CHEM-E0120: An Introduction to Wood Properties and Wood Products

Material properties III:

Toughness and the long-term behaviour of wood

Mark Hughes

14th October 2021

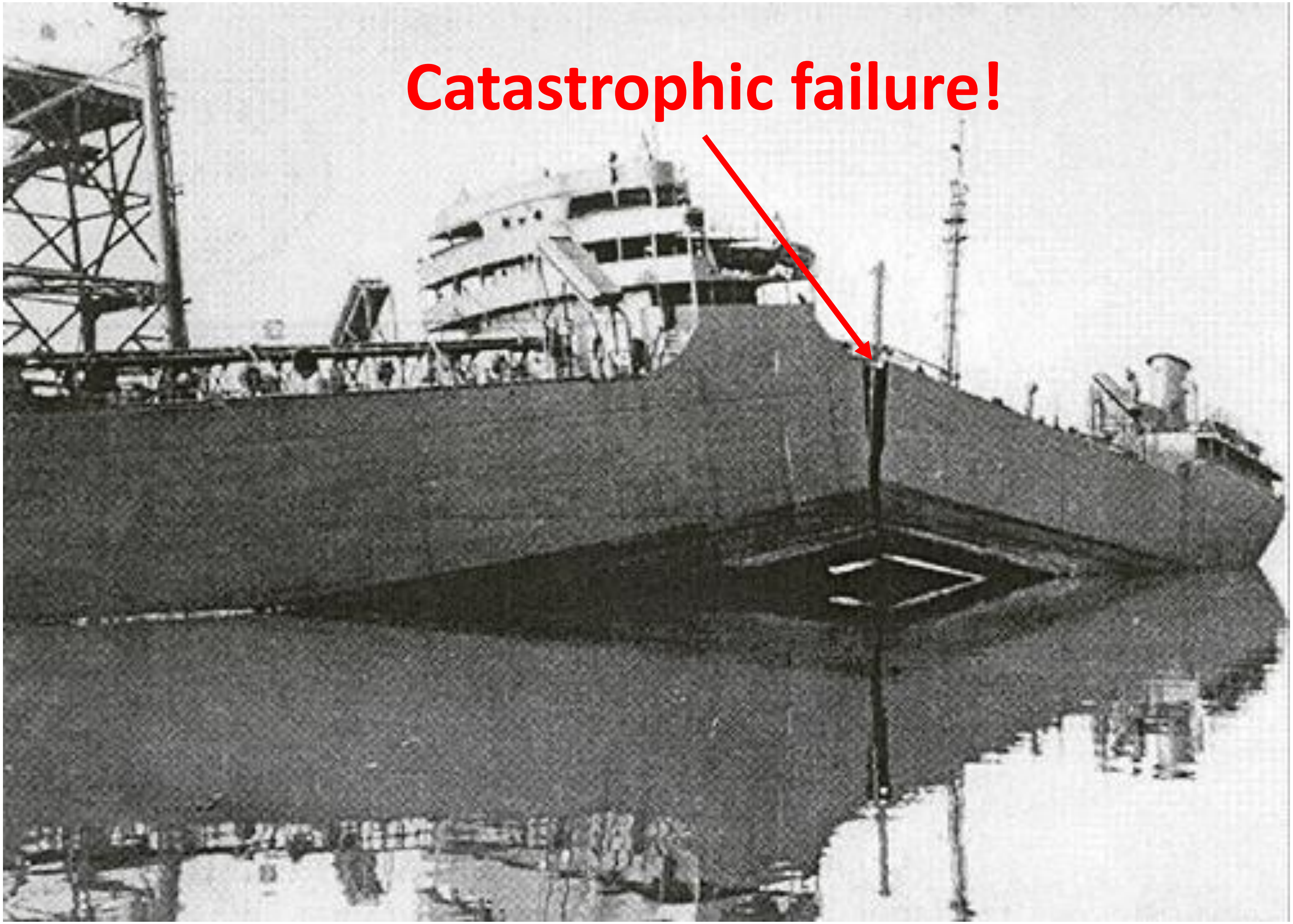
Today’s topics

- Toughness of wood: why wood is a good engineering material
- Long-term mechanical behaviour: creep and fatigue

Toughness

"The worst sin in an engineering material is not lack of strength or lack of stiffness, desirable as these properties are, but lack of toughness, that is to say, lack of resistance to the propagation of cracks"

J.E. Gordon, The New Science of Strong Materials



WW II Liberty ship

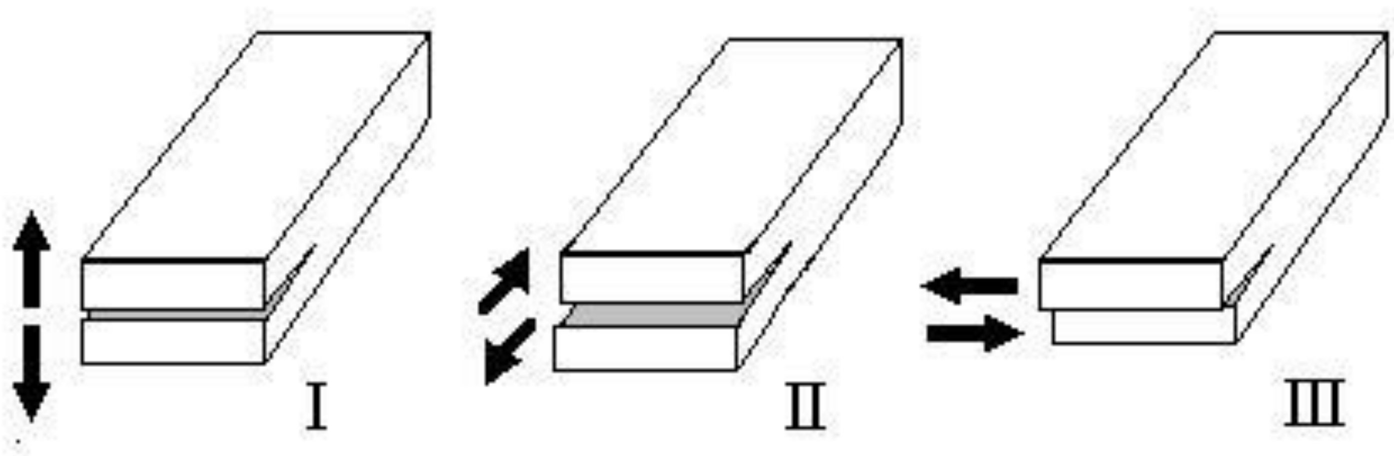
How are materials loaded? Tension, compression and shear

- In most structures there is the need to carry **tensile and shear** as well as compressive loads
- Brittle materials are okay in compression (mainly) as cracks are not “opened”
- Think of how, for example, masonry (brick, stone) is used in construction

Tension:
The Menai suspension bridge, Wales

Compression:
A Roman arch

Cracks and crack “opening” modes



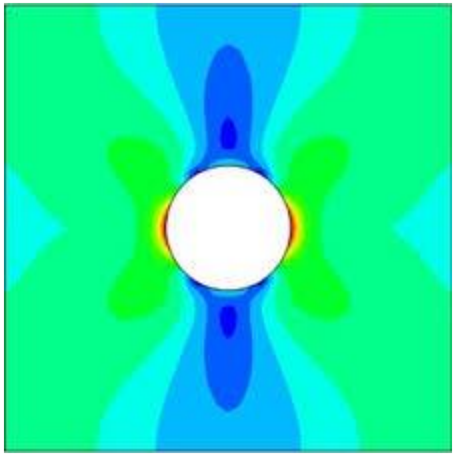
Tension Forward shear Anti-planar shear

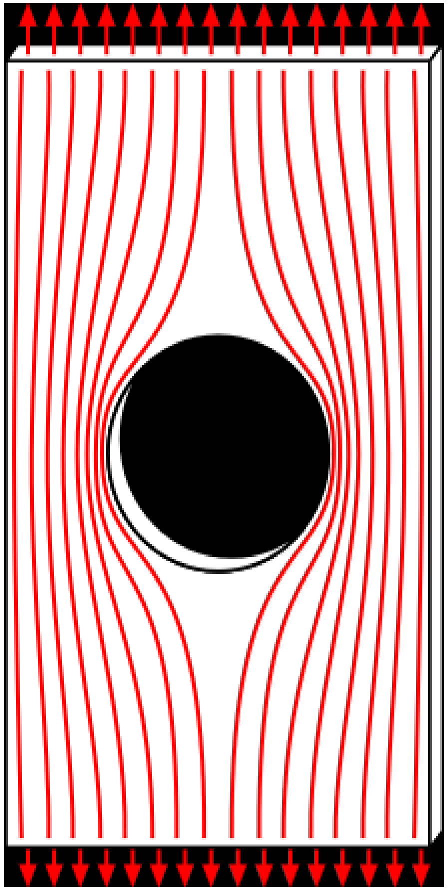
Cracks and "crack-like" defects

- All ***real*** materials contain cracks or crack-like defects at **<u>some scale</u>**
- These could be macroscopic cracks or "stress concentrators" or "stress risers" such a holes or sharp changes in section
  - The failure of the Liberty ships initiated at the corners of hatches (openings in the decks)
- Or they could be microscopic cracks
- There will be some kind of cracks or discontinuities (changes in section or in material properties) in all forms of material. Here cracks can initiate and propagate

What is the effect of a crack?

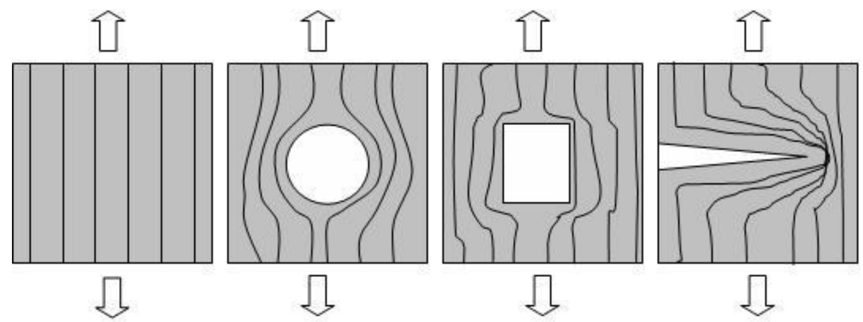
- These cracks result in localised stress concentrations, the magnitude of which depend upon the size and shape of the crack





What is the effect of a crack?

- If the stress concentrations are high enough, the material near the crack-tip may fail. Under certain conditions a crack may propagate catastrophically, leading to sudden failure of the material
- The crack-tip may, therefore, be viewed as a mechanism whereby local stresses in the material are raised sufficiently for fracture to occur



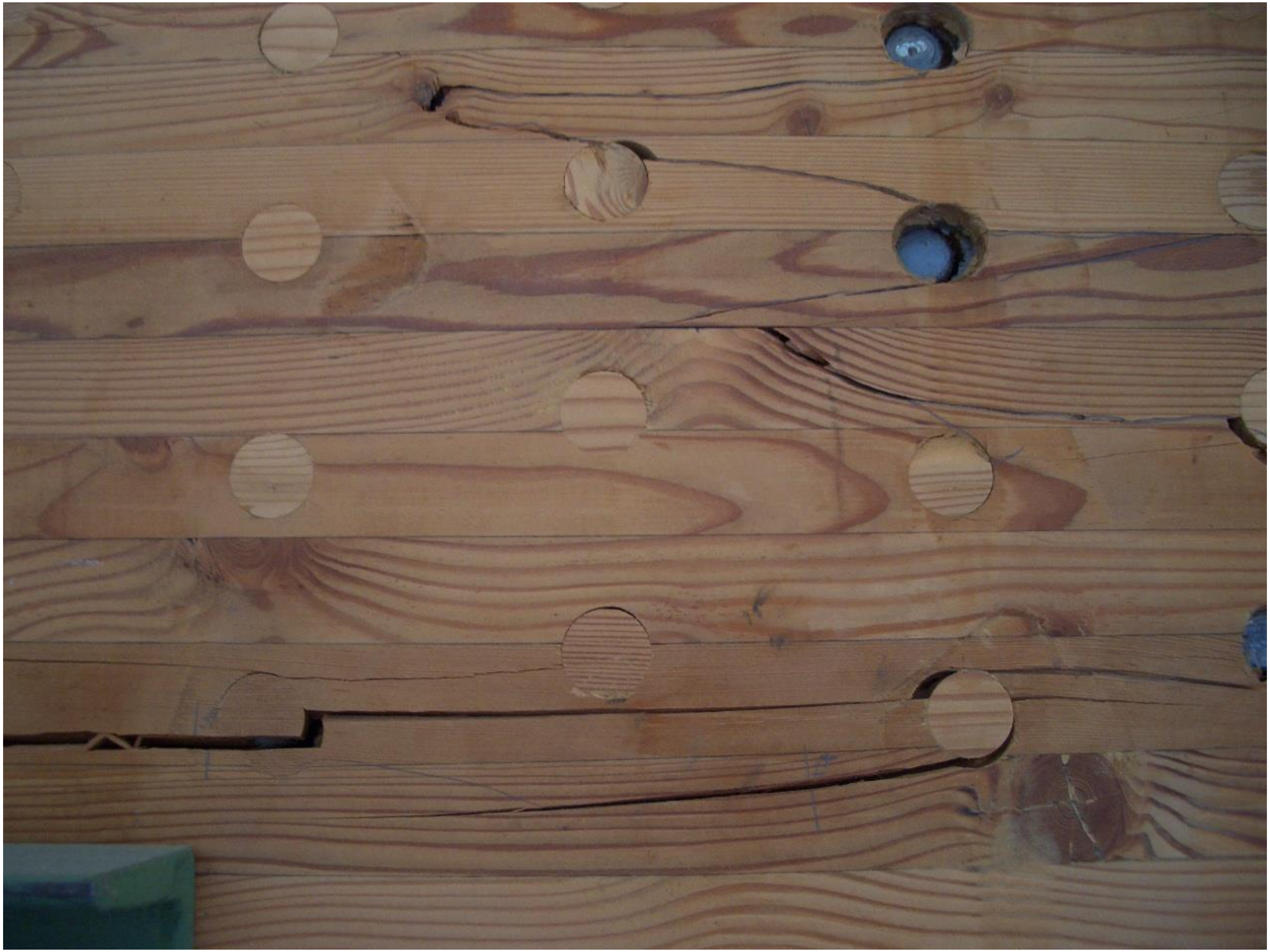
Joensuu sports arena

“Roof collapses in Jyväskylä; major disaster narrowly averted”

Kuva 4. Kuva vaurioalueelta raivaustyön alkuvaiheesta. Kuva on otettu b3-oven ulkopuolella. (Kuva: Poliisin arkisto)

Figure 4. Site of the incident at the beginning of the clearing work. Photo taken from behind the B3 door.

Kuva 8. Rikkoutunut tappivaarnaliitos. (Kuva: Poliisin arkisto)
Figure 8. Broken dowel joint.



Engineering materials

Engineering materials need to be “tough” (i.e. be resistant to crack propagation) in order to carry loads safely!

What is tough and what is brittle?

- Examples of brittle materials:
  - Glass
  - Thermosetting resins (phenol formaldehyde, epoxy, unsaturated polyesters)
  - Cookies!
- And tough materials:
  - Mild steel
  - GRP (glass fiber Reinforced Plastic)

Toughness of materials

Table 9.1 *Typical fracture energy and fracture toughness values for various materials. (After Ashby and Jones 1980)*

Material	Fracture energy G_c (kJ m^{-2})	Fracture toughness K_c (MPa $\sqrt{m}$)
Polymers		
epoxy resins	0.1–0.3	0.3–0.5
Nylon 6.6	2–4	3
polypropylene	8	3
Metals		
pure Al	100–1000	100–350
Al alloy	8–30	23–45
mild steel	100	140
Ceramics		
soda glass	0.01	0.7
SiC	0.05	3
concrete	0.03	0.2
Natural materials		
woods (crack ⊥ grain)	8–20	11–13
woods (crack // grain)	0.5–2	0.5–1
bone	0.6–5	2–12
Composites		
fibreglass (glass/epoxy, planar random fibres)	40–100	42–60
Al-based particulate MMC	2–10	15–30
SiC laminate (crack ⊥ layers)	5–8	45–55

(Source Hull and Clyne 1996)

Conditions for fracture

- Cracks or crack-like defects provide the “mechanism” for high local stresses to be generated
- However energy is needed to “drive” the crack forwards. This is provided by the stored “strain energy” and any external work
  - Think of bows and arrows: energy is stored in the bow as strain energy by pulling the string back, this is converted to the kinetic energy of the arrow as the arrow is released

Stress concentrators

- Stress concentration is dependent upon the shape of the crack
- Can be modelled as an ellipse
- As the crack tip radius approaches zero (i.e. very sharp – ratio of major to minor axis is high) then the theoretical stress concentration approaches infinity

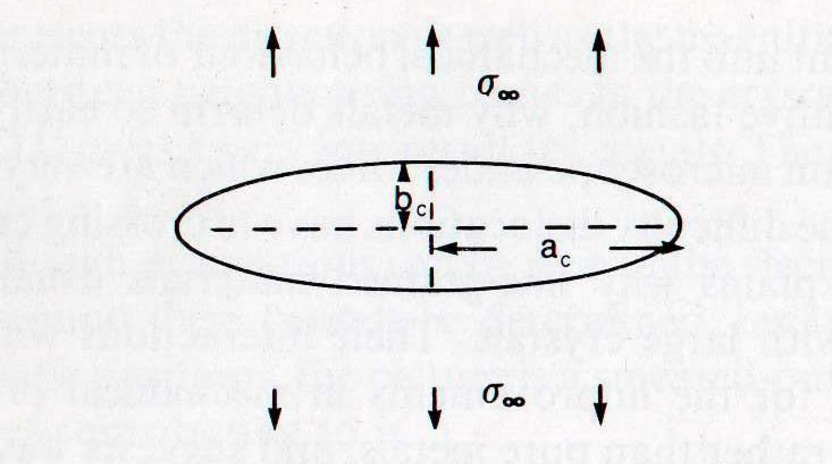


FIG. 2.9. Elliptic crack.

$$\sigma_{\max} = \sigma\left(1 + 2\frac{a}{b}\right)$$

Conclusion: "sharp" cracks are <u>bad</u>, so if a crack can be "<u>blunted</u>" then it will not be as problematic!

(Not all cracks are bad though!)

- Stress concentrators can be used to advantage too…

Fracture in wood

- Wood contains numerous crack-blunting/deflecting mechanisms as well as energy absorbing mechanisms
- These are once again directionally dependent
- Think structure!!

Crack propagation directions

Notation:
1. The **first** letter, “T” (tangential), denotes the <u>**orientation**</u> of the crack relative to the structure of wood (note that the crack plane is *perpendicular* to the anatomical orientation)
2. The **second** letter, “L” (longitudinal), denotes the direction of crack **propagation**

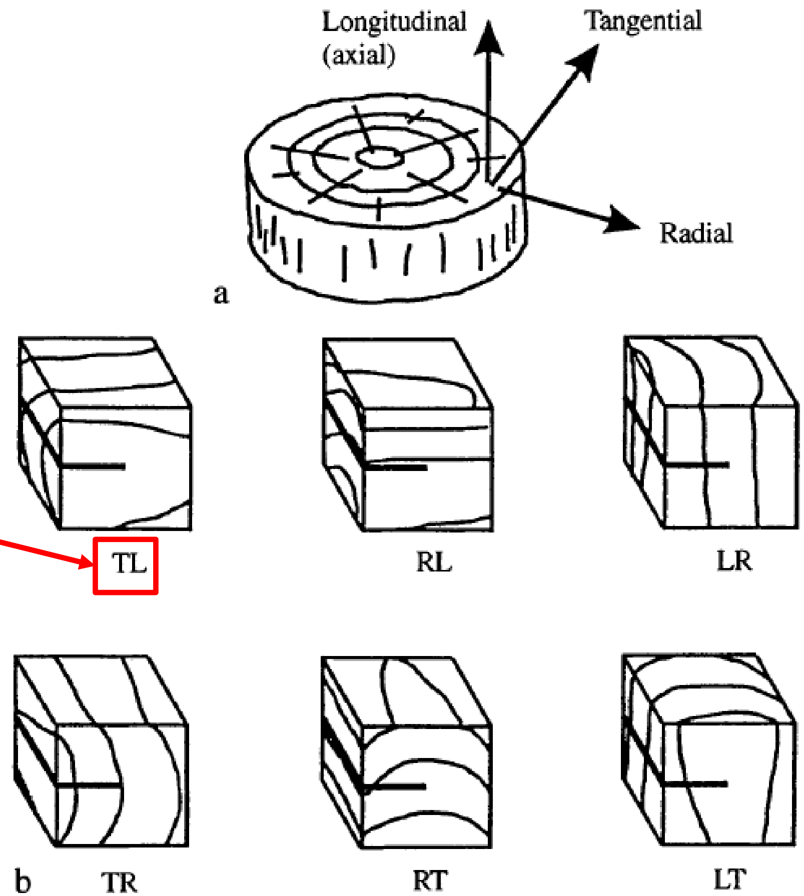


Fig. 1a, b. Crack propagation directions for wood. (**a**) cross-section of tree stem showing axis of directions (**b**) the six principal crack propagation directions in wood. L, T and R correspond to the longitudinal, tangential and radial directions respectively

Dependence of fracture toughness on crack propagation direction

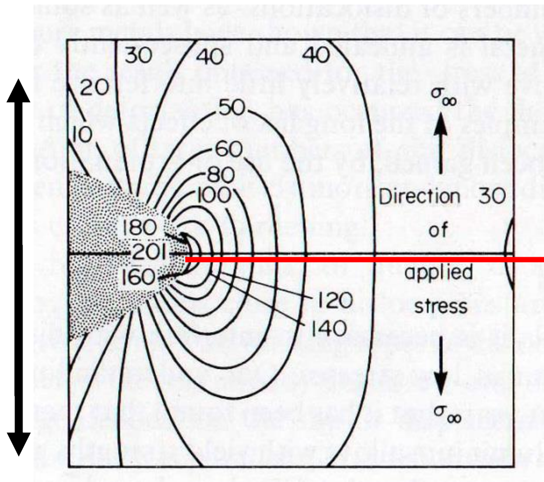
wood species	system of propagation	fracture toughness $K_{IC}/(\mathrm{kPa\ m^{\frac{1}{2}}})$	reference
softwoods			
Douglas fir	TR	390	Schniewind & Pozniak (1971)
	TL	260	
	TR	355	Schniewind & Centeno (1973)
	TL	309	
	RL	410	
	RT	355	
	LT	2417	
	LR	2692	
western white pine	TL	190	Johnson (1973)
western red cedar	TL	185	Johnson (1973)
hoop pine	TL	494	Walsh (1971)
sitka spruce	LR	7000	Jeronimidis (1980)
hardwoods			
hard maple	TL	492	Johnson (1973)
paper birch	TL	564	
red oak	TL	407	
lauan	TL	478	
messymate stringbark	TL	505	Walsh (1971)
maiden's gum	TL	681	
balsa	TL and RL	112	Wu (1963)
	LR	2500	Jeronimidis (1980)
mahogany	TL	480	Williams & Birch (1976)
	TL	960	
	TL	840	
	TR	350	

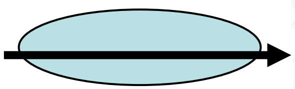
(Source: Ashby et al, 1980)

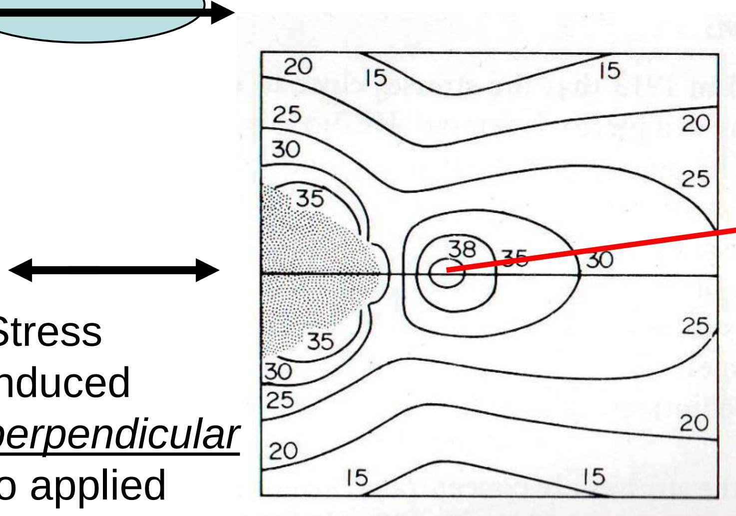
Why is wood tough “across the grain” but not along it?

A bit more about cracks…

Direction of applied stress (σ_y)

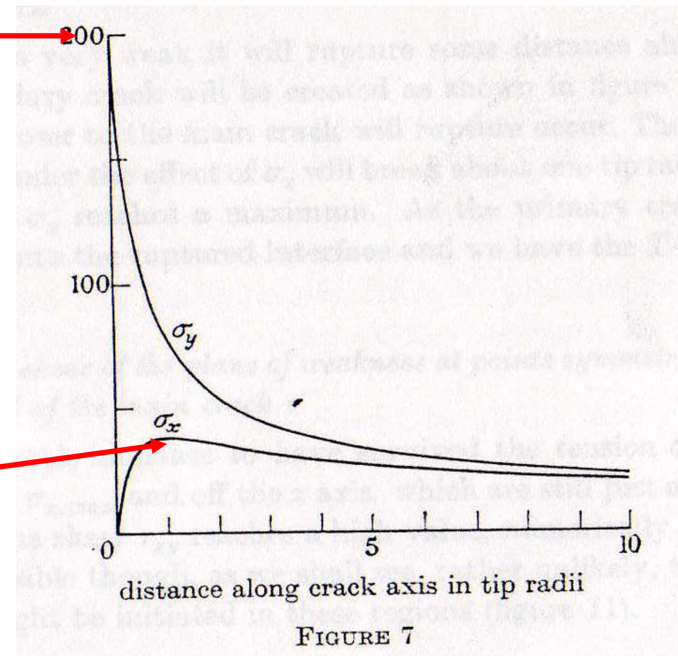






Stress induced *perpendicular* to applied stress (σ_x)

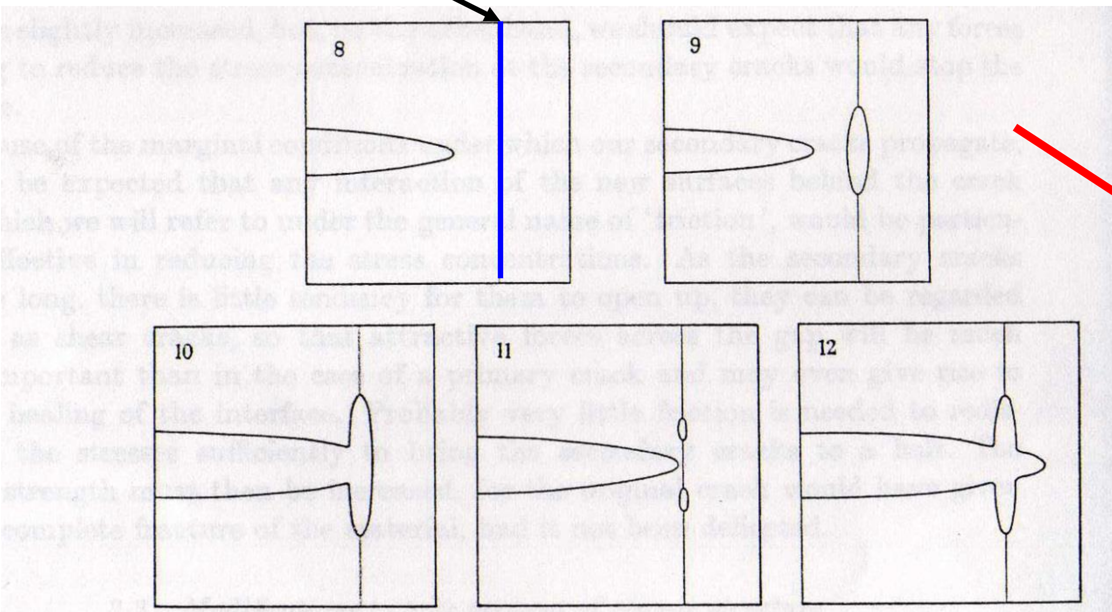
(Source: Piggott, 1980)



(Cook & Gordon 1964)

“Weak interfaces”: crack-stopping/blunting mechanisms

Interface



FIGURES 8 to 12. Interaction between an advancing crack and a plane of weakness under various conditions.

Figure 7.18 Crack-stopping in a fractured rotor blade. The orientation of the secondary cracks corresponds to the microfibrillar orientation of the middle layer of the secondary cell wall (× 990, polarised light.) (© BRE.)

- If an interface is “weak” (about one fifth of the cohesive strength of the material), it can open up and effectively blunt or stop a propagating crack, or divert its path
- Wood contains multiple interfaces at several hierarchical levels!

Energy absorption

- Work of fracture of wood is ~ **10-30** kJ m^{-2}, but:
  - The "intrinsic toughness" of cell wall material across the cell wall is ~ **1.65-3.45** kJ m^{-2}
  - And the "intrinsic toughness" of cell wall material along the cell wall ~ **0.2-0.3** kJ m^{-2}
- These are much lower than wood itself
- The difference due to energy absorbing mechanisms such as fibre pull-out ($\approx$1.6 kJ m^{-2}) and pseudo-plastic buckling of cell wall (90% of overall work of fracture)

“Pseudo-plastic buckling”: The ‘secret weapon’ of the wood cell wall

- Observations that wood pulp fibre collapsed inwards during tensile testing, showing a distinct yield point, with post yield extension being significant, indicating large energy absorption
- Hypothesis was tested by making glass and carbon fibre analogues of wood and testing these
- Showed the dependence of work of fracture of the winding angle

Dependence of work of fracture on microfibril angle

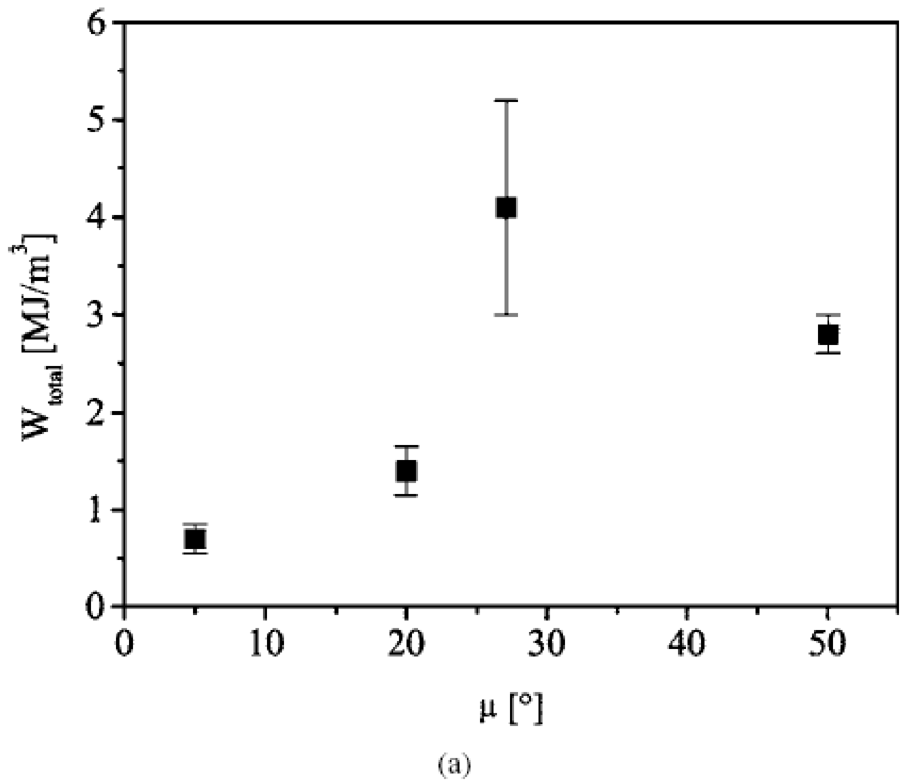
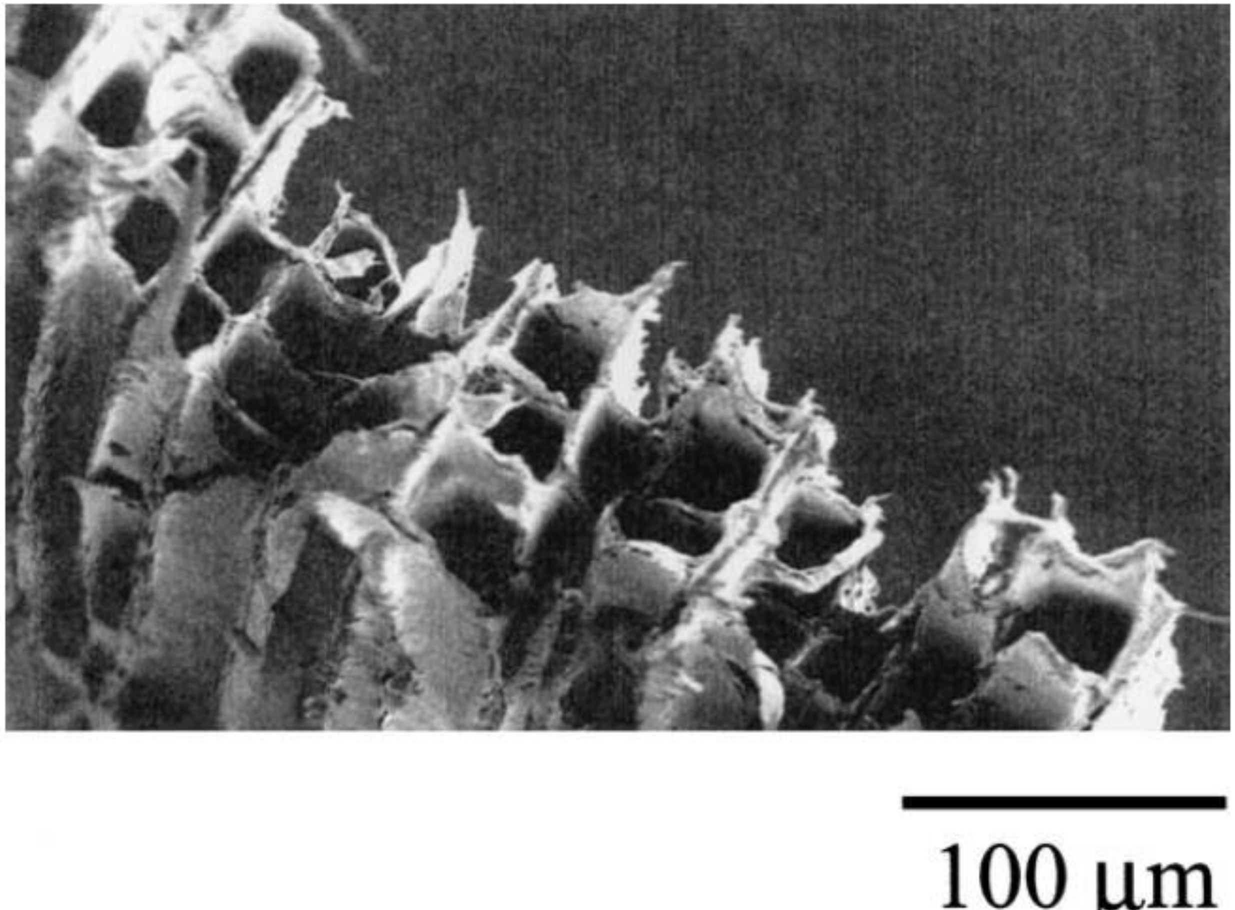


Figure 6 (a) Total work of fracture W_{total} versus the microfibril angle μ. (b) Ratio of the part of the work of fracture due to elastic deformations W_{er} to the total work of fracture W_{total} versus the microfibril angle μ.

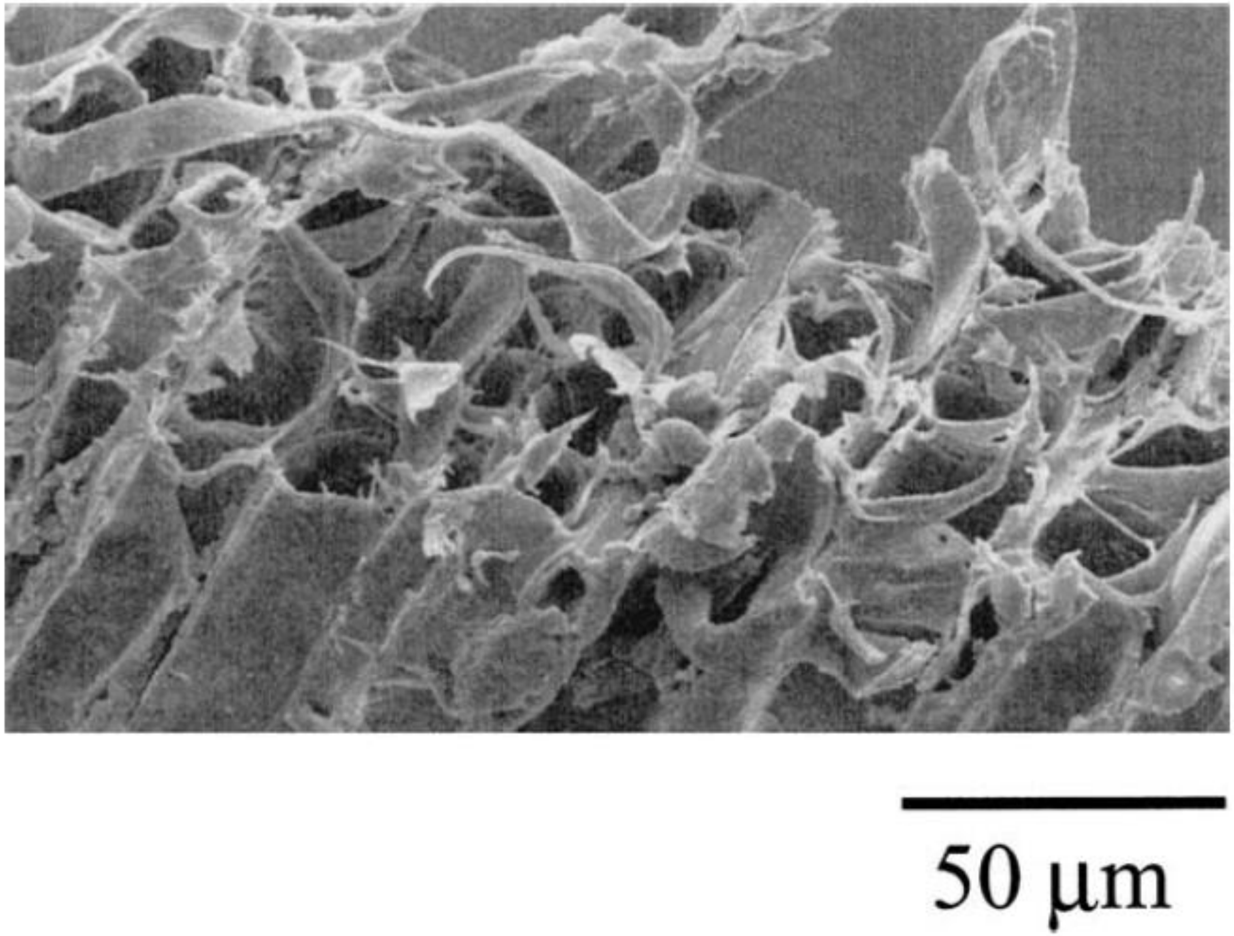
(Source: Reiterer et al, 2001)



(a)

Figure 7 (a) SEM picture of the fracture zone of a specimen with a microfibril angle of about 5°. The fracture surface is smooth; (b) SEM picture of the fracture zone of a specimen with a microfibril angle of about 50°. The fracture surface is heavily deformed and torn cell wall fragments are spiraling out of the tracheids.

(Source: Reiterer et al, 2001)



(b)

Figure 7 (a) SEM picture of the fracture zone of a specimen with a microfibril angle of about 5°. The fracture surface is smooth; (b) SEM picture of the fracture zone of a specimen with a microfibril angle of about 50°. The fracture surface is heavily deformed and torn cell wall fragments are spiraling out of the tracheids.

(Source: Reiterer et al, 2001)

Long-term mechanical properties

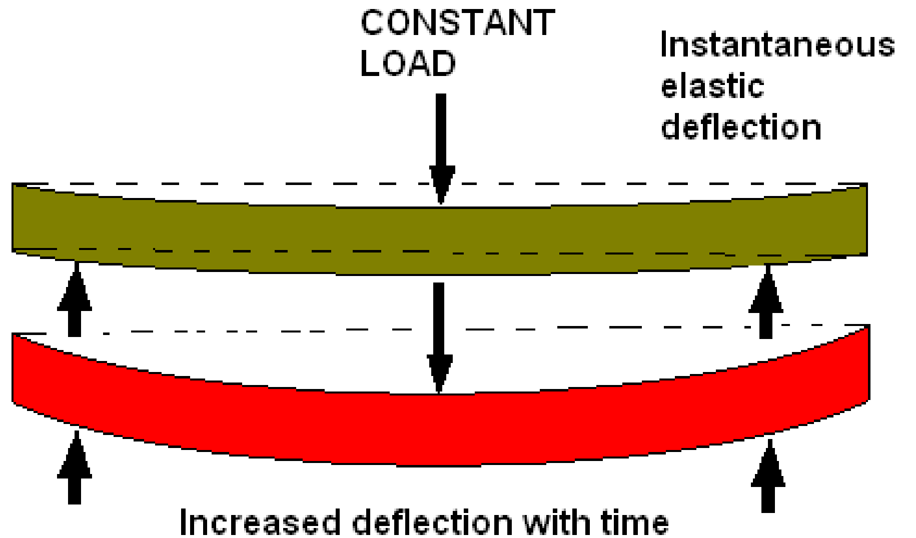
Creep & fatigue

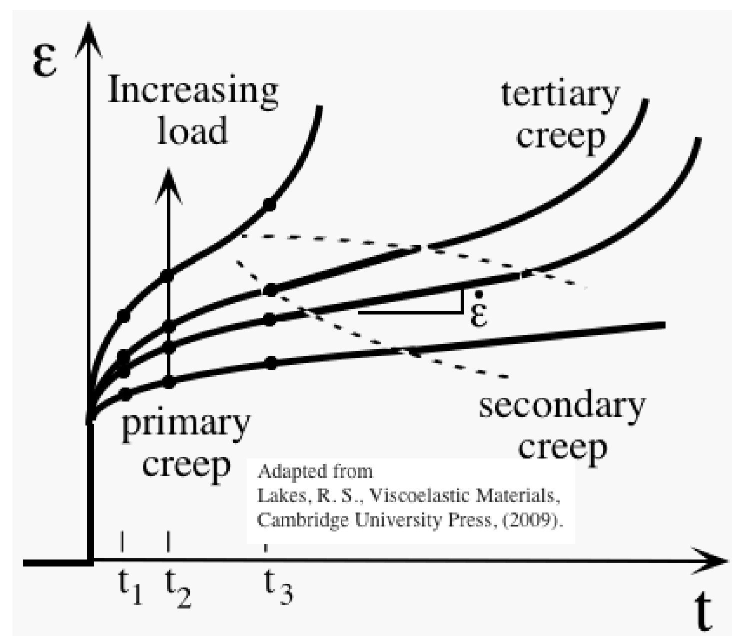
Creep

- Over time, wood "creeps", in other words it undergoes further deformation under a static load
- This is often visible as sagging bookshelves, and roofs in old buildings..........
- Creep happens at stress levels below the ultimate stress (strength) of the wood
- Creep is not only particular to wood, but is also observed in materials such as concrete, bitumen and plastics

Time dependent deformation

- When load is applied, there is an instantaneous deflection
- If the load is maintained the deflection will gradually increase (the wood is said to "creep")
- If the load is removed, the wood will recover….. but often not fully!
- If the applied load is a significant percentage of the ultimate load, then in time the creep may lead to failure!
- It has been established that if a piece of wood is to carry a load for 100 years then the imposed load must be < 50% of max. load





Wood material behaviour

- Wood behaviour is neither fully **elastic** (i.e. when loaded it fully recovers it shape), nor is it fully **viscous** (i.e. it flows and does not recover its initial shape at all), but displays behaviour somewhere in between
- This is known as ***viscoelastic*** behaviour
- Creep is a form of this behaviour. Creep is the deformation under constant load over and above the elastic component of deformation
- Total deflection after a certain time can be thought of as consisting of three components:
  - Elastic deflection (the initial deflection due to the applied load, that is recovered fully and instantaneously when the load is removed)
  - Delayed elastic (further, but time dependent, recoverable deformation – therefore ‘elastic’). Recoverable ‘creep’
  - Irreversible or ‘plastic’ deflection that cannot be recovered when the piece of wood is unloaded). Irrecoverable ‘creep’

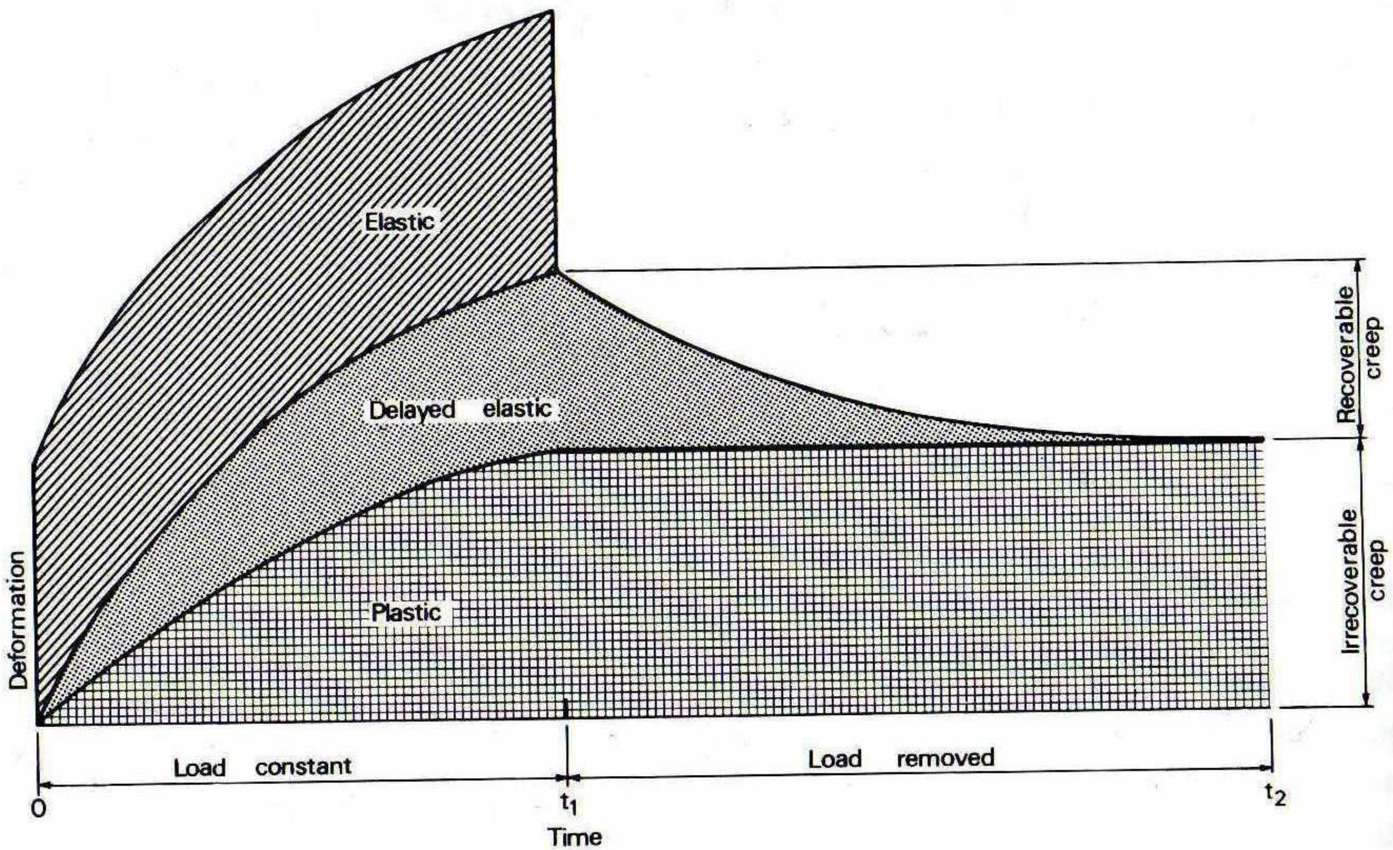


Figure 6.1 The various elastic and plastic components of the deformation of timber under constant load. (© BRE.)

(Source: Dinwoodie, 2000)

Creep deflection

- Rate of creep is dependent on the stress level, i.e. the how big the dead load is
- Creep is accelerated by moisture and especially changes in moisture content

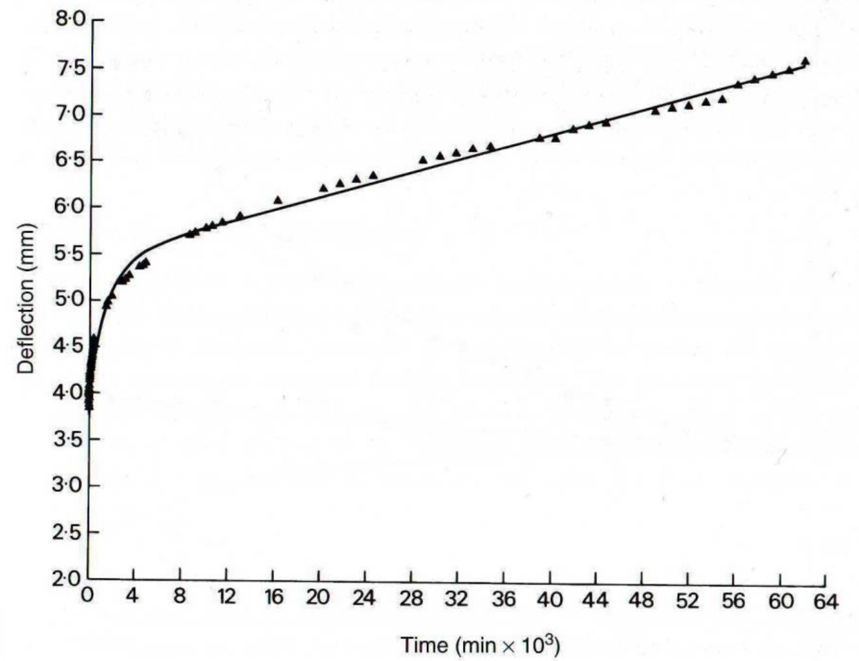


Figure 6.15 The increase in deformation with time of urea–formaldehyde (UF)-bonded chipboard (particleboard) in which the regression line has been fitted to the experimental values using Equation (6.36). (© BRE.)

(Source: Dinwoodie, 2000)

Creep and moisture cycling

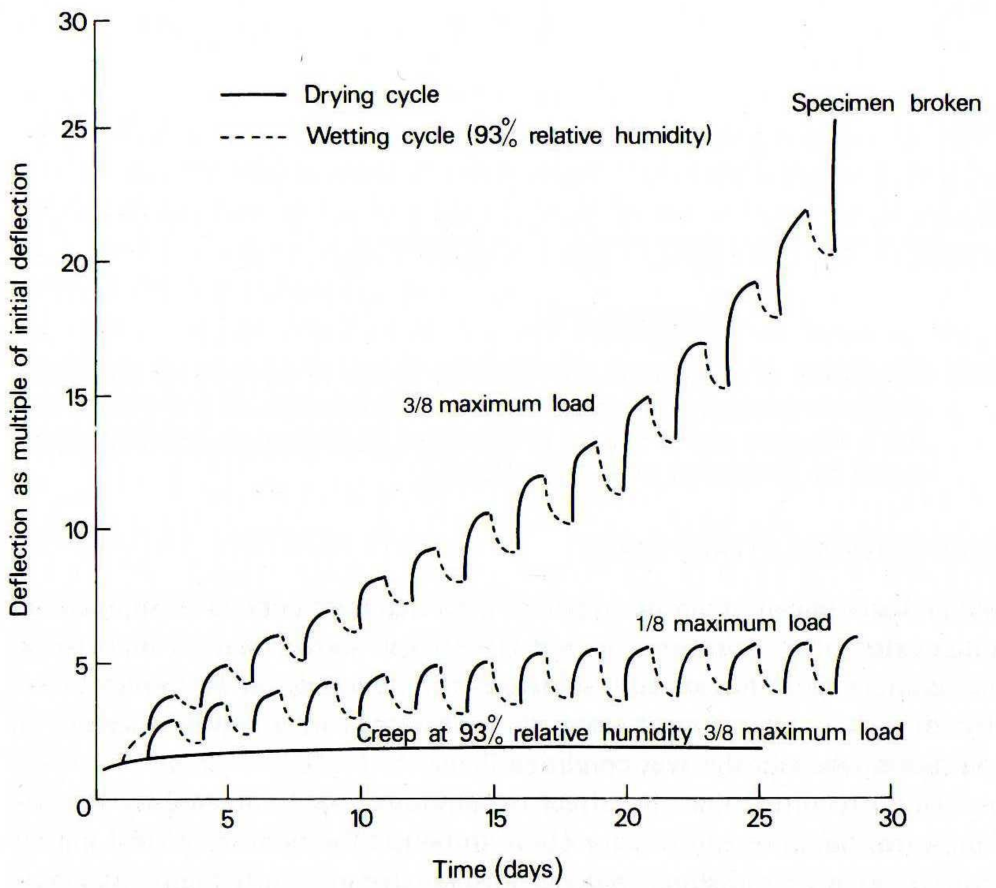


Figure 6.22 The effect of cyclic variations in moisture content on relative creep of samples of beech loaded to 1/8 and 3/8 of ultimate load (© BRE.)

(Source: Dinwoodie, 2000)

Some further thoughts about creep

- Important property in buildings and structures
- Most long term creep behaviour is extrapolated from “short-term” tests
- “Stress relaxation” is another manifestation of viscoelastic behaviour – this is important in the manufacture of wood-based panels

Fatigue

- In certain situations, cyclic loading will take place
- This leads to a process known a fatigue (literally the material becomes “tired”)
- This may become very important in certain applications such a wind turbines for example, where gravitational forces and wind will result in complex cyclical stressing

Fatigue in wood

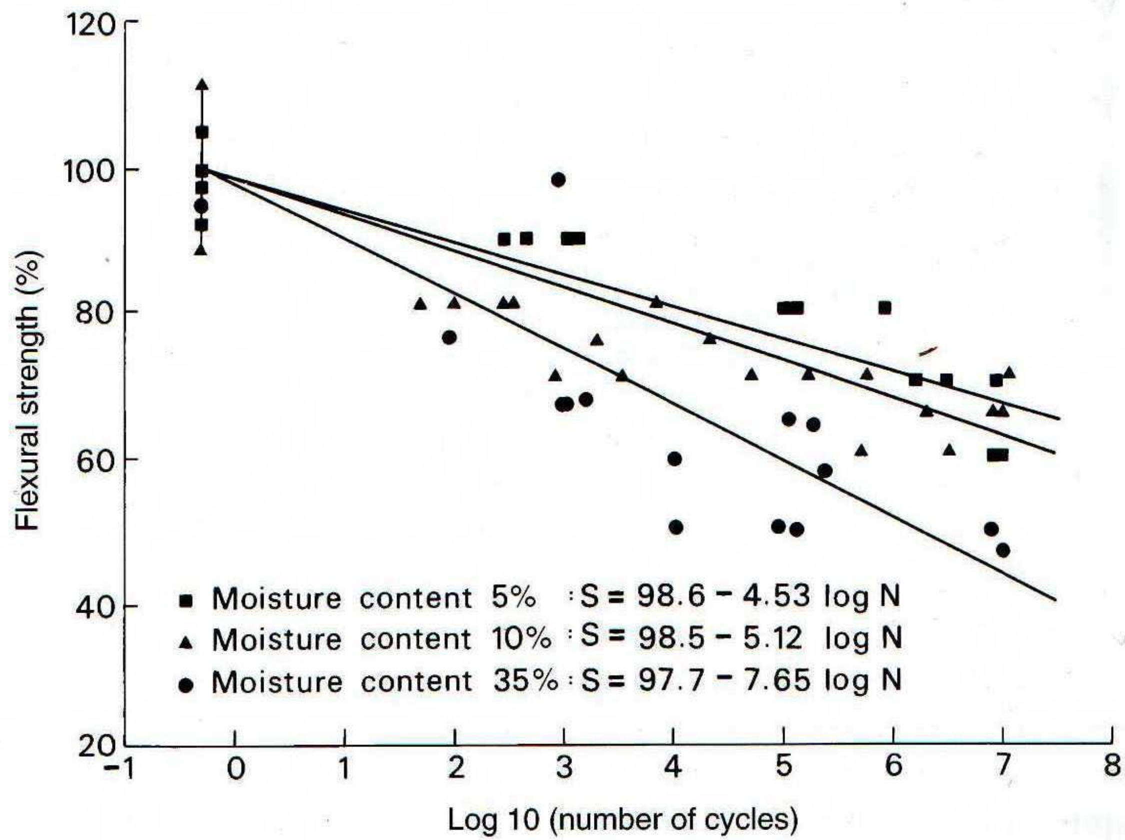


Figure 7.19 The effect of moisture content on sliced Khaya laminates fatigued at $R = 0$. The maximum peak at stresses are expressed as a percentage of static flexural (bending) strength. (From Tsai, K.T. and Ansell, M.P. (1990) *J. Mat. Sci.*, **25**, 865–878, reproduced by permission of Kluwer Academic Publishers.)

(Source: Dinwoodie 2000)

Literature and further reading

- Ashby, M.F., Easterling, K.E., Harrysson, R. and Maiti, S.K. (1985). The Fracture Toughness of Woods. *Proc. R. Soc. Lond. A*, **398**: 261-280.
- Cook, J. and Gordon, J.E. (1964). A Mechanism for the Control of Crack Propagation in All-Brittle Systems. *Proc. Roy. Soc. Lond*. *A*, **282**: 508-520.
- Dinwoodie, J.M. (2000). Timber: Its nature and behaviour
- Desch H.E. and Dinwoodie, J.M. (1981): Timber: Its structure, properties and utilisation, 6th Edition, Macmillen
- Gordon, J.E. The New Science of Strong Materials: Or Why You Don't Fall Through the Floor (Penguin Science)
- Gordon, J.E. Structures: Or Why Things Don't Fall Down (Penguin Science)

Literature and further reading

- Griffith, A.A. (1920). The Phenomenon of Rupture and Flow in Solids. *Phil. Trans. R. Soc. Lond. A*, **221**: 163-198.
- Hull, D. and Clyne, T.W. (1996). *An Introduction to Composite Materials*. Cambridge University Press, Cambridge, UK.
- Jeronimidis, G., (1980). The Fracture Behaviour of Wood and the Relations Between Toughness and Morphology. *Proc. R. Soc. Lond. B*, **208**: 447-460
- Piggott, M.R. (1980). *Load-Bearing Fibre Composites*. Pergamon, Oxford
- Reiterer, A, Lichtenegger, H., Fratzl, P. and Stanzl-Tschegg, S.E. Deformation and energy absorption of wood cell walls with different nanostructure under tensile loading, JOURNAL OF MATERIALS SCIENCE 36 (2001) 4681 – 4686
- VTT (Creep: http://www.vtt.fi/inf/pdf/publications/1996/P278.pdf)