NATURAL MATERIALS

Velcro mechanics in wood

The remarkable deformability of wood in a moist environment resembles that of ductile metals. A combination of traditional mechanical tests and cutting-edge diffraction experiments reveal the molecular mechanism that determines such behaviour.

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The applications of polymers, lightweight ceramics, metals, semiconductors and superconductors have improved dramatically based on advances in our understanding of the material structure at themicroscopicoreven nanoscpo piclevel. Wood performswell in a large number ofstructural applications and has been around much longer then most synthetic materials, but a materials science approach to model itsmechanical behaviour has seriously lagged behind. On page 810 of this issue, Jozef Keckes and colleagues analyse the mechanistic contribution of the cell wall components of wood to explain why permanent tensile deformationcan occur in wood without serious damage to the material[1].

Wood can exhibit stressstrain behaviour that is dramatically different under different conditions. At low moisture contents, it behaves much like a dassic brittle material. At higher moisture levels, it behaves more like a ductile metal, with considerable plastic deformation. Determining the mechanisms thatgovern such complex behaviour requires a dose look at how the molecular components ofwood interact. There have been a few attempts[2] to explain hiluremechanisms in wood. However, most mechanical modelsthat predict structural performance in wood continue to rely on simplified characterizationsthat treat the material as homogeneous, and plainly neglect the structural differences at the micrometre scale.

The experiments presented by Keckes and colleagues focus on wood foils and individual wood cells, and help unravel the behaviour of wood at a molecular level. They demonstrate a 'stick-slip' mechanism operatingin wood cell wallsthat provides anexplanation for the plastic deformation of wood.

Wood has a complicated hierarchical structure. The material it is made of is a layered composite of polymeric cellulose microfibrils embedded in a matrix of hemicelluloses and lignin. The stiffness of wood comes from semi-crystalline cellulose microfibrils wound in a left-handed helix around the lumen, the centre of each tube-shaped wood cell. Wood cells, or tracheids (schematically described in Fig. 1), are made up of multiple layers a primary wall — the most external layer — and three secondary layers S_1, S_2 and S_3, successively positioned towards the lumen. Cells are connected to each other by the middle lamella. The thickest and most critical of the secondary layers is the S_2 layer. The microfibril angle (MFA), the angular deviation of the microfibrils in the S_2 layer relative to the longitudinal cell axis, plays a crucial role in determining themechanical behaviour ofwood.

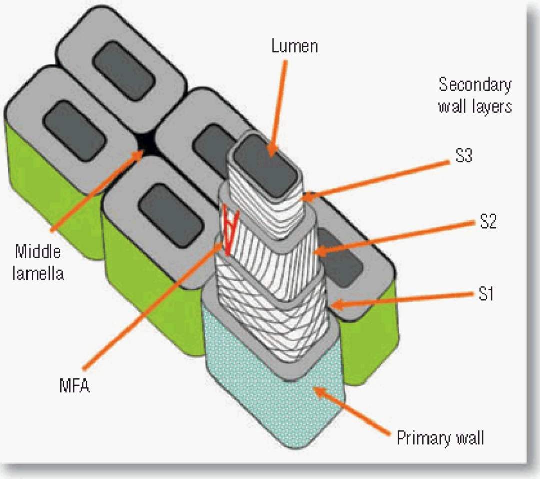

Figure 1 The anatomy ofwood cells. The most up front cell has been sectioned in order to show the layered structure characteristic of each cell, comprising the primary wall, the three secondary wall layers (S1, S2, S3) and the lumen. The grey lines in the secondarywalls layers represent idealized cellulose microfibrils. The cellulose microfibresinthe middle secondary layer appear twisted with respect to the cell's vertical axis. The angle they form, called the microfibril angle (MFA), plays a crucial role in determining the stiffness of the wood.

Other researchers have used chemical maceration techniques, which alters cell walls, to studywood cell fibres[3]. However, Keckes and his colleagues used a 'peeling' process to obtain individual cells with intact cell wall polymers. In a series of ingenious tests, Keckes and colleagues looked at connected wood tissue and individualwood cells from that same tissue. They used a micro-tensile testingapparatus in conjunction with a near-real-timeX-ray diffraction technique to determine the position of micro fibrils (that is, the MFA) under

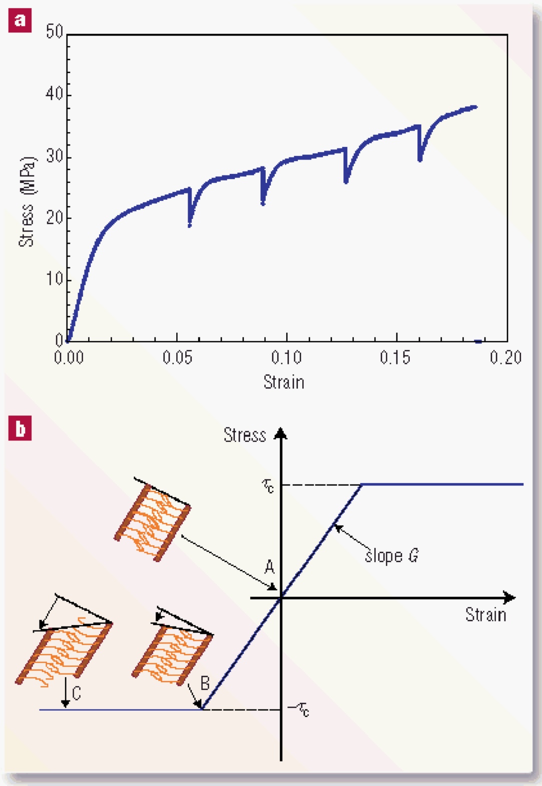

Figure 2 The macroscopic behaviour of wood and the molecular mechanism behind it. **a,** The stress–strain curve obtained by pulling a slice of wood tissue is qualitatively similar to that expected for a metal. During the experiment, thestraining isinterrupted four times for 30 seconds. In this period stress is released, but when the tensile strain reprises, thematerials response is unchanged. **b,** The molecular-level model of thedeformation process shows the relation of shear-stress and strain between the cellulose fibrils in the cell wall. Elastic shear occurs from A until B, with the shear modulus *G*. At point B the critical shear stress $-\tau_c$ is reached, bonds between the fibrils start to break and further deformation to C occurs at a constant stress through an irreversible gliding of the matrix. The behaviour is exactly symmetric for the opposite signs, as seen in the right half of the figure. This gliding corresponds to a permanent deformation similar to the gliding of dislocations in metals. It occurs without damage because the interaction of the fibrils with thematrixhas the character of a Velcro-like connection. When the straining is interrupted, the bonds between the fibrils reform in the new position and the material returns to its original stiffness.

various stress-strain states (Fig. 2a). The simultaneous information obtained suggests that the mechanical response of individual cells is the same as for intact tissue, and therefore the observed response must occur in thecell wall material but not in the connecting middlelamella. The experiments, performed on three different types of wood at high moisture content, reveal a 'stick-slip' mechanism during tensile loading.

Furthermore, Keckes and colleagues present a molecular-level model of what occurs at the interconnections between the hemicellulose matrix and the cellulose fibrils (see Fig. 2b). Hemicellulose side chains attached to the cellulose fibrils act as 'Velcro' hooksthatentangleanddisentanglewith therestofthe matrix Accordingto this model, when a certain shear-stresslevel is reached, bonds between the cellulose fibrils and the matrix break, followed by a viscous flow in the matrix material. When stress is released, the molecules do not return to their original position, but instead new bonds are reformed immediately in the new position of the fibrils. This mechanism, which appears to take place in the walls of the wood cells, would explain the plastic response ofwetwood under tensile loading. This stick–sliprelaxation plays a similar role to that of moving dislocations in ductile metals.

Previouswork, conducted at our laboratory[4-7], on woodmaterials under conditions of low moisture and high temperature suggests that hemicelluloses, in particular the arabinose and galactose components of hemicelluloses, playa critical role in the structural integrity of wood. The work of Keckes and his colleagues has renewed our curiosity about the importance of bonding mechanisms of the hemicellulose side chains.

The results of Keckes and colleagues demonstrate how two drastically different yield mechanisms, in such distinct materials as wood and metal, can produce similar mechanical responses. Work of this type and the questions it raises reinforce the importance of further investigating how molecular interactions and dynamic bond recovery control the mechanical properties of natural materials such as bone or wood.

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