Moisture Gradient as Loading of Curved Timber Beams

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Summary

Under normal climatic conditions moisture gradients in wood induce stresses perpendicular to grain, 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. As an example, the effect of moisture gradients on the capacity of curved glued laminated timber beams is discussed based on experimental results and combined moisture and structural analysis. Finally, it is proposed that moisture gradients should be considered as another natural loading case to be combined with external loads as snow and wind.

Keywords: timber structures, moisture load, curved glulam, tension perpendicular to grain

1. Introduction

Wood is a hygroscopic material and the moisture content of wood (MC) settles down to equilibrium with the air humidity. This is of importance, because the MC has a direct effect on the strength of wood. In addition, fast changes cause moisture gradients in wood, which induce stresses in the perpendicular to grain direction and may cause splitting of wood. Fig. 1 shows the variation of the mean moisture content of glulam in a barn in Åsa, Sweden. Annual minimum and maximum values are ranging from 12 to 19% MC. The moisture content in glulam under transient situation is illustrated in Fig. 2 where calculated values of moisture contents in different depths are shown, when a cyclic RH has a cycle length of 4 weeks with maximum of 90% and minimum 55%, inducing 4% MC difference between surface and middle of 90 mm thick glulam.

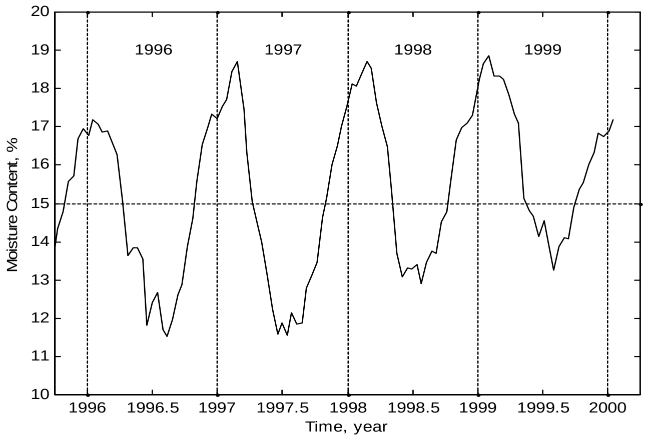


Fig. 1 Mean moisture content in wood (glulam 90x100x600) versus time in a barn in Southern Sweden (Åsa) [1]

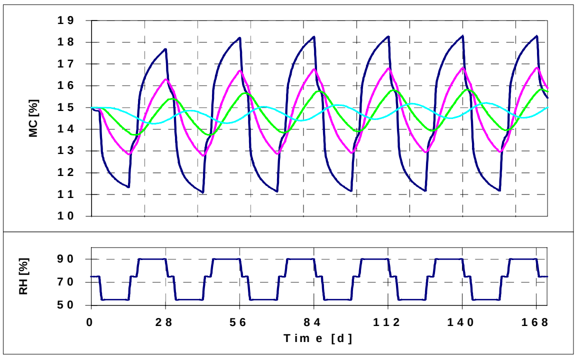


Fig. 2 Calculated moisture history in cyclic humidity environment for different depths from surface (0, 10, 20 and 45 mm) of 90 mm thick glulam [2]

2. Experimental results

Two different 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 during 1991-1993 [3]. The later, more comprehensive project (EU/AIR) was completed in 1997 [2,4]. 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 each stress level of the stepwise rising load, 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 1), whereas the ratio in similar experiments at constant humidity is about 0.8. The difference is caused by the moisture gradients. k_{DOL} is determined for the average beam in each test series with variable humidity. The results reveal 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. Normal surface treatment with alkyd paint appears to be an effective protection against changing moisture. It prevents the major part of the effect of moisture cycling with a cycle length of 4 weeks.

Table 1 Comparison of k_{DOL}- factors obtained in cyclic humidity tests [4]

	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

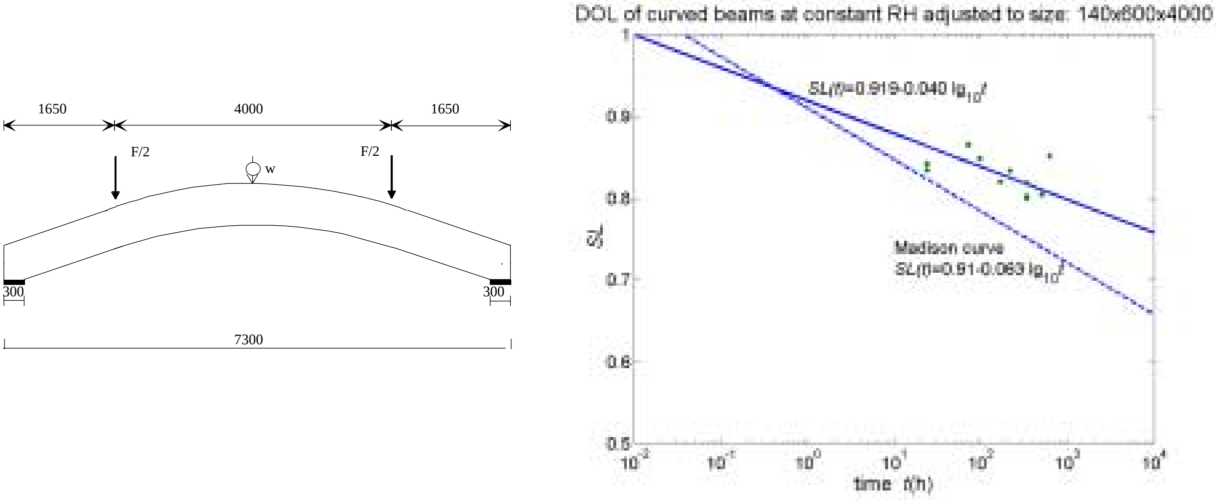


Fig. 3 Test specimen and relative stress vs. time-to-failure graph of curved beams at constant moisture content failing due to tension perpendicular to grain

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 cause of failure, not the number of cycles or duration of load. Nearly all failures took place during the humid part of the moisture cycle, when the surface of the beam was under compression stress, and the internal part under increased tension stress.

Duration of load results at constant humidity show that strength reduction due to load duration is smaller than predicted by the often used Madison curve. Results are illustrated in Fig. 3 as a stress level vs. log time-graph. 11 of 16 beams failed during the experiment. The fitted line is based on least squares method. For comparison, also the Madison curve is shown. Stress levels of 90 mm wide beams (series S4, 8 specimens) are adjusted multiplying by 0.83 when combining with results of 140 mm wide beams (test series S8, 8 specimens). Results have been ranked firstly according to the stress level at failure, and those failing under the same stress, are then ranked according to time-to-failure. Relative stress level for each specimen has been determined according to a matching technique: short term strength estimation is based on the Weibull fitting to short term experiments.

3. 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 primarily appear 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.

3.1 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 calculation procedure is described in an earlier paper [5], and only some main features are given here. Moisture transport inside wood can be calculated using the diffusion equation with an effective diffusion coefficient, which can be written as:

$$\frac{\partial}{\partial t}\int_V u\,dV = \oint_{\partial V} D_{eff}\,\frac{\partial u}{\partial x}\,dS \qquad (1)$$

where u is the MC in wood. The effective diffusion coefficient can be determined as dependent on the MC. The boundary condition can be formulated in terms of the MC difference or vapour pressure difference. The equations can be solved by numerical methods as 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 components:

$$\varepsilon_{tot} = J_0 \cdot \sigma + \varepsilon_{ve}(\sigma) + \varepsilon_{ms}(\sigma) + \varepsilon_s \qquad (2)$$

It is essential to include mechano-sorptive effect in the equation. Otherwise we obtain far too high stresses. As a background reading on constitutive modelling of wood, a paper of Hanhijärvi [6] is recommended.

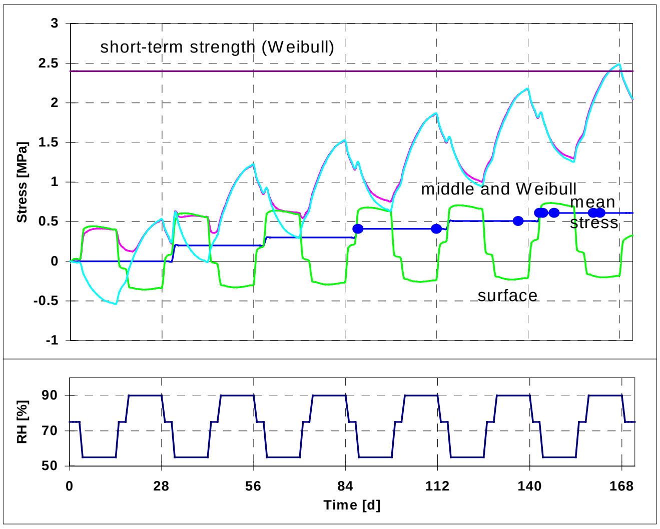
Stresses perpendicular to grain in curved glulam beams caused by external load (bending moment) and varying humidity of air have been calculated and an example of stress distribution at different times is shown in Fig. 4. The great variability of stress in width direction rises a question about strength criterion: does the failure take place when critical value of stress is exceeded locally or should we adopt a more advanced criterion. 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 these aspects into consideration and should preferably be based on fracture mechanics. We have applied, instead, Weibull theory, which is normally used for the analysis of 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

$$\sigma_W = \left(\frac{1}{V_{\mathrm{ref}}} \int_V \sigma_{t,90}{}^{k} \, dV \right)^{1/k} \tag{3}$$

where $\sigma_{t,90}$ means tension stress perpendicular to grain. Equivalent stress calculated by eqn.(3) 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. Depending on the value of V_{ref} used in the calculation, the volume effect can be incorporated or left out from this calculation ($V_{\mathrm{ref}} = V$). More details on the calculation are reported in other papers [2,4,5].

3.2 Calculated examples

The method described above has been used to analyse the experiments made with curved beams and tension specimens. Fig. 4 shows that the stress in the middle of beam is higher than that at the 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 the 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 also shown in Fig. 4. Obviously, the time needed for development of maximum moisture induced stresses depends on the dimensions of the timber member.



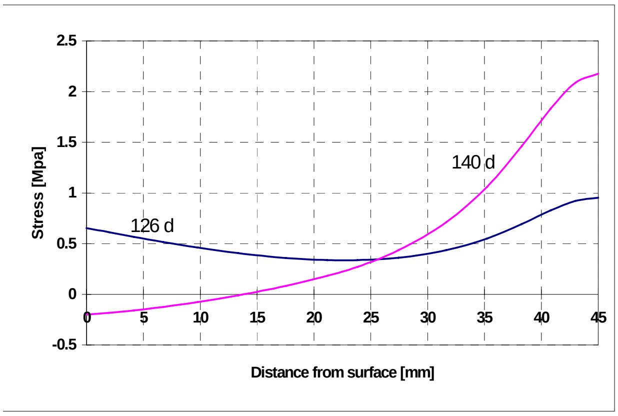


Fig. 4 Calculated vertical stresses in the middle and at surface of 90 mm wide beam (left) simulating test at RH cycling between 55 and 90 %, and stress profiles (above) [2]

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 the combination of mechanical and moisture load. The results are given in Table 2. 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 some 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 2 (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 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 FMPA cycle was calculated as a single change from 65 to 90%RH.

Table 2 Calculated equivalent (mean) stresses for combinations of moisture cycling and load [5]

Thickness (mm)	RH cycle	Equivalent load for external load 0.2 MPa	combined effect 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% [2]painted	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.

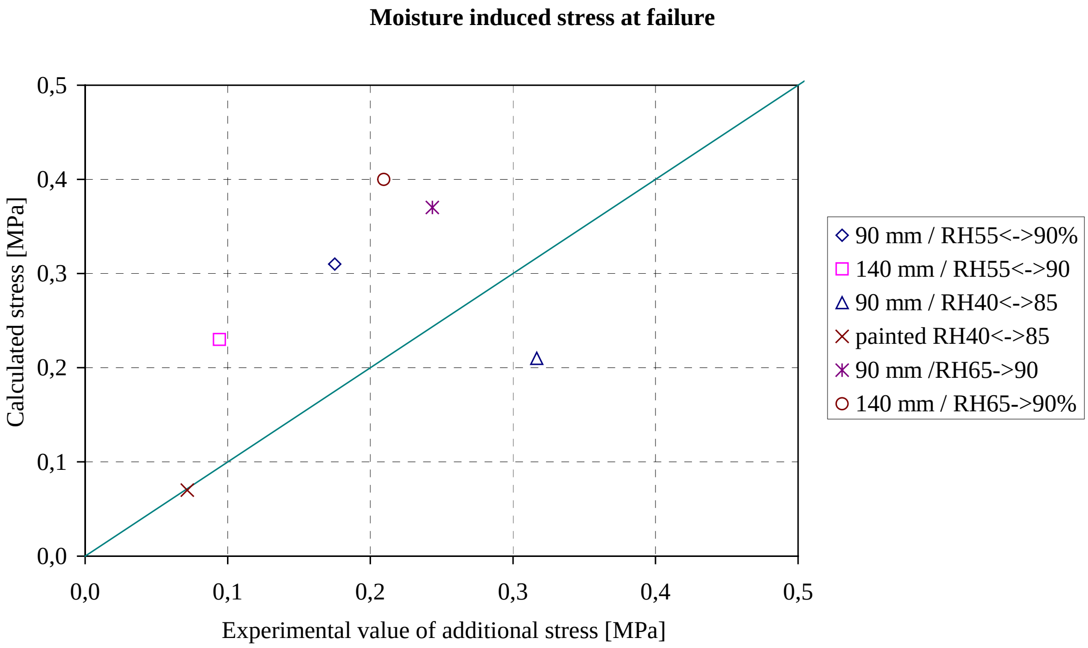


Fig. 5 Comparison of calculated moisture stresses and experiments

4. Consideration of moisture gradients in structural design

It is suggested that transient moisture conditions would be considered as a loading case instead of applying a 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:

$$\gamma_G \sigma_G + \gamma_Q (\sigma_{Q1} + \psi \sigma_{Q2}) \leq \frac{k_{\mathrm{mod}} f}{\gamma_M} \tag{4}$$

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 have extremely seldom maximum values 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 can be, for instance, 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. (4) ?
2. What should be the combination factor ψ when combining moisture loads with other loads ?

The first question can be discussed by comparing the effective stress values obtained for different mechanical loads in case of curved beam (Table 2). 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 overcome 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 the maximum. Instead, it is difficult to see any meteorological reason why maximum wind and humidity could not take place simultaneously. Accordingly, we can speculate that the combination factor of wind and moisture loads could be about the same as the combination factor of wind and snow, whereas the combination factor for snow and moisture might be lower.

A simple approach to consider moisture-induced loads would be to give values for moisture stresses in a 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 glulam beams. These values could be reduced by a factor ψ when combined to 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.

5. Conclusion

This work demonstrates that moisture gradients in would should and can be taken into consideration as loading of timber structures when tensile stresses perpendicular to grain are of concern.

6. References

[1] Gustafsson P.J., Hoffmeyer P., and Valentin G.. “DOL behaviour of end-notched beams” *Holz als Roh- und Werkstoff*, Vol. 56, No. 5,1998, pp. 307-317.

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

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

[4] Aicher S., Dill-Langer G., and Ranta-Maunus A. “Duration of load effect in tension perpendicular to the grain of glulam in different climates” *Holz als Roh- und Werkstoff* Vol.56, No 5, 1998, pp. 295-305.

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

[6] Hanhijärvi A. “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.