Effects of climate and climate variations on strength

Ranta-Maunus, Alpo

1. Introduction

Wood is hygroscopic material which takes water from surrounding air, and the moisture content of wood tends to settle down to equilibrium with the air humidity. As a consequence, moisture content of wood is different under different climatic conditions. This is of importance, because moisture content has a direct effect on the strength of wood: normally the strength is low when the moisture content is high. However, not only the level of moisture content is important: fast changes cause moisture gradients in wood, which induce stresses in perpendicular to grain direction and may cause splitting of the wood. In addition, varying moisture has negative effects on the strength and stiffness of timber under long term loading; this is however not the topic of this paper, but is covered in other papers.

This paper first briefly describes the range of variation of the moisture content of wood under different climates and seasons. Next chapter is about the influence of moisture content level on the strength of timber, which is an area where a large amount of research has been done, and it will be covered only partly, to an extent which is thought to be relevant to the design of timber structures. The rest of the paper illustrates cases where weather change, and related transient moisture content in the wood increase the risk of failure and should be considered as an extra loading of the structure. This is a fairly new topic in research, and has not yet been included in design standards.

2. Moisture content in wood caused by naturally varying climate

Long-term mean values of equilibrium moisture contents (EMC) of wood exposed to outdoor air in different climates have been published in Wood Handbook for different locations in the USA. In northern climate the maximum is during winter, and the minimum during summer. In continental climate in the North (Missoula, Minnesota), the range is from 9,8 to 17,6%. In southern areas maximum is reached during summer and minimum during winter, as in Los Angeles (EMC=12 to 15%). In addition, there are zones with fairly constant moisture contents from dry desserts (below 10%) to humid coastal areas (14-15% in New Orleans). In heated or air conditioned rooms RH is normally lower than outdoors. RH may be increased by moisture producing activities as cooking, bathing or drying laundry. American recommendations on moisture contents to which wood should be dried when used indoors are shown in Fig. 2.1. In Nordic climate the average moisture content of wood is often 12% during summer, and 6% during winter. Accordingly, wood should be dried to this range, and often 8% is recommended.

Conditions in heated and in sheltered, unheated buildings in Nordic countries are characterised by Figures 2.2 to 2.4. Fig. 2.2 shows RH and temperature measurement in heated (left) and unheated (right) buildings in Finland. Both buildings are massive: the heated building is VTT underground research hall in base rock, which is ventilated but RH is not regulated, and the unheated building is an old granary made of stone. As part of long term loading experiments, measurements of the average moisture content have been made by weighting test pieces.

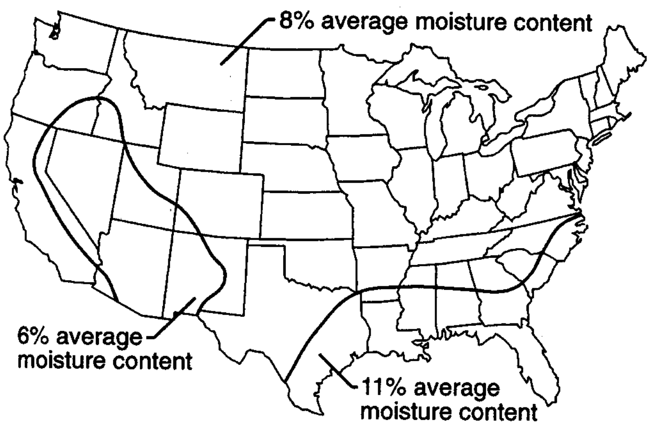

Figure 2.1 Recommended moisture content of wood for interior use in the USA (FPL Wood Handbook)

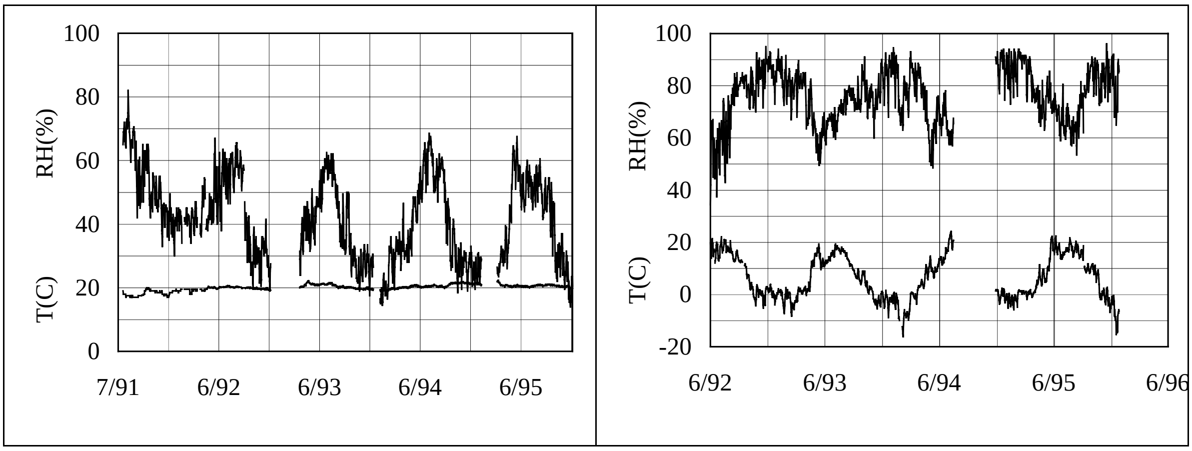

Figure 2.2 Changes in relative humidity and temperature (daily mid-day values) in heated room in Espoo (left) and in sheltered environment in Kirkkonummi (right)

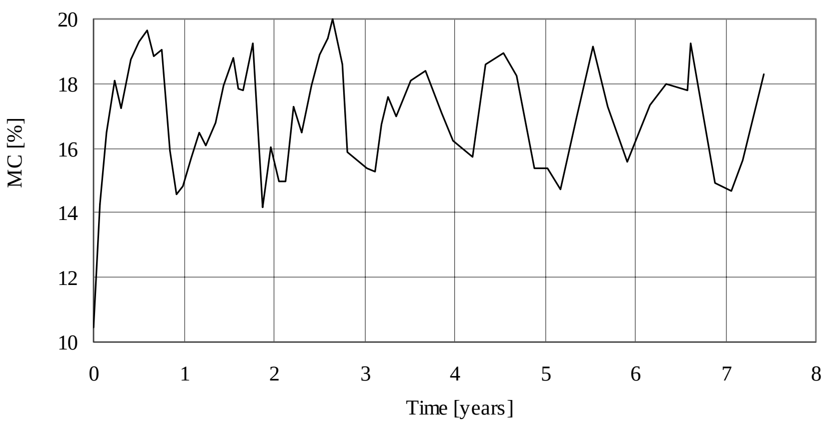

Figure 2.3 Mean moisture content of 3 end-sealed, untreated 16 to 22 mm thick boards in sheltered environment in an unheated room in southern Finland (Kirkkonummi). Time scale begins in June 1992

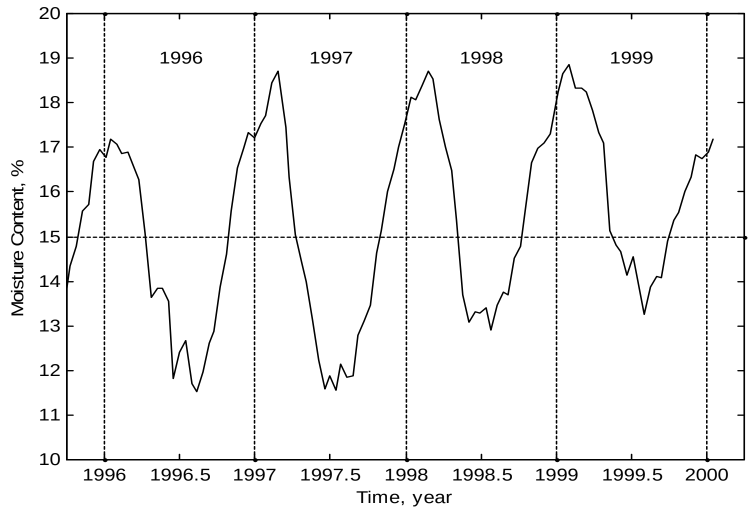

Figure 2.4 Mean moisture content in wood (glulam 90x100x600) versus time in a barn in Southern Sweden (Åsa) (Gustafsson et al 1998)

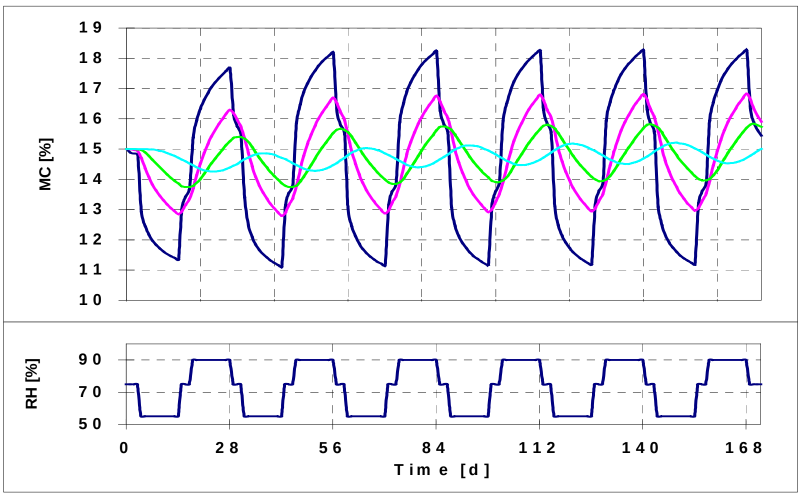

Figure 2.5 Calculated moisture history in cyclic tests in different depths from surface (0, 10, 20 and 45 mm) of 90 mm thick glulam (Fig. 61, Gowda et al 1998)

Fig. 2.3 shows the variation of the mean moisture content in thin timber in the Kirkkonummi building, and Fig. 2.4 that of glulam in a barn in Åsa, Sweden. The latter measurements are made more often and regularly, once in every 2 weeks, and give a more accurate picture of moisture variation, annual minimum and maximum values ranging from 12 to 19%MC.

Moisture content in glulam under transient situation is illustrated in Fig.2.5 where calculated values of moisture contents in different depths are shown. The RH cycle has a length of 4 weeks with maximum RH of 90% and minimum of 55%.

3. Strength at different equilibrium moisture contents and temperatures

Changes in moisture content of wood products cause shrinkage (or swelling), as well as changes in strength and elastic properties. Shrinkage reduces member cross-sectional area, section modulus and moment of inertia.

The experimental results show that bending and compression strengths generally increase with decreasing moisture content below the fibre saturation point. For member capacities similar trend is observed in spite of the opposite effect of shrinking dimensions of cross-section. Tension strength depends less on moisture content, and this dependence is normally neglected.

Mechanical properties in high quality material are affected more by moisture than in law quality. Numerical models for strength and capacities of American and Canadian lumber are given in handbooks (Barrett et al 1994, FPL Wood Handbook 1999). Moisture effects are often expressed in a simplified way: change in property (%) caused per one percent point change of moisture content. Table 3.1 shows such results for clear wood (Hoffmeyer 1995), round timber (Ranta-Maunus 1999) and values adopted in CEN-standard EN 384 to adjust 5th percentile values of sawn timber. In standard EN 384 no adjustment is used for bending and tension strengths. This reflects the fact that the lowest 5th percentile of the material is very little influenced by moisture. More detailed illustration of the effect of moisture on different fractiles of strength of European and American timber is shown in Figures 3.1 to 3.3.

Even if dry wood has higher strength than wet wood, and the trend is obvious, there is a limit in moisture content below which wood is not getting stronger when drying; on the contrary it may become weaker. This limit is not identical for all species and loading directions, but as a rule of thumb wood has its maximum strength around 10% moisture content. If the low moisture content is a result of long term exposure to elevated temperatures, this may be an additional reason for reduced strength. When the temperature is above 60°C, the exposure degrades wood, and the strength is permanently reduced (Fig. 3.4). Also the strength of normal timber tested at elevated temperatures is reduced, depending on temperature and moisture content. Structures are, however, seldom at so high temperatures that the strength and stiffness reduction needs to be considered.

Table 3.1 Effect of moisture content change to mechanical properties of softwoods (%/%) between 8 and 20% MC. Values of clear wood and round timber are average effects, values of sawn timber are for characteristic values.

Property	Clear wood	Round timber	Sawn timber (EN 384)
Compression strength (// and ⊥)	5	5	3
Bending strength	4	1	0
Tension strength (//)	2,5		0
Tension strength (⊥)	2		
Shear strength	3		
Impact bending strength (//)	0,5		
Modulus of elasticity (//)	1,5		2

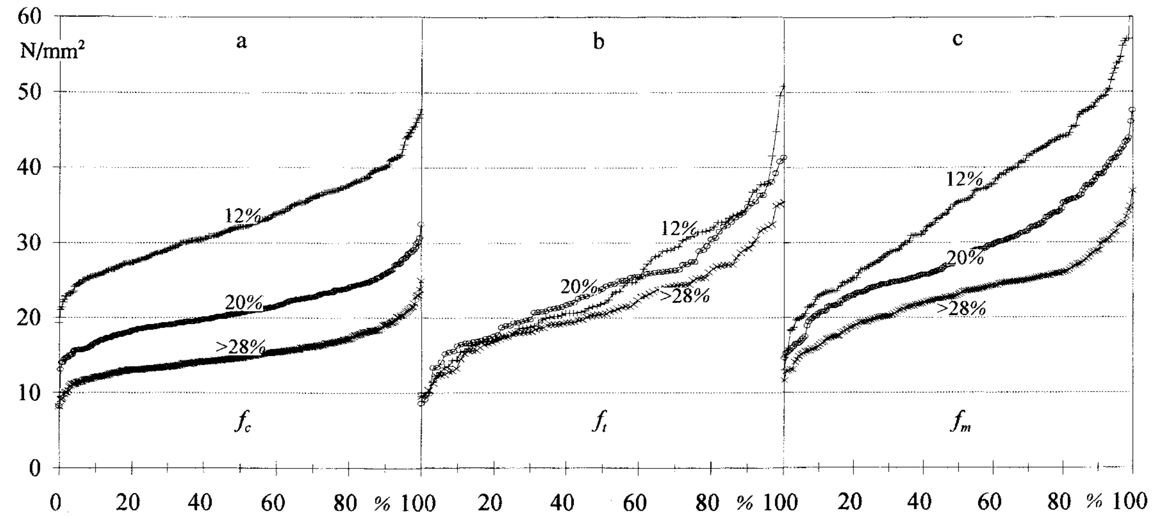

Figure 3.1 Compression (f_c), tension (f_t) and bending (f_m) strength vs. percentile of matched samples of spruce (Picea abies) at moisture contents 12, 20 and over 28 according to Hoffmeyer (1995)

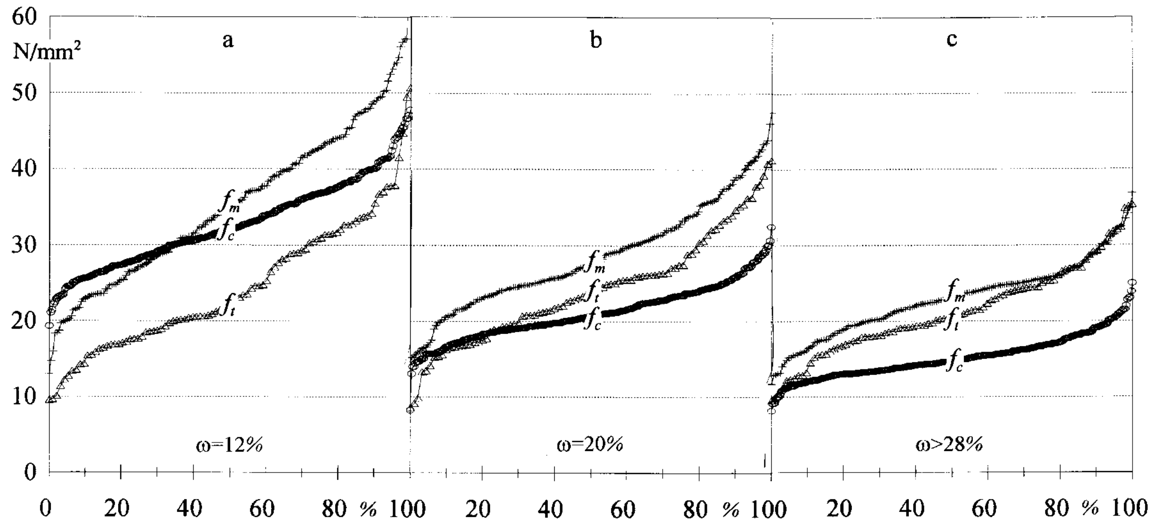

Figure 3.2 Bending (f_m), tension (f_t) and compression (f_c) strength vs. percentile of matched samples of spruce (Picea abies) at moisture contents 12, 20 and over 28 according to Hoffmeyer (1995). Reorganisation of results shown in Figure 3.1.

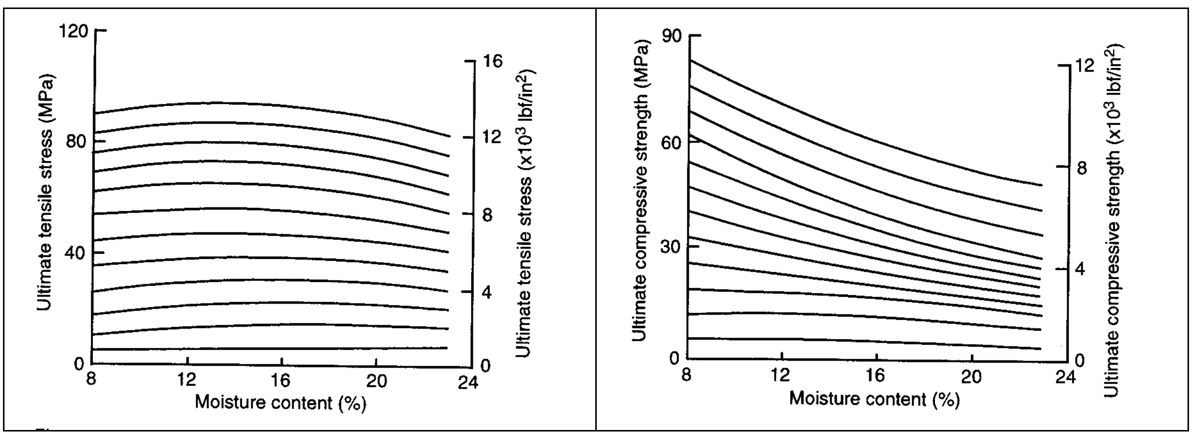

Figure 3.3 Effect of moisture content on tensile and compressive strength on different quality levels of American lumber (FPL Wood handbook)

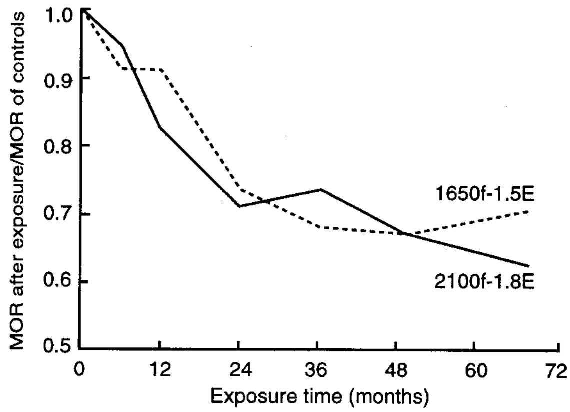

Figure 3.4 Permanent effect of exposure to 66 °C temperature to the bending strength of timber (FPL Wood Handbook).

4. Effect of moisture gradients on load carrying capacity

4.1 Experimental results on capacity of curved beams with moisture gradients

Two programs have been carried out to determine the duration of load effect on the tension strength perpendicular to grain in different sized curved beams exposed to cyclically varying humidity. The earlier project (VTT) was made 1991-1993 (Ranta-Maunus et al 1994). The later, more comprehensive project (EU/AIR) was completed 1997 (Aicher et al 1998, Gowda et al 1998). As part of the AIR-project tensile tests with specimen volumes 0.01 and 0.03 m^3 were made by FMPA in Germany.

In the experiments with 4 weeks duration on one stress level, the ratio of failure load under changing humidity to the short term strength, k_{DOL} ranges from 0,45 to 0,66 for uncoated specimens (Table 4.1) whereas the ratio in similar experiments at constant humidity is about 0,8, the reference DOL-curve at constant humidity being given in Fig. 4.1 (Ranta-Maunus 2001). The difference is caused by the moisture gradients. k_{DOL} is determined for the average beam in test series with variable humidity. The results show that the moisture cycles used will roughly double the effect of load duration. Wider cross-sections are less sensitive to moisture cycling than narrow ones. An effective protection against changing moisture appears to be normal surface treatment with alkyd paint. It prevents the major part of the effect of moisture cycling with cycle length of 4 weeks.

Based on the first experiments it was observed that when curved beams loaded under constant load experienced several similar moisture cycles, the beams surviving the first cycle did not fail during the following moisture cycles. The conclusion is that the magnitude of moisture induced stresses is the primary reason for failure, not the number of cycles or duration of load. A combined moisture and structural analysis indicates that the stress distribution is essentially the same during successive moisture cycles, which supports the assumption that it is enough to analyse the most severe moisture change, not the whole history. Accordingly, the effect of cyclic moisture history affecting on structures loaded by tension stresses perpendicular to grain, may be seen rather as an extra load than part of duration-of-load effect weakening the material under long term loading. If this effect is considered as a DOL-effect, and results obtained during a few weeks loading are extrapolated on logarithmic time scale to several years duration, extremely low and unjustified strength values would be obtained.

Nearly all failures took place during the humid part of the moisture cycle, when the surface of the beam was under compression stress, and internal parts under increased tension stress.

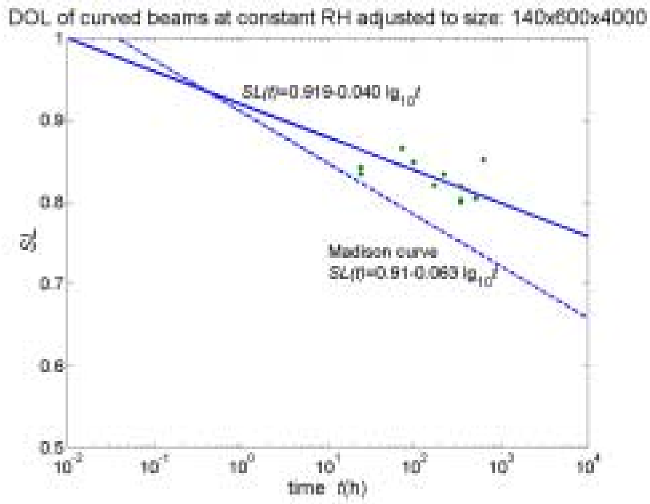

Figure 4.1 Relative stress vs. time-to-failure graph of curved beams at constant moisture content failing due to tension perpendicular to grain. Madison curve is here for comparison.

Table 4.1 Comparison of DOL- factors obtained in cyclic humidity tests (Aicher et al 1998)

	VTT S2 painted curved beams	VTT S1&3 curved beams	AIR S2 curved beams	AIR S6 curved beams	FMPA small tensile	FMPA small tensile	FMPA large tensile	FMPA large tensile
Conditioning RH (%)	70	70	75	75	65	65	65	65
RH cycle (%)	40<->85	40<->85	55<->90	55<->90	55<->90	natural	55<->90	natural
Width (mm)	90	90	90	140	90	90	140	140
Time to failure (days)	13	20	28	17	18	2.6	19	25
k_{DOL}	0.76	0.55	0.60	0.66	0.45	0.60	0.50	0.64

4.2 Experiments with notched beams

Experiments similar to those of curved beams, described in Chapter 4.1, have been made with end-notched beams both in cyclic laboratory and natural environments (Gustafsson et al 1998). The result is different from curved beams: highest load capacities are obtained during season when moisture content is increasing, and lowest when wood is drying or at equilibrium moisture content.

Obviously, due to humidity variation, a moisture gradient is created also in the grain direction in the notched area causing compressive or tensile stresses perpendicular to grain, depending on the moisture transient. If the potential crack initiation area at the notch is compressed, a friction like phenomenon is observed: load capacity is increased, but when the failure occurs, it is fast and brittle. Whereas the load level at failure is lower and the fracture development is slower, if the crack is initiated and kept open by a drying moisture transient. When the notch is coated, the effect of moisture transient is smaller, and the time to failure in long term experiments is longer. The moisture related effects to strength were more pronounced in large (300 mm high) than in small (100 mm) beams.

4.3 Connections

Some failures have taken place in timber structures, because shrinkage of glulam cross-section has been prevented structurally in connection area. It is quite obvious, that a beam may crack, when it is rigidly fastened at two locations far from each other in direction perpendicular to grain, and exposed to a moisture transient. Another reason for failure of this type of structure is that after moisture movement, load distribution to connectors may change drastically. However, these important cases when the shrinkage of entire cross-section creates stress resultants in direction perpendicular to grain, are not analysed in this paper.

Also moisture gradients in wood may reduce the capacity of connections, even if the moisture movement of the cross-section is not restricted and moisture induced stresses are self balancing as in case of curved beams. The author is, however, not aware of published results in which the effect of moisture changes could be separated from the pure mechanical load effect.

5. Calculation of moisture induced stresses

The state of stress in wood is affected not only by external loading, but also by moisture variation, because free moisture movement is restricted. Swelling and shrinkage are strongest in directions perpendicular to grain and therefore moisture induced stresses appear primarily in that direction. Most directly moisture induced stresses are caused in drying of wood: when green wood is dried, often many cracks are created even without any external load. Stress development and cracking during drying has been analysed by several researchers, but will not be elaborated here. There are some basic differences to structural applications: initial moisture content is above fibre saturation point, and drying temperature is higher than in normal environment of structures. This makes creep phenomena still more important in the analysis of industrial wood drying than in the analysis of structures. Also, the coupling of heat and mass transfer is more important in kiln drying: heat is transferred to wood in order to dry it via circulated air, which is also transporting the humidity. Accordingly, the needs in analysis of structures are different from those of in wood drying, and an excellent engineering procedure in wood drying may be inadequate for structures and vice versa.

5.1 Calculation method

Calculation of moisture induced stresses in directions perpendicular to grain includes calculation of moisture distributions in wood at different times, and calculation of stresses caused by restrained moisture deformations and external loads. The numerical calculation can use basic equations as follows:

Moisture transport inside wood in one dimension can be calculated using the diffusion equation with an effective diffusion coefficient D_{eff}:

$$\frac{\partial}{\partial t}\int_V u\,dV = \oint_{\partial V} D_{eff}\frac{\partial u}{\partial x}dS \qquad (5.1)$$

where u is moisture content. The equation states that the rate of moisture change in volume V is proportional to the gradient of moisture content, integrated over the boundary of the volume V. The effective diffusion coefficient can be determined as dependent on moisture content u as

$$D_{eff} = \exp(a_0 + a_1 u) \tag{5.2}$$

The mass flux density at the boundary is calculated using an analogy between heat and mass transfer given by the boundary-layer theory:

$$F_u = k_{paint} \beta_l (p_v^* - p_v) \frac{\beta_w}{\beta_l} \tag{5.3}$$

where k_{paint} is the resistance caused by surface coating (where applicable), and β_l is the mass transfer coefficient from liquid water. p_v is the vapour pressure, and p_v^* the vapour pressure at the wood surface which is characterised by the sorption curve. The last correction term is the difference between vapour emission from wood and liquid water surfaces and is a function of the moisture content of the wood surface. More details on moisture transport can be found in literature (e.g. Hukka 1999).

Boundary condition can be formulated also in terms of moisture difference instead of vapour pressure difference. The equations can be solved by numerical methods like finite element, finite difference or control volume method.

The calculation of stress is based on a constitutive model including shrinkage, elastic, viscoelastic and mechano-sorptive strain component:

$$\varepsilon_{tot} = J_0 \cdot \sigma + \varepsilon_{ve}(\sigma) + \varepsilon_{ms}(\sigma) + \varepsilon_s \tag{5.4}$$

It is essential to include mechano-sorptive effect in the equation. Otherwise we obtain far too high stresses. We have modelled the viscoelastic behaviour using the generalised Kelvin material model with seven Kelvin-units in series, and the elastic response is included within the viscoelastic model. Time-moisture content equivalence and a shift factor is used in modelling the dependency of creep rate on moisture content. Mechano-sorptive creep is also modelled using four Kelvin units in series, whose deformation depends on the absolute value of the moisture content change but not on time. As a background reading on constitutive modelling of wood, a paper of Hanhijärvi (2000) is recommended.

In one-dimensional case when only moisture gradient through thickness is considered, and if additionally tension stress perpendicular to grain is caused by a bending moment loading a curved beam, boundary conditions have been applied as follows:

1: condition of equilibrium of forces:

$$\int_A \sigma dx = \frac{3M}{2Rh} \tag{5.5}$$

where A is area of through width of cross-section with unit length, M is the bending moment acting on the curved beam, R is the mean radius of curvature and h is the height of the beam.

2: as condition of compatibility, total strain is assumed to be constant throughout the cross-section.

In the cross-section of glued laminated timber, the different elastic properties in radial and tangential directions have to be taken into account. In 2-D analysis this is done by considering the pith location of each lamella and local material orientation accordingly. In 1-D analysis this has been done by using local effective E-values depending on pith location (Gowda et al 1998).

Numerical methods to solve the equations are not discussed here. Instead, some published results will be reported. Stresses perpendicular to grain in curved glulam beams caused by external load (bending moment) and varying humidity of air have been calculated and an example of stress distribution at different times is shown in Fig. 5.4. The great variability of stress in the width direction rises a question about the cracking criterion: does the failure take place when the critical value of stress is exceeded locally or should a more developed criterion be adopted. At least in principle, the maximum stress can be anywere in the cross-section, most likely in the middle of beam or at surface. Another complication is that strength is different in different orientations in the RT-plane. Accordingly, we should use a criterion which takes all these aspects into consideration and preferably is based on fracture mechanics. We have applied, instead, Weibull theory, which is normally used for the analysis of different size effects and load configuration factors. Here it has been applied also to analyse the severity of stress distribution within a cross-section. The effective Weibull stress caused by external mechanical loads and moisture effects is calculated as

$$\sigma_W = \left(\frac{1}{V_{\mathrm{ref}}} \int_V \sigma_{t,90}{}^k dV \right)^{1/k} \tag{5.6}$$

where $\sigma_{t,90}$ means tension stress perpendicular to grain. Equivalent stress calculated by eqn.(5.6) gives the value of constant stress in the reference volume V_{ref} causing the same probability of failure as the actual stress distribution in the actual volume V. More details on the calculation are reported in other papers (Gowda et al 1998, Aicher et al 1998, Ranta-Maunus 1998).

5.2 Calculated examples

The method described above has been used to analyse the experiments made with curved beams and tension specimens. Fig. 5.2 shows that the stress in the middle of beam is higher than at surface, and the maximum is reached during the wetting part of the moisture cycle. This is caused by the cylindrical orthotropy of wood: the central part of the material carries most of the load because wood is much stiffer in radial direction than in directions between R and T. In this case the effective Weibull stress is nearly the same as the value of stress in the middle of beam. The stress distribution at time 126 and 140 days is shown in Fig. 5.4. Stresses depend on the width of the beam: results for 140 mm wide beam are shown in Fig. 5.3 for comparison to 90 mm wide beam in Fig. 5.2. Obviously, the time needed for development of maximum moisture induced stresses depends on the dimensions of the timber member.

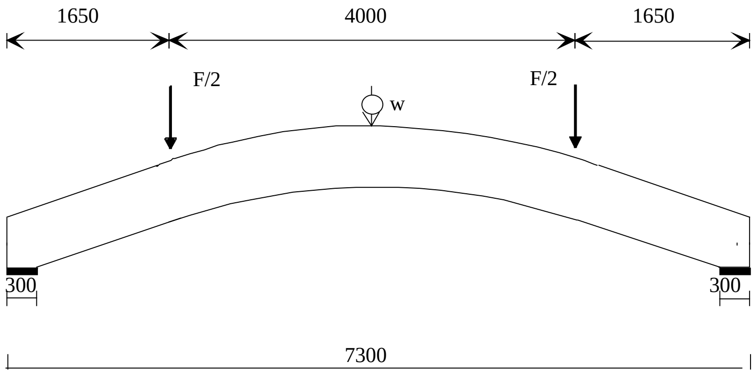

Figure 5.1 Example of the analysed and tested curved glulam beam.

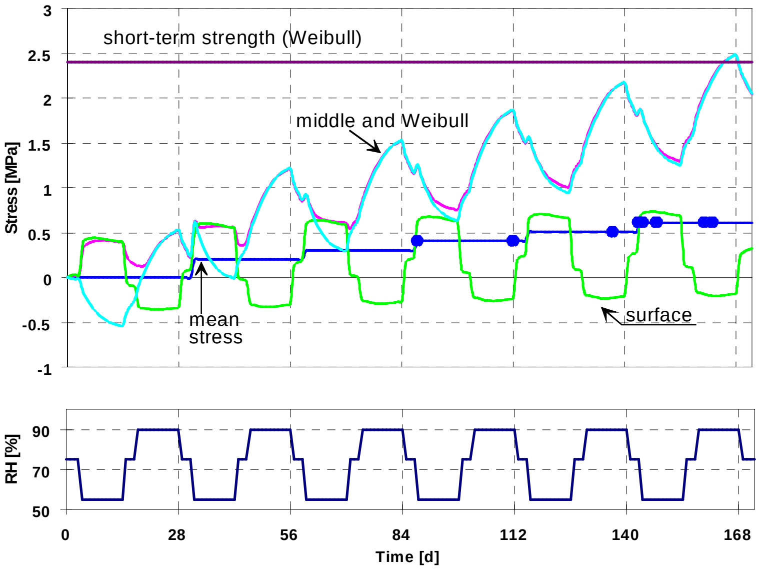

Figure 5.2 Calculated vertical stresses in the middle and at the surface of 90 mm wide beam simulating test at relative humidity cycling between 55 and 90 %. Dots on the mean stress curve denote the times of failures of beams in test (Fig. 58, Gowda et al 1998).

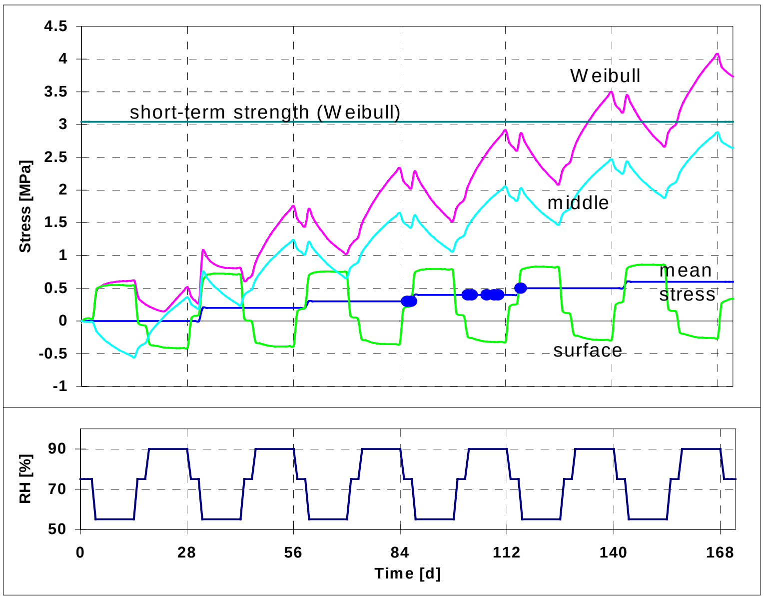

Figure 5.3 Calculated vertical stresses in the middle and at the surface of 140 mm wide beam simulating test at relative humidity cycling between 55 and 90 %. Dots on the mean stress curve denote the times of failures of beams in test (Fig. 62, Gowda et al 1998).

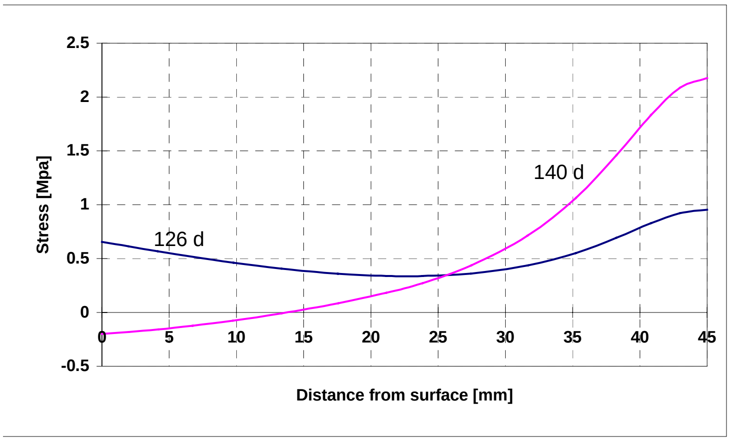

Figure 5.4 Calculated stress distribution for half thickness of 90 mm wide beam in test after dry period (126 d) and wet period (140d). The calculated Weibull stresses at the same times are 1.01 and 2.17 MPa, respectively (Gowda et al 1998)

The effect of moisture cycles is compared to the effect of mechanical loading at equilibrium moisture content by computing the value of mechanical load (average stress) which causes the same Weibull stress as a combination of mechanical and moisture load. The results are given in Table 5.1. Test cycles and a single humidity changes have been analysed. Moisture load corresponds to an extra load of 0.15 to 0.35 MPa when acting simultaneously with mechanical load of 0.2 MPa, when the beam is not surface coated. A good surface coating (vapour barrier) will decrease the moisture load from 0.15 to 0.05 MPa. A single fast change from 65 % RH to 90 % RH seems to be more severe than the test cycles analysed. The conclusion is that fast changes of climate from dry weather to wet season with duration of several weeks are most harmful for structures loaded by tension stress perpendicular to grain. A comparison of calculated moisture loads and observed failure loads is made in a simple way. Results of Table 5.1 (external load 0.5 MPa) are compared to test results: difference of failure load at constant and cyclic humidity test. Results plotted in Fig. 5.5 indicate that calculated stresses are normally higher than observed ones. This discrepancy may be partly caused by differences between the real test conditions and the simplified ones used in the analysis: the cycle used at FMPA was calculated as a single change from 65 to 90%RH.

Table 5.1 Calculated equivalent (mean) stresses for combinations of moisture cycling and load (Ranta-Maunus 1998).

Thickness (mm)	RH cycle	Equivalent load for combined effect external load 0.2 MPa	external load 0.5 MPa
90	55%<->90% 1	0.45	0.81
140	55%<->90% 1	0.36	0.73
90	40%<->85% 2	0.35	0.71
90	40%<->85% 2painted	0.25	0.57
90	76%->90%3	0.40	0.73
90	65%->90%3	0.52	0.87
140	76%->90%3	0.41	0.75
140	65%->90%3	0.55	0.90

1) Test cycle in AIR experiments at FMPA and VTT
2) Test cycle in earlier VTT study
3) Single fast change from equilibrium, lasting for 4 weeks.

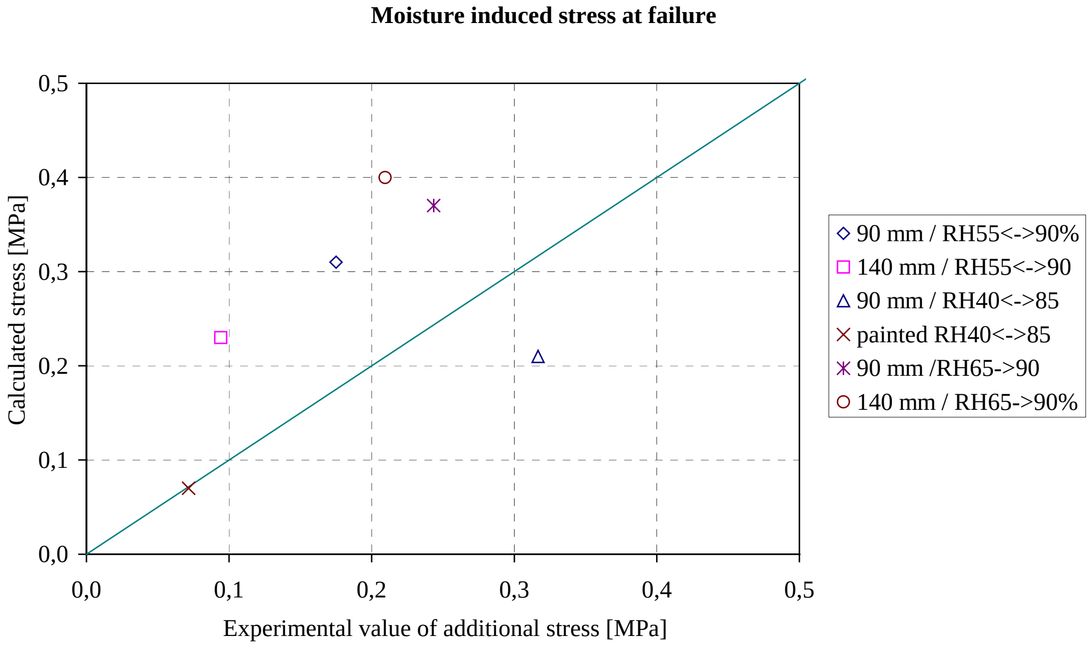

Figure 5.5 Comparison of calculated moisture stresses and experiments

6. Effect of moisture gradients to test results

Stresses caused by moisture gradients are very important also in test situations. When tested under tension in direction perpendicular to grain, test specimens should be conditioned to test moisture content with a special care. The moisture gradients have a considerable effect to test result which may be too low or high depending on the gradient. This is important both in short term and long term testing. If a long term test is made at constant humidity, but the conditioning humidity is not exactly the same as during loading, a moisture gradient will be created. If the difference is 3% in EMC, so that the test specimen is wetting during experiment, as much as 35% lower strength values may be obtained. If the change is in drying direction, the result is too high strength value. This is illustrated in Fig. 6.1 where a long term test under stepwise increasing load is analysed at constant humidity when the conditioning moisture content is correct, and when it is 3% higher or lower. The effective Weibull stress is shown for these 3 cases indicating that the highest effective stress is nearly double the lowest one. This is expected to increase the variability of test results obtained.

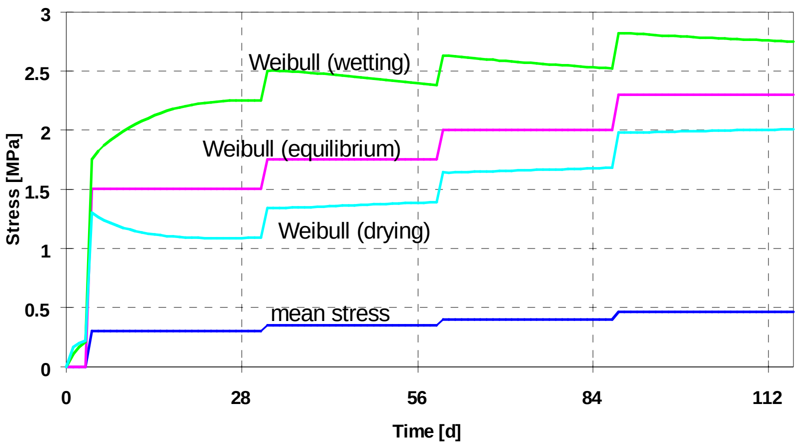

Figure 6.1 Calculated Weibull stresses in 140 mm wide test beams when pre-test conditioning moisture content is the same as during the test or 3% EMC lower or higher (Fig. 57, Gowda et al 1998)

7. Consideration of moisture gradients in structural design

It is suggested that transient moisture conditions should be considered as a load case instead of strength reducing factor in design calculation of timber structures when wood splitting is the failure mode.

The design equation for multiple loads is expressed in design codes in principle as follows:

$$\gamma_G \sigma_G + \gamma_Q (\sigma_{Q1} + \psi \sigma_{Q2}) \le \frac{k_{mod} f}{\gamma_M} \tag{7.1}$$

where σ_G is stress caused by permanent load, σ_{Qi} is stress caused by variable load Q_i, γ-factors are the partial safety factors for loads and material, ψ is the combination factor (less than 1) indicating that two different variable loads extremely seldom have maximum values at the same time, and f is strength, modified to the appropriate service condition (load duration, moisture) by factor k_{mod}. Loads Q_1 and Q_2, for instance, can be snow and wind. When wood is loaded in tension perpendicular to grain, also moisture gradients should be considered as another natural load. When doing so, two interesting questions arise:

1. are the stresses additive, as assumed when writing eqn. (7.1), and
2. what should be the combination factor ψ when combining moisture loads with snow and wind loads.

The first question can be discussed by comparing the effective stress values obtained for different mechanical loads in case of curved beam (Table 5.1). The answer was “no but yes” meaning that the theoretically correct method is to analyse all effects simultaneously, but due to severe problems in doing so in structural design, the effects have to be analysed separately. The error made when stress components are added can be tolerated, and overcame in the development of the design method.

The combination factor question has not yet been analysed. It seems likely that the humidity changes are not most severe when snow load has its maximum. It is, however, difficult to see any meteorological reason why maximum wind and humidity could not take place simultaneously. Accordingly, we can suggest that combination factor of wind and moisture loads is about the same as the combination factor of wind and snow, whereas combination factor for snow and moisture might be lower.

A simple approach to consider moisture induced loads would be, based on experimental and calculated results presented here, to give values for moisture stresses in design code unless a more precise analysis is made. Rough estimates for moisture induced stresses perpendicular to grain could be 0,25 MPa for uncoated, and 0,1 MPa for well coated beams. These values could be reduced by factor ψ when combined with other stresses. In a similar way moisture induced stresses should be added to mechanical stresses in design of end-notched beams and large mechanical connections.

8. Summary

Strength of wood, especially compression strength depends on moisture content. Under normal climatic conditions moisture gradients in wood enhance the risk of cracking, and can have an effect on load carrying capacity. This is true when the failure mode is splitting of wood as that caused by tension stress perpendicular to grain or shear stress or a combination of them.

Effect of moisture gradients is not taken into account in design calculations. Sometimes effect of moisture gradients is considered as part of duration of load effect, decreasing the strength of wood. The problem in this approach is that when test results obtained during a certain period of time are extrapolated to a long load duration, extremely low strength values are obtained. More correct approach would be to consider stresses caused by transient moisture conditions as loads, and combine these moisture induced stresses with mechanical stresses.

9. References

Aicher, S., Dill-Langer, G., Ranta-Maunus, A. 1998. Duration of load effect in tension perpendicular to the grain of glulam in different climates. Holz als Roh- und Werkstoff 56, 295-305.

Barrett, J.D., Lau, W. 1994. Canadian Lumber Properties. Canadian Wood Council. Ottawa. 346 p. ISBN 0-921628-28-5

Forest Products Laboratory. 1999. Wood Handbook - Wood as an Engineering Material. Gen. Tech. Rep. FPL-GTR-113. Madison, WI: US Department of Agriculture, Forest service, Forest products laboratory. 463 p.

Gowda, S., Kortesmaa, M., Ranta-Maunus, A. 1998. Duration of load effect on curved glulam beams. Part 2. Long term load tests and analysis. VTT Publications 334, Espoo. 76 p. + app. 28 p.

Gustafsson, P.J., Hoffmeyer, P., Valentin, G. 1998. DOL behaviour of end-notched beams. Holz als Roh- und Werkstoff 56, 307-317.

Hanhijärvi, A. 2000. Advances in the knowledge of the influence of moisture changes on the long-term mechanical performance of timber structures. Materials and Structures/Materiaux et Constructions. Vol. 33 (2000) No: Jan.-Feb., pp 43 - 49

Hoffmeyer, P. 1995. Wood as building material. STEP Lecture A4. Centrum Hout. Holland.

Hukka, A. 1999. The effective diffusion coefficient and mass transfer coefficient of Nordic softwoods as calculated from direct drying experiments. Holzforschung 53, 534-540.

Ranta-Maunus, A., Gowda, S. 1994. Curved and cambered glulam beams. Part 2. Long term load tests under cyclically varying humidity. VTT Publications 171, Espoo. 36 p. + app. 18 p.

Ranta-Maunus, A. 1998. Duration of load effect in tension perpendicular to grain in curved glulam. CIB W18 Meeting in Savonlinna, Paper 31-9-1. 12 p.

Ranta-Maunus, A. 1999. Round small.diameter timber for construction. Final report of project FAIR CT 95-0091. VTT Publications 383, Espoo. 191 p. +a pp. 19 p.

Ranta-Maunus, A. 2001. Moisture gradient as loading of curved timber beams failing in tension perpendicular to grain. IABSE Conference Innovative Wooden Structures and Bridges, 29.-31. August 2001. Lahti. Finland

Thelandersson, S. 1994. Variation of moisture content in timber structures. In: Creep in timber structures. ed. P. Morlier. RILEM Report 8. E&FN SPON, London.