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Thermo-mechanical behaviour of wood and wood products

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The dynamic mechanical behaviour of solid wood, fibreboard, and wood laminates has been examined in the temperature range −100 to +150° C. Two events are apparent in the response of the solid wood, a low-temperature (−50° C) transition which is interpreted as being associated with the onset of movement of bound water, and a higher temperature (40 to 120° C) thermal softening process. With fibreboard, the relationship between the shear storage modulus and density is shown to be described by a simple packing efficiency factor applicable over a wide range of temperature. The behaviour of the laminates is strongly dependent upon the orientation of the outer ply. A model is proposed which analyses the response of the laminate in terms of its constituent plies and allows calculation of numerical values of the component shear storage moduli. With both the fibreboard and the laminates the binder, urea-formaldehyde resin, is shown to have a significant influence on the absolute values of tan δ observed.

1. Introduction

The application of dynamic mechanical analysis to wood has been investigated as a means of identifying the individual molecular level contributions of the various components of this natural composite material. An advantage of the technique is that it offers a route by which the microstructural variation may be studied without resorting to structure changing chemical techniques. Work has tended to concentrate on the thermomechanical response of the chemical components of wood and on whole wood itself, particularly with regard to prediction of behaviour during mechanical and chemical pulping processes [1–4]. A further area of interest has been the effect of bound water and other plasticizing agents on response [5]. Despite their commercial importance, relatively little work has been done on wood products such as fibreboard and laminates. Whilst superficially more complex, these systems may, in respect of the improved definition of fibre orientation, offer a potentially simplified analysis. The ability to control more precisely component ratios allows a better assessment of component contribution to composite mechanical behaviour.

Previous work [6] has examined the dynamic mechanical behaviour of a variety of wood species, including both tropical and temperate, soft and hard woods. The species examined were chosen to represent a wide range of density and morphology. It was found that the response of dried samples was non-species specific. In particular, although the absolute values of shear storage modulus and tan δ showed considerable variation, the form of the modulus–temperature and tan δ–temperature relationships was consistent. In the work described here the results obtained with solid wood and fibreboard are reviewed, and the behaviour of wood laminates is described and compared with that of solid wood.

2. Experimental procedure

Details of solid wood species examined and fibreboard preparation procedures have been given previously [6, 7].

Laminates were prepared from sapele (*Entandophragma cylindricum*) veneer of original thickness 0.5 mm, and urea–formaldehyde adhesive. Adhesive content was between 22% and 25% based on dry weight. Laminates were constructed to the following geometry:

0°/90°/0°
0°/90°/0°/90°/0°
0°/90°/0°/90°/0°/90°/0°
0°/90°/0°/90°/0°/90°/0°/90°/0°
90°/0°/90°
90°/0°/90°/0°/90°
90°/0°/90°/0°/90°/0°/90°
90°/0°/90°/0°/90°/0°/90°/0°/90°

Dynamic mechanical analysis was carried out using a Du Pont 982 resonant frequency instrument and a Du Pont 9900 data analysis system. A heating rate of $5°\mathrm{C\,min^{-1}}$ was used between −100 and 150° C in a nitrogen atmosphere. Specimens were 35 mm long by 12 mm wide, and in the case of solid wood and fibreboard, 4.2 mm thick. With the laminates thickness varied between 1.55 and 4.66 mm according to finished dimensions. With solid wood a pre-conditioning programme involving heating at $10°\mathrm{C\,h^{-1}}$ to 100° C followed by a further 2 h at 100° C was required to minimize dimensional change during testing. This

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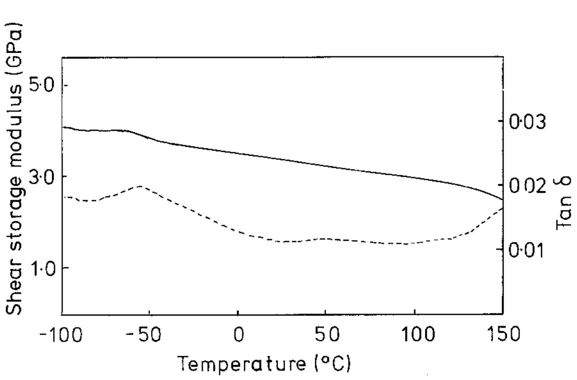

Figure 1 Dynamic mechanical response of solid wood (sapele). (———) Shear storage modulus, (– – –) tan δ.

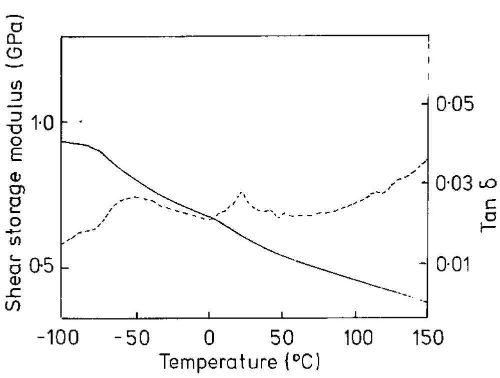

Figure 2 Dynamic mechanical response of fibreboard. (———) Shear storage modulus, (– – –) tan δ.

was not required with the manufactured materials. Laminate specimens were mounted so that the geometry specified above was defined relative to the plane of the clamping system. In all cases three specimens were tested and results averaged.

To verify consistency of construction, laminates were also subject to a three-point bending test according to ASTM D-790 method 1, allowing calculation of flexural strength.

3. Results and discussion

Fig. 1 shows the variation in both shear storage modulus and tan δ with temperature for sapele [6] and is typical of all solid wood species examined. Two principal features are evident. Firstly at around −50° C a β peak in the tan δ plots is observed. This has previously been ascribed [6] to side-group movement in the cellulose chain; however, an examination of the dynamic mechanical behaviour of spruce at different moisture content [5] has shown this peak varies in both position and magnitude with moisture content. In work reported [8, 9] on cellulose esters plasticized by water and by diethyl phthalate the β peak is present in both systems. Comparison of the activation energy reported for spruce/water and that for cellulose/DEP indicates that the process is the same. Therefore it seems more probable that the peak is associated with the general movement of hydrogen-bonded species from one chain site to another. Similar effects are observed in other hygroscopic polymers [10] and therefore it seems probable that the β peak in wood is associated with the onset of movement of bound water from one hydrogen bonding site to another. Such sites must be presumed to be within the amorphous components of the cellulosic materials [11].

At temperatures above 50° C a progressive increase in tan δ is associated with the increasing thermoplasticity of the proto-lignin and hemi-cellulose [12, 13], and also volatilization of moisture from the system. Calorimetric analysis [14] has shown close enthalpic correspondence between measured moisture contents and the magnitude of the thermal event occurring between 50 and 120° C.

The dynamic mechanical response of a typical fibreboard is illustrated in Fig. 2, full results having been reported previously [7]. As anticipated, the β peak is present and is presumed to be associated with the spruce fibres. Water saturation has the effect of lowering the onset temperature of the peak in this material but not altering its magnitude. High-temperature plasticization and dehydration are also evident. At all temperatures, values of tan δ are higher than those of the solid spruce, indicating the importance of the urea–formaldehyde binder in determining damping behaviour. The additional density related peak in the tan δ plots has been ascribed to fibre–matrix shear slippage [7].

Treating this material as a short-fibre composite system, in which the reinforcement is random, it is reasonable to suppose that the material properties would be related to the whole wood from which it is made. Thus, at any specified temperature, modulus variation within the composite could be described by a relationship of the type

$$G'_f = B(\varrho)\, G'_s$$

where G'_f is the shear storage modulus of the fibreboard at temperature T, G'_s is the shear storage modulus of spruce at the same temperature, and $B(\varrho)$ is an efficiency factor which is a function of degree of compaction and is thus density related.

Table I lists the shear storage moduli of fibreboards of varying density, and solid spruce at −80, 20 and 120° C.

Fig. 3 shows plots of G'_f/G'_s against density for the temperatures −80, 20 and 120° C, and least squares analysis yields values of $(\mathrm{d}B/\mathrm{d}\varrho)$ of 5.47×10^{-4}, 5.86×10^{-4} and $6.4 \times 10^{-4}\,\mathrm{m^3\,kg^{-1}}$, respectively. The values obtained are consistent, which indicates that the reinforcing parameter is relatively insensitive to temperature over the range considered. The minor variation may be caused by differences in thermal expansion coefficients.

Table II details the flexural strength of the laminates. The results for the 0° outer ply materials show a high level of consistency, indicating structural

TABLE I Shear storage moduli of fibreboard

Density ($\mathrm{kg\,m^{-3}}$)	Shear storage modulus (GPa)		
	−80° C	20° C	120° C
580	0.75	0.50	0.30
654	0.91	0.63	0.44
691	0.94	0.70	0.53
729	1.29	0.81	0.53
spruce	3.34	2.91	2.47

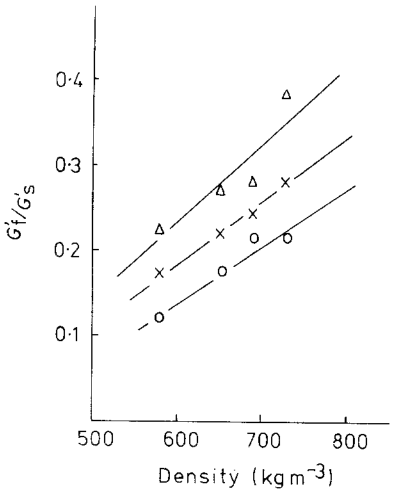

Figure 3 Plot of normalized shear storage modulus of fibreboard against density at (△) −80° C, (x) 20° C, (○) 120° C.

homogeneity within each particular laminate and uniformity between laminates. As would be expected, materials tested in the 90° outer ply condition are less consistent, reflecting the consequences of tensile stressing of wood across the grain.

The variation in shear storage modulus with temperature of all the laminates is illustrated in Fig. 4. Fig. 5 shows the variation in tan δ with temperature; for the sake of clarity only curves for the 0° outer ply materials are shown. Plotting shear storage modulus against ratio of 0° plies, as in Fig. 6, shows a non-linear relationship. Using a mechanics of materials approach, and invoking the correspondence principle, an expression for the shear storage moduli of the laminates was derived. It was assumed that the response of the laminate was a function of four specific constituent responses, that is the shear storage moduli of interior 90° plies, of interior 0° plies, of exterior 90° plies and of exterior 0° plies. The proportion of these various components in the laminates was defined in terms of normalized fractions which were calculated from the initial lay-up geometry. The interfacial regions between the plies were assumed to be thin and therefore did not enter the expression obtained. The set of equations generated was:

0° outer ply, 3 ply

$$G' = \frac{G_{00}G_{90}}{F_{90}G_{00} + F_{00}G_{90}}$$

0° outer ply, 5 to 9 plies

$$G' = \frac{G_{90}G_0G_{00}}{F_{90}G_{00}G_0 + F_{00}G_{90}G_0 + F_0G_{90}G_{00}}$$

TABLE II Flexural strength of laminates

Number of ply	Flexural strength (MN m^{-2})	
	0° outer ply	90° outer ply
3	88.4	33.0
5	89.3	55.9
7	78.7	87.8
9	81.7	56.0

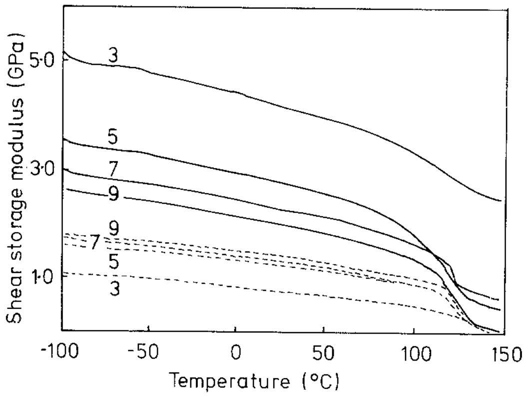

Figure 4 Variation of shear storage modulus of laminates with temperature. (———) 0° outer ply, (– – –) 90° outer ply.

90° outer ply, 3 ply

$$G' = \frac{G_{090}G_0}{F_{090}G_0 + F_0G_{090}}$$

90° outer ply, 5 to 9 plies

$$G' = \frac{G_0G_{90}G_{090}}{F_{90}G_0G_{090} + F_{090}G_0G_{90} + F_0G_{090}G_0}$$

where G' is the shear storage modulus of the laminate and G_0, G_{90}, G_{00} and G_{090} are the shear storage moduli of the interior 0° plies, the interior 90° plies, the exterior 0° plies and the exterior 90° plies, respectively. F_0, F_{90}, F_{00} and F_{090} are the corresponding effective volume fractions.

Using the measured values of shear storage moduli of the laminates at 20° C the equations were solved iteratively. The procedure adopted was the Numerical Algorithm Group mathematical library routine EO4FDF which uses a quasi-Newton gradient descent method to minimize the sum of the squares of the residuals in the equation. This yielded a unique set of values:

G' outer	0° ply	10.5 GPa
G' outer	90° ply	1.1 GPa
G' inner	0° ply	1.1 GPa
G' inner	90° ply	3.0 GPa

The value of shear storage modulus obtained for outer 0° ply is three times higher than that obtained for solid wood [6]. It is thought that this arises from the better alignment of the stiff structural polymers in the ply. In

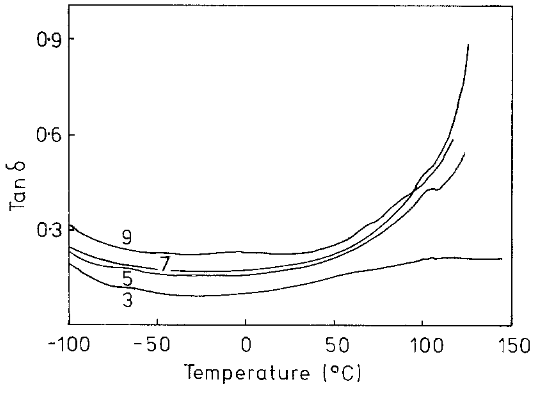

Figure 5 Variation on tan δ of laminates with temperature.

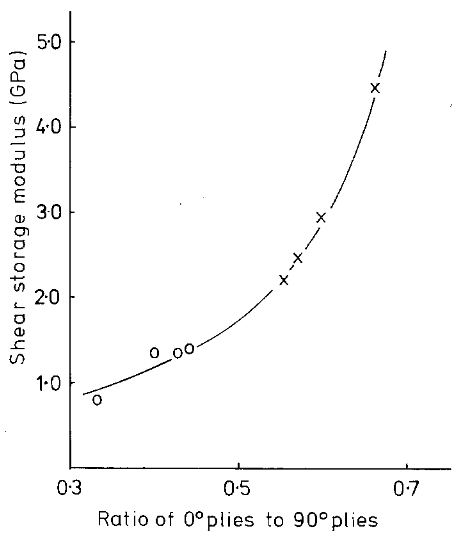

Figure 6 Plot of laminate shear storage modulus against ply geometry ratio. (x) 0° outer ply, (O) 90° outer ply.

addition, the urea–formaldehyde binder will produce a stiffening effect. The relative values of the shear storage moduli of the 0° and 90° outer plies are comparable with modulus and toughness values obtained in solid wood parallel and perpendicular to the grain direction. However, the value obtained for the shear storage modulus of the inner 90° ply is somewhat higher than expected and may reflect more effective penetration of the binder material compared with the 0° plies.

Taking a general view of the values obtained and comparing these with the trend apparent in Fig. 4, confirms the concept that in all the laminates the response is dominated by the orientation of the outer ply. The physical basis for this phenomenon could lie in the mechanisms of stress transfer between the point of applied stress on the outer surfaces and the stress distribution to the interior plies.

The importance of the interfacial region in damping behaviour is shown by the progressive increase of tan δ with number of plies irrespective of geometry, as shown in Table III.

TABLE III Variation in tan δ with mode of construction and temperature

Number of plies	tan δ		
	−80°C	20°C	80°C
3a*	0.0165	0.0109	0.0155
b	0.0248	0.0292	0.0460
5a	0.0176	0.0167	0.0318
b	0.0156	0.0154	0.0323
7a	0.0192	0.0171	0.0316
b	0.0237	0.0192	0.0332
9a	0.0257	0.0223	0.0352
b	0.0232	0.0200	0.0368

*a, Specimens in which outer plies are 0°.
b, Specimens in which outer plies are 90°.

It is thought that in the case of the three-ply 90° sample the high value of tan δ obtained arises from the magnitude of the clamping effects in this thin specimen. However, the general observation that the values of tan δ show no dependence on geometry and only depend on the total proportion of interfacial material suggests that this behaviour is dominated by the response of the urea–formaldehyde binder. A consequence of this is that the previously observed peak at −50°C is absent in these materials. Whilst this may be due in part to the reduced water content of the laminates the primary effect is presumed to be the predominance of the urea–formaldehyde resin. This is supported by the observed values of tan δ in the laminates being significantly higher than those for solid wood samples [6].

4. Conclusion

Despite the chemical and physical complexity of their constituent materials, the dynamic mechanical behaviour of wood products such as fibreboard and laminates can be analysed using simplifications commonly used in synthetic composites. This has allowed the relative importance of the components to be identified and their relative contributions quantified. In the case of fibreboard an efficiency factor relatively independent of temperature has been defined which is a measure of the degree of compaction obtained during the manufacturing process. For laminates the dominating role of the outer plies, in determining dynamic stiffness, has been identified. In both systems it has been found that the damping response is higher than that of solid wood because of the presence of urea–formaldehyde resin whether in the role of fibre binder or ply adhesive.

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