaps by plastic flow in the middle lamella;
  (d) pulling apart of adjacent cell walls by failure of the middle lamella in tension or shear;
  (e) macroscopic buckling, causing formation of localised "plastic hinges".

These mechanisms would have very different consequences for the post-deformation material properties. Mechanism (a) might have relatively little effect, although the deformation of initially-straight cell walls into permanent S-shapes would reduce the effective Young's moduli in the RT plane. This strain-softening tendency is responsible for the possibility of mechanism (b). Collapsed bands in the wood would have much lower stiffness to further deformation, so would constitute "weak links" in the structure. This would reduce the macroscopic Young's moduli, by an amount depending on the pattern of deformation and the volume fraction occupied by such bands. The magnitude of this reduction could be estimated quantitatively using honeycomb theory (Gibson and Ashby 1988), with an appropriate aggregating procedure (Kahle and Woodhouse 1992). The reduced stiffness of collapsed bands would simply add in series with that of the stiffer undamaged material. If collapse were sufficiently complete to cause local densification, however, this conclusion would be modified. Further elastic strain in the same sense as the plastic deformation would be resisted by contact in the densified region, but reversed strain might encounter relatively little resistance. This could cause nonlinearity of macroscopic response.

Mechanism (c), if geometric compatibility of cell-wall patterns allowed it to occur without leaving voids by mechanism (d), might change the properties very little provided the middle lamella recovered its strength after the plastic deformation ceased. Mechanism (d) would produce several effects on the macroscopic properties, most of them detrimental: the residual microcracks are likely to reduce fracture toughness; friction between the detached cell walls might increase vibration damping; and the effective Young's moduli will be reduced. Finally, mechanism (e) would indicate a failure of the intended forming process. If deformation occurs at local plastic hinges, the new shape will be polygonal rather than smoothly curved. The hinge regions will be much less stiff than the rest of the material, and are likely to contain residual damage which makes them possible sites of fatigue fracture.

For uniaxial deformation in the RT plane, the behaviour of wood is very dependent on the angle to the annual rings. There is some anisotropy between the R and T principal directions (about a factor of 1.7 in Young's modulus, mainly due to the pattern of cell growth and the influence of the annual rings) but a much stronger effect is observed in intermediate directions. Because the RT-plane shear modulus has a very low value, the effective Young's modulus at 45° to the principal axes is an order of magnitude smaller than the maximum value (in the R direction) (McIntyre and Woodhouse 1988, Fig. 1). This sensitivity to orientation is likely to carry over to plastic deformation. For a specimen cut at a significant angle to the R axis, both the tension and compression sides during bending might be able to deform substantially by local shearing. The opposite extreme is a "quarter-cut" sample, aligned exactly in the R direction. When bent, the compression side will probably exhibit small-amplitude deformation of the near-radial cell walls into S-shapes, or catastrophic buckling of those walls. The equivalent deformation on the tension side will involve stretching zig-zag lines of cell walls, but such motion is subject to a form of strain hardening as the lines pull straight, and tension failures of the middle lamellae might occur if strains become too large.

3. EXPERIMENTAL PROCEDURE

To test these ideas and determine which mechanisms actually operate, experiments were carried out on small beam samples of air-dried Norway spruce. Three sets of specimens were prepared: series 1, of nearly quarter-cut samples, approximately 7° to the R direction in the RT plane; series 2, samples at 20° to the R direction in the RT plane; and series 3 in the L direction. In order to see the deformation clearly, rather thick specimens were desirable. Plastic deformation was achieved by bending the samples around a cylinder of diameter 25 mm, using a symmetrically-placed flexible strap with a weight suspended from it. Sample dimensions were then governed by the maximum stress which could be applied without immediate fracture, and by the size of the environmental chamber available. The samples of series 1 had dimensions 30×6.5×5.8 mm (the last being the through-thickness dimension for bending), those of series 2 30×6.5×5.3 mm, and those of series 3 30×6.5×1.6 mm. A weight of 2 kg was used for loading.

Under ambient conditions, this loading produced negligible plastic bending. Two environments were used to encourage deformation: ammonia gas at ambient temperature, and 100% humidity at a temperature of 80°C. Both produced significant bending in the samples of series 1 and 2 (through about 30°) within 12 hours. Control samples were exposed to the same environments without load. The samples of series 3 did not deform as required: they invariably failed by mechanism (e), with a single sharp crease forming across the width. A more tightly-constrained method of bending would appear to be necessary for L-direction samples, and they are not discussed further in this study.

To monitor changes in effective Young's modulus, measurements were made of the fundamental frequency of free-free bending vibration. As a direct measure of Young's modulus this would not be expected to be very accurate for samples of such high thickness-to-length ratio with unknown through-thickness shear behaviour. However, changes in frequency before and after plastic bending give a direct indication of changes in modulus (after allowance for any weight change), the control samples revealing whether such changes are due in part to the effect of the environment alone. (Curvature itself also influences frequencies, but with such relatively modest curvature the effect is small.) The frequencies in question lay in the range 4–11 kHz, and required some care to measure reliably with such small samples. Following impulsive excitation, the radiated sound was registered by non-contacting microphone while a sample was in free fall. The signal was recorded by digital data-logger and subjected to normal FFT analysis to identify the required mode frequency in each case.

After the vibration measurements, each specimen was prepared for scanning electron microscopy. Clean cuts were made to reveal appropriate regions of the cell structure, and the specimens were gold-coated. Careful examination was made in the SEM to look for evidence of the various deformation mechanisms listed above (or indeed of any others not anticipated). Photographic montages were prepared to show sufficiently large areas that the volume fraction of severely deformed cell structure could be estimated.

4. RESULTS AND DISCUSSION

The measured properties of the specimens as prepared were as follows:

	Series 1	Series 2	Series 3
Density	466 kg/m^3	435 kg/m^3	466 kg/m^3
Young's modulus	0.50 GPa	0.30 GPa	13 GPa

The difference in Young's modulus between series 1 and series 2 is broadly in keeping with their different angles of cut, according to orthotropic elasticity theory (McIntyre and Woodhouse 1988, Fig. 1).

After bending, the Young's moduli of all RT-plane specimens was reduced significantly. The series 1 samples gave values of about 0.32 GPa after bending in ammonia, and about 0.37 GPa from heat/humidity. The series 2 samples gave values around 0.25 GPa with both environments for bending. In calculating these estimates, allowance has been made for the fact that in some cases the specimen thickness was reduced during bending, due mainly to gross shearing motion.

Such a reduction of course implies a corresponding increase in density. It occurred to a marked extent in all samples plasticised by heat/humidity, but very much less with ammonia as the plasticising agent.
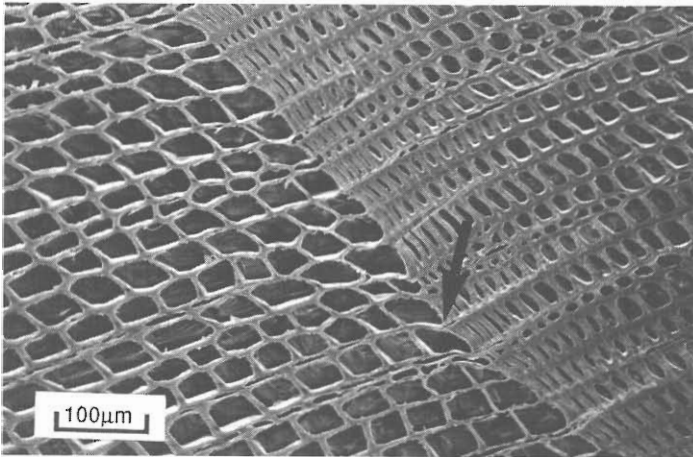

Fig. 1. Specimen from series 2, showing shear deformation in the thin-walled early spring wood to the left of the annual ring (arrowed). Only the densest summer wood, closest to the ring boundary, is relatively undeformed. Note that a typical cell diameter in spring wood is about 40μm.

The mechanisms of deformation are illustrated with a series of micrographs. Among the various specimens, examples were found of all the mechanisms previously listed, except (c): no clear evidence of gross sliding of layers of cells over one another was found. Specimens from series 2 deformed predominantly by mechanism (a) in both plasticising environments. Because of the angle of cut, macroscopic bending could occur by shear deformation, mainly in the thin-walled cells of the spring growth. This was equally true of the tension and the compression sides of the specimens. Figure 1 shows a typical example: an obvious discontinuity in the angle of the lines of cell walls occurs at the annual ring boundary, where largely undeformed summer growth gives way to sheared spring growth. Not much strain-softening is associated with this pattern of deformation, which explains why the effective Young's modulus of the series 2 specimens was changed relatively little.

The specimens of series 1 deformed by different variants of mechanism (b) in the two plasticising environments. In ammonia, rather narrow collapsed bands were formed, with relatively undeformed material around them. Again, the deformation occurred mainly in the spring growth, but was confined largely to the compression side of the specimen. A typical example is shown in Fig. 2, where two distinct collapsed bands are evident. In the heat/humidity environment, behaviour was rather different. Large areas of the spring growth on the compression side of the
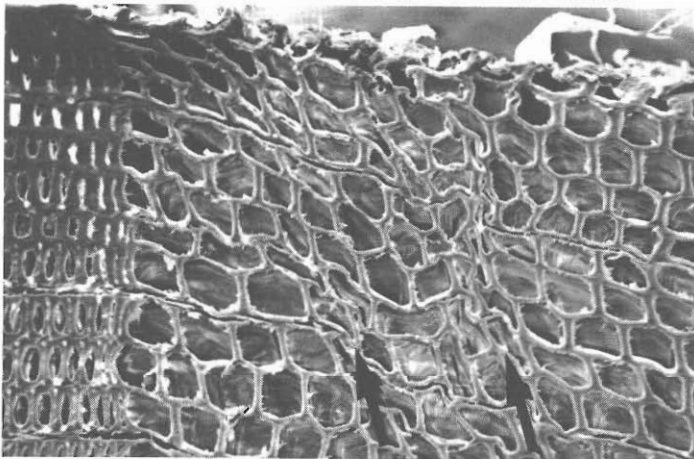

Fig. 2. Specimen from series 1, plasticised in ammonia. Two bands of collapsed cells (arrowed) are evident in the early spring wood.

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specimen had collapsed completely. It appears that some strain-softening mechanism is operating strongly in the ammonia environment, tending to concentrate collapse in bands, whereas with heat/humidity any such mechanism is less effective and collapse occurs over a wider area of the RT plane. An example is shown in Fig. 3. Here, two complete annual rings are seen, and there is a broad band of collapsed cells in the early spring growth in both. Both deformation patterns for these series 1 specimens involve significant strain softening in the collapsed regions, which accounts for the relatively large reduction in effective Young's modulus, compared with that found for the series 2 specimens.
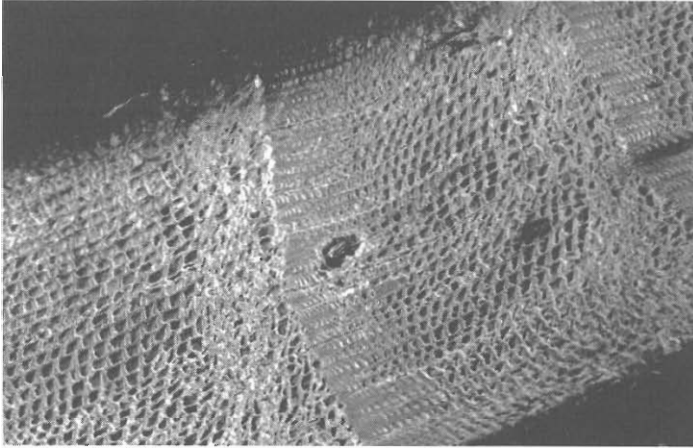

Fig. 3. Specimen from series 1, plasticised with heat/humidity. Two complete annual rings are visible, and there is a broad band of collapsed cells in the early spring growth of both.

Failure of the middle lamella, mechanism (d), occurs in all samples plasticised with ammonia, but only very rarely when heat/humidity is used. A typical pair of examples appear in Fig. 4(a) and (b). Both come from specimens of series 2. The tendency of cells to "pop apart" along the middle lamellae after treatment with ammonia is very obvious in Fig. 4(a), whereas one can barely discern the middle lamellae in Fig. 4(b). It seems very clear that damage of the kind revealed in Fig. 4(a) would be very undesirable in a structural member of any kind, and certainly in a violin plate. With age and cycling of environment and stress, one might expect the inter-cell cracks to grow until the wood literally fell apart — such behaviour is indeed sometimes encountered in old wood.

Finally, as has already been noted, the long-grain specimens of series 3 deformed by mechanism (e), with localised macroscopic buckles creating sharp bends. An example is shown in Fig. 5. Very strong deformation is evident, extending through about 1/3 of the specimen thickness in a localised region. Study at higher magnification revealed that the individual cell walls in this region had failed by forming kink bands (Dinwoodie 1989), leaving them very much less stiff. This is the strain-softening mechanism which causes an instability leading to the formation of the localised plastic hinge.
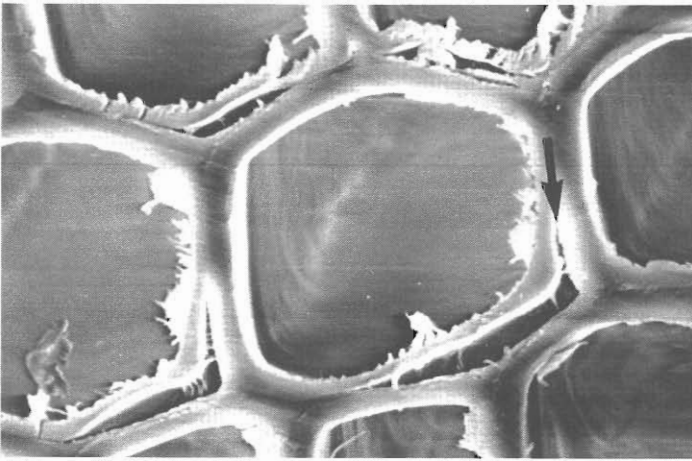
Fig. 4(a). Specimen from series 2 plasticised with ammonia, showing failure of the middle lamellae, for example along the line arrowed.
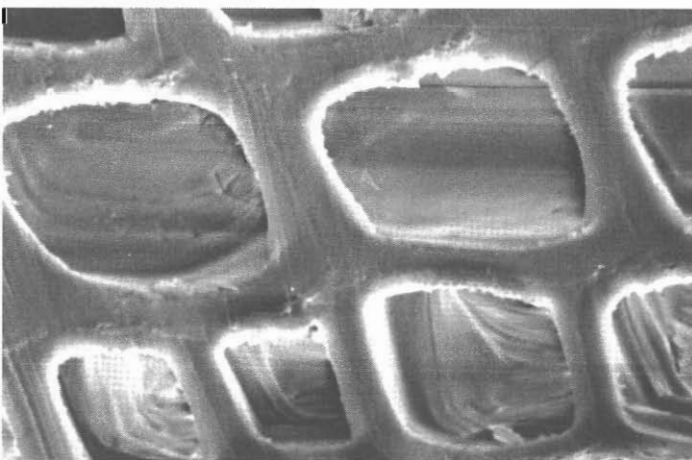

Fig. 4(b). Specimen from series 2 plasticised with heat/humidity, at the same magnification as Fig. 4(a), showing no significant failure of the middle lamellae.
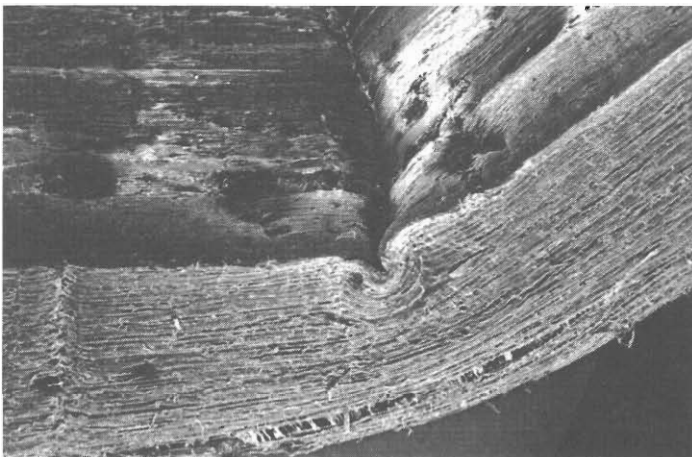

Fig. 5. Specimen from series 3 (longitudinal cut), showing failure by gross buckling. The highly-deformed region on the compression (upper) side contains cells weakened by kink bands, while on the tension (lower) side a crack has formed between layers of cells.

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