Tension and compression

STEP lecture B2
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Objective
To describe the strength and stiffness of timber loaded in tension and compression at different angles to the grain.

Prerequisites
A4 Wood as a building material

Summary
This lecture deals with tension and compression actions when parallel to the grain, perpendicular to the grain and at an angle to the grain and considers both clear wood and structural timber. Each of the four basic cases: tension parallel and perpendicular to the grain and compression parallel and perpendicular to the grain are first discussed for clear wood. The influence of different parameters on the strength and stiffness properties on a small-scale and at macroscopic level is presented together with examples of failure modes.

The more general case of loading at an angle to the grain is described, noting wood as an orthotropic material, with the application of different failure theories such as Hankinson's formula. The final section considers tension and compression actions in structural timber.

Introduction
Wood is an anisotropic material, i.e. it has different properties when loaded in different directions, e.g. parallel or perpendicular to the grain. A tree trunk may as an idealisation be regarded as being cylindrically orthotropic (i.e. orthogonally anisotropic), Figure 1a. In Figure 1b the directions L, R and T denote the longitudinal, radial and tangential directions, respectively. The properties in the R- and T-directions are often treated together as one group, i.e. regarded as properties *perpendicular* to the grain.

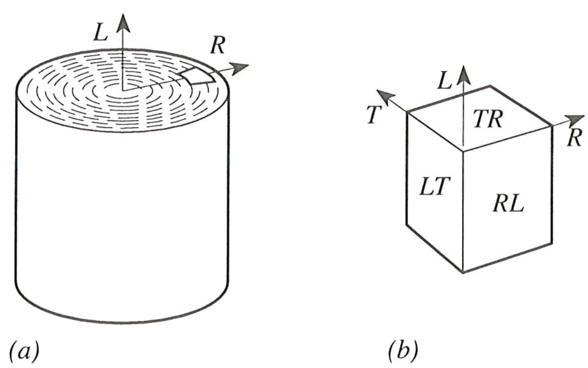

Figure 1 *Principal axes and principal planes in wood. For a small rectangular block taken out from the outer part of the tree trunk the rectangular coordinate system L,R,T, (b), can be defined.*

The following sections deal primarily with both the strength and the stiffness properties of wood under short term loading. Unless otherwise stated the values are selected for a typical European softwood with a moisture content of 10 to 15%.

Structural timber, i.e. timber with normal defects prepared in structural sizes for structural purposes, is inhomogeneous. There is a large variation in the raw material properties (density, strength, modulus of elasticity etc.), i.e. over the cross section of a log and along the log. Further, there is also a variation in the properties between different trees of the same species and, of course, between different species. Also within one annual ring the properties vary, namely between earlywood and latewood. These variations are, however, not further discussed in this lecture.

First, the properties of clear wood (small specimens) will be treated, then sawn timber in structural sizes with defects.

Clear wood in tension and compression

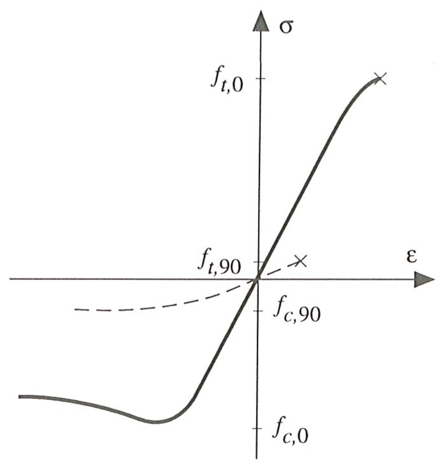

Figure 2 *Stress-strain curves for clear wood loaded parallel to the grain (solid line) and perpendicular to the grain (dashed line) at a constant strain rate. Typical values for softwood:* $f_{t,0}$ = *80 to 100 N/mm²*, $f_{c,0}$ = *40 to 50 N/mm²*, E_0 = *11000 to 15000 N/mm²*.

Tension parallel to the grain

When testing small wood specimens, selected to be as homogeneous as possible, and loaded parallel to the grain, a stress-strain diagram of the type shown in Figure 2 (fully drawn curves) is obtained.

It should be noted that the tensile strength $f_{t,0}$ is larger than the compressive strength $f_{c,0}$. The stress-strain curve in tension is linear almost up to failure and the fracture mode is sudden and brittle. In compression a more ductile failure is obtained.

Tension perpendicular to the grain

The lowest strength for wood is in tension perpendicular to the grain $f_{t,90}$. It is roughly of the order of magnitude of 1 to 2 N/mm^2, but there is an important dependence on the stressed volume, see Table 1 and STEP lecture B1. The volume effect for the other strength properties is less pronounced. The tensile strength $f_{t,90}$ is considerably reduced by defects like fibre disturbances and initial cracks, especially in the earlywood.

EC5: Part 1-1: 5.1.3

Also the modulus of elasticity is much lower perpendicular to the grain, E_{90} = 400 to 500 *N/mm²*, than parallel to the grain.

In the design of timber structures tensile stresses perpendicular to the grain should be avoided or kept as low as possible. It is important to identify areas of a structure, where tensile stresses perpendicular to the grain occur and to make design improvements to reduce their magnitude. Examples are members like curved beams and frame corners in glulam structures, notched beams at the support or beams with holes, certain connections, see STEP lectures B5 and C2.

Compression parallel to the grain
The compression test specimens have to be short enough to avoid overall (column) buckling. As can be seen from the curve in Figure 2, the fibres will successively yield until a maximum load is reached. The failure mode is by buckling of a row of fibres, see Figure 3. It is a kind of local instability due to shear along a sloping plane.

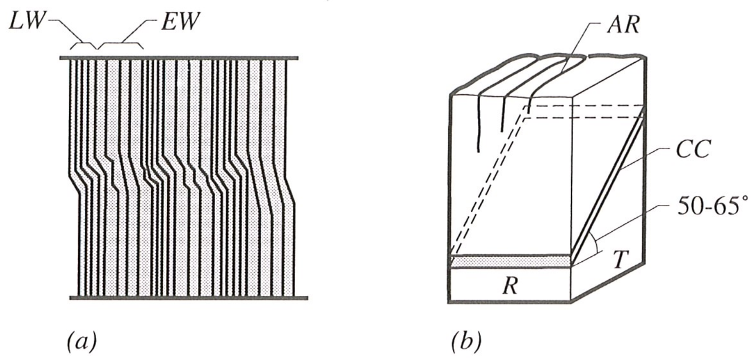

Figure 3 *Compression failure at $f_{c,0}$. Buckling of fibres. (Hoffmeyer, 1990). LW latewood, EW earlywood, AR annual rings, CC compression creases.*

The modulus of elasticity is $E_{c,0}$ = 11000 to 15000 *N/mm²* as in tension, but the stress-strain-curve levels off earlier, so the limit of proportionality is also of interest.

Compression perpendicular to the grain
In the case where the whole specimen is loaded (case (*a*) in Figure 4), the fibres are just squeezed together like a bundle of tubes until a kind of squash load is reached, where the tangent modulus becomes very low. At the maximum load the strain is very large.

When just a portion of the upper wood surface is loaded, the stiffness is higher and the change in stiffness will occur at a higher stress than for case (*a*), and this stiffness change will be less pronounced than for case (*a*) and corresponds to a bend in the stress-strain-curve, see Figure 4. The reason for this is that the concentrated load will be carried over by the fibres to the neighbouring unloaded parts. In case (*b*) these unloaded parts are too short so a maximum load is reached just above the bend.

For cases (*c*), (*d*), and (*e*) the loading test can be continued to a higher strain than that in Figure 4 without any pronounced failure. However, the deformations will be considerable. Therefore, it is practical to limit the strains to a certain value, say 1%, and to use the corresponding stress as a kind of strength (or "proof stress") value. In this case $f_{c,90}$ = 2 to 4 *N/mm²*. However, the values will also depend on the orientation of the annual rings in the cross sections of the loaded bar, see Figure 5.

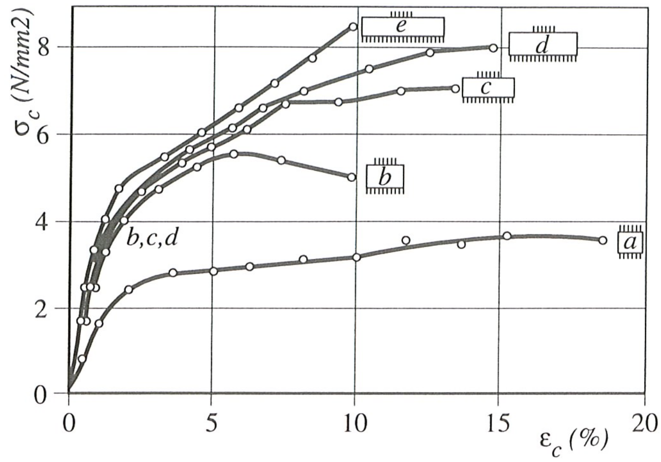

Figure 4 *Applied stress perpendicular to the grain vs. vertical compressive strain from tests on timber 15 x 15 cm². Suenson (1938).*

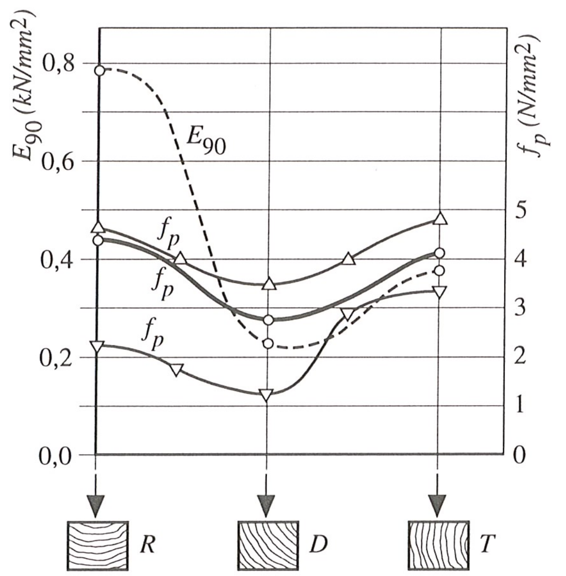

Figure 5 *Wood in compression perpendicular to the grain. Modulus of elasticity and stress limit. Here f_p = $f_{c,90}$ is the limit of proportionality. Values from Siimes and Liiri (1952) and Gaber (1940).*

Loading at an angle to the grain

Let α be the angle between the load direction and the grain direction.

Hankinson (1921) proposed the following equation for the failure stress $f_{c,\alpha}$ in compression.

$$f_{c,\alpha} = \frac{f_{c,0}\, f_{c,90}}{f_{c,0}\,\sin^2\alpha + f_{c,90}\,\cos^2\alpha} \tag{1}$$

which gives good agreement with test results. For the strength under tensile load at an angle to the grain an analogous expression can be used, i.e. with f_c being replaced by f_t, compare Figure 6a and 6b.

It is seen in Figure 6, that for small angles α the strength is very sensitive to changes in α, i.e. small deviations in slope of grain will cause a significant strength reduction, especially for tensile load. On the other hand, for $\alpha \approx 90°$, i.e. near $f_{t,90}$ and $f_{c,90}$, there is practically no change in tensile and compressive strength when the angle is changed by 10 to 12 degrees. It may be shown (Edlund, 1982) that, for the case of a symmetric orthotropic material, Equation (1) is a real linear approximation to the more general Tsai-Wu failure criterion for orthotropic materials.

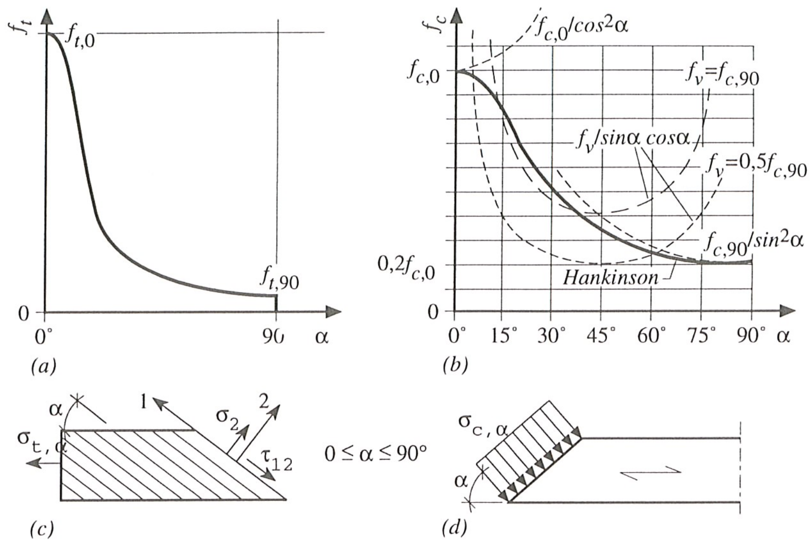

Figure 6 *Failure due to load at an angle to the grain. (a) tension; (b) compression. The fully drawn curves are according to Hankinson, Equation (1); the dashed curves are when the failure condition of one pure stress $f_{c,0}$, $f_{c,90}$ or f_v is attained.*

For uniaxial tension or compression with an angle α to the 1-axis (the natural axes of orthotropic materials are 1 and 2), Figure 6c, 6d, the equilibrium equations are:

$$\sigma_1 = \sigma_\alpha \cos^2\alpha \qquad (2)$$

$$\sigma_2 = \sigma_\alpha \sin^2\alpha \qquad (3)$$

$$\tau_{12} = \sigma_\alpha \sin\alpha \cos\alpha \qquad (4)$$

For comparison, the limit curves for the three separate failure conditions $\sigma_1 \le f_{c,0}$, $\sigma_2 \le f_{c,90}$ and $\tau_{12} \le f_v$ are also plotted in Figure 6b (dashed curves).

Structural timber under tension and compression

General

For timber in structural sizes used in load-carrying structures the effect of different inherent defects such as knots and slope of grain must be considered. A knot of "ordinary" size reduces the effective cross-section of a board and is associated with local fibre disturbances. This often results in load eccentricities and high local stresses. Further, where the fibres change direction around a knot in a uniaxially loaded board stresses perpendicular to the grain will be induced. This is especially important for timber loaded in *tension* parallel to the grain.

Although the tensile strength for clear wood loaded parallel to the grain is much higher than in compression, the reverse is true for structural timber. This is partly due to the sensitivity to slope of grain mentioned above in connection with Figure 6, partly to the brittle type of failure and the size effect (see STEP lecture B1), which comprises all other types of defect as well.

With regard to important influences of load duration (creep) and moisture see STEP lectures A4 and A19.

Tension
The inhomogeneities and other deviations from an ideal orthotropic material, which are typical for structural timber, are often called defects. As just mentioned, these defects will cause a fairly large strength reduction in tension parallel to the grain. For nordic softwood (spruce, fir) typical average values are in the range of $f_{t,0}$ = 10 to 35 *N/mm*^{2}. In several investigations the mean of $f_{t,0}$ was found to decrease proportionally with the increase in size of the largest knot diameter. However, the scatter is large and the correlation poor. The values obtained also depend on the test method, since failure may be induced by the stress concentrations at the end grip devices.

EC5: Part 1-1: 3.2.2

In EC5 the characteristic strength values of solid timber are related to a width in tension parallel to the grain of 150 *mm* and to a volume of 45 x 180 x 70 *mm*^{3} = 5,67 $\cdot$ 10^{-4} *m*^{3} for the tensile strength perpendicular to the grain. For widths in tension of solid timber less than 150 *mm* the characteristic values may be increased by a factor k_h which is the smallest of $(150/h)^{0,2}$ and 1,3.

EC5: Part 1-1: 3.3.2

For *glulam* the reference width is 600 *mm* and, analogously, for widths smaller than 600 *mm* a factor k_h should be applied which is given as the smallest of $(600/h)^{0,2}$ and 1,15.

Tests by Johansson (1976) on 296 spruce (*Picea abies*) laminations 33,3 x 155 *mm* show that there is also poor correlation, $|r|$ = 0,5 to 0,6, between the tensile strength on one hand and density and ring width on the other. But, if knot data and density are combined into one parameter a considerably better prediction of the tensile strength may be achieved (coefficient of correlation r = 0,80). The modulus of elasticity measured near the location of failure (called ESF) is the single parameter, measured by Johansson (1976), that gives the best correlation with the tensile strength (r = 0,86). Some improvement was obtained if the parameters ESF and knot data were combined (r = 0,89). Similar conclusions are drawn in an investigation by Glos (1982).

For long boards under uniaxial tension due consideration should be taken both of the size effect (length effect) and of the lengthwise variation of the tensile strength, see, for example Barrett (1974) and Lam and Varoglu (1991).

For tension perpendicular to the grain the size effect is especially important, see Table 1.

Volume (*m*^{3})	2,6 $\cdot$ 10^{-2}	2,5 $\cdot$ 10^{-3}	2,8 $\cdot$ 10^{-4}	2,7 $\cdot$ 10^{-5}
$f_{t,90}$ (*N/mm*^{2})	0,63	1,0	1,8	2,4

Table 1 *Tensile strength $f_{t,90}$ perpendicular to the grain - dependence on the stressed volume. (Larsen and Riberholt, 1981).*

Compression
The strength in compression *parallel* to the grain will be somewhat reduced by the growth defects to $f_{c,0}$ = 25 to 40 *N/mm*^{2}. The reduction in strength depends on the testing method. If the specimen is compressed between two stiff end plates, which are restrained from rotation, a local failure of some fibres will lead to stress redistribution over the rest of the cross section. This will result in a higher average stress than if the specimen had been loaded via a hinged end-plate.

The influence of growth defects on the strength perpendicular to the grain is small.

Concentrated loading perpendicular to the grain
As mentioned above and demonstrated in Figure 4 the stress $\sigma_{c,90}$ at the bend of the stress-strain curve is much higher when the distribution length of a (compressive) load becomes smaller, provided that there is enough unloaded length a from the load to the end of the loaded member, see Figure 7.

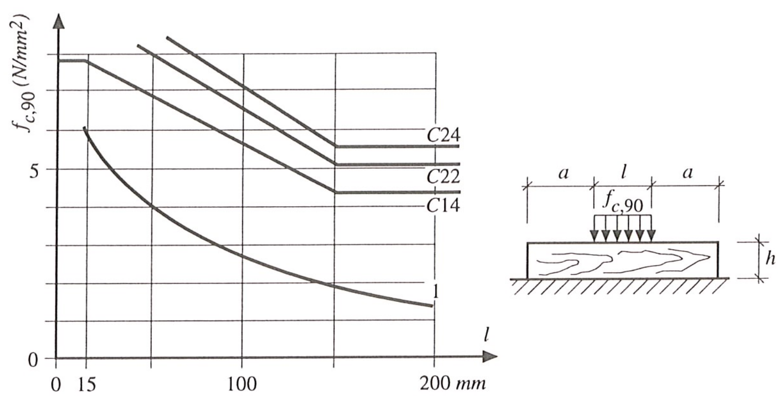

Figure 7 *Compressive "yield" stresses for patch loading with length l on a member supported along its whole length (bottom line) compared with strength values for different strength classes according to EC5 (a ≥ 100 mm). Values from Baumann and Lang (1927) and Backsell (1966).*

In structural codes this effect is usually taken into account by the coefficient $k_{c,90}$ in a condition of the type

EC5: Part 1-1: 5.1.5

$$\sigma_{c,90,d} \leq k_{c,90}\ f_{c,90,d} \qquad (5)$$

In EC5 there will be no increase in bearing strength for $l \geq 150$ *mm*, see Figure 7. If $a \geq 100$ *mm* a linear increase may be assumed for the coefficient $k_{c,90}$ in the interval $15 \leq l \leq 150$ *mm* up to a value $k_{c,90}$ = 1,8 for $l \leq 15$ *mm*. For smaller edge distances, i.e. $a < 100$ *mm*, the increase will be smaller, see Table 2.

	a < 100 *mm*	$a \geq$ 100 *mm*
$l \geq$ 150 *mm*	1	1
15 *mm* < $l \leq$ 150 *mm*	1 + a(150 - l)/17000	1 + (150 - l)/170
l < 15 *mm*	1 + a/125	1,8

Table 2 *Values of $k_{c,90}$ in Equation (5) given by EC5 for the case shown in Figure 7.*

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