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Climate and moisture induced stresses in block-glued glulam members of timber bridges

Bettina Franke[1], Marcus Schiere[2], Steffen Franke[3]

1 Introduction

Wood as a hygroscopic material interacts with the ambient climate variations of relative humidity and temperature and leads to moisture content (MC) variations across the cross section. The MC affects the physical and mechanical properties as well as the dimensions due to shrinkage and swelling below the fibre saturation point (FSP). Due to constrained volumetric strains, e.g. due to swelling and shrinkage, changes in moisture content impose moisture induced stresses (MIS) which, if exceeding the tensile strength perpendicular to the grain of the material, can cause fractures such as cracks or delaminations. Thus, the correct estimation of the MC is important for the design, quality assurance, and durability of timber bridges.

There was the question especially for large glulam members as produced by block-gluing about the impact of ambient climate variations on the moisture induced stresses and possible failure. Block glulam beams form wide cross-sections by gluing single glulam beams to each other. They are used as, e.g., main structural elements for timber bridges, see Figure 1. Therefore, cross sections of practical dimensions were classified regarding the assumed ambient climate in service by numerical simulations that showed the moisture content and gradient over the cross section. Finally, the moisture induced mechanical response was simulated using a coupled moisture diffusion and mechanical model. The results were summarized to a practical advice for the dimensioning.

Figure 1: Bridge Horen Switzerland, block glued glulam members as main structural elements, Source: BFH, Switzerland

2 Material and method

2.1 Climate impact

The ambient climate depends on the building occupation, their use, on the meteorological conditions, local topography or environment, and altitude. The moisture content of wood follows the variations in ambient climate. The ambient climate and moisture content in timber structures and on timber bridges is being monitored with different objectives, duration, and results by various monitoring campaigns as shown in [1], [2], [3], [4]. Some elements are monitored to investigate moisture gradients, detect leakages, or to obtain equilibrium moisture contents. A large number of various monitoring data from own measurements as well as published data were analysed using the minima and maxima value over one year. They are presented as an envelope of the measurement data for one object, see Figure 2 for timber bridges and/or for other structures and objects in [4].

[1] Bettina Franke, Research Associate, Bern University of Applied Sciences, Switzerland, bettina.franke@bfh.ch
[2] Marcus Schiere, Research carried out at Bern University of Applied Sciences, now: Product Manager, Hupkes Wijma B.V., The Netherlands, mjs@hupkeswijma.com
[3] Steffen Franke, Professor for Timber Engineering, Bern University of Applied Sciences, Switzerland, steffen.franke@bfh.ch

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The moisture contents observed close to the surface, in a depth of around 15 mm, was filtered with a moving average filter and analysed for one year. The envelope shown in Figure 2 helps to calculate the difference in moisture content throughout the year, Equation (1).

$$\Delta u_{15\,\mathrm{mm}} = \max\left(u_{15\,\mathrm{mm}}\right) - \min\left(u_{15\,\mathrm{mm}}\right) \tag{1}$$

A further value called $\Delta u_{\mathrm{Surface}}$ can be obtained from the theoretical equilibrium moisture contents calculated at the surface using temperature and relative humidity of the ambient climate. The relation between the two is then calculated as:

$$r_u = \Delta u_{Surface} \,/\, \Delta u_{15\,\mathrm{mm}} \tag{2}$$

This value defines the relation between the moisture content developments. If this value is high, large variations of short duration occur at the surface. If it is small, variations in relative humidity at the surface are smooth and not very large either. For the approximation of the moisture content of timber members and the distribution over the cross sections or the calculation of moisture induced stresses, a simplified climate model over the year was applied. Instead of specific daily or seasonal changes, a model based on the cosines shape (Equation (3)) or a simple step model can be chosen, as shown in Figure 3. The mean equilibrium moisture content was set to 16 M% forcovered timber structures outdoors according to Service Class 2 (SC2), EN 1995-1-1:2004. By using the specified values for the moisture content from Figure 2, variations of $\Delta u_{\mathrm{Surface}}$ = 4.48 r_u =· 3.23 and $Ø_u$ = 15.7 M% could be calculated for the bridges.

$$u(t)_{SC2} = 16 + \frac{\Delta u_{Surface}}{2}\cos\left(2\pi \frac{t}{365}\right) \tag{3}$$

Where:

t Time in Days, $t = 0 \mathrel{\hat{=}} 1^{st}$ of January

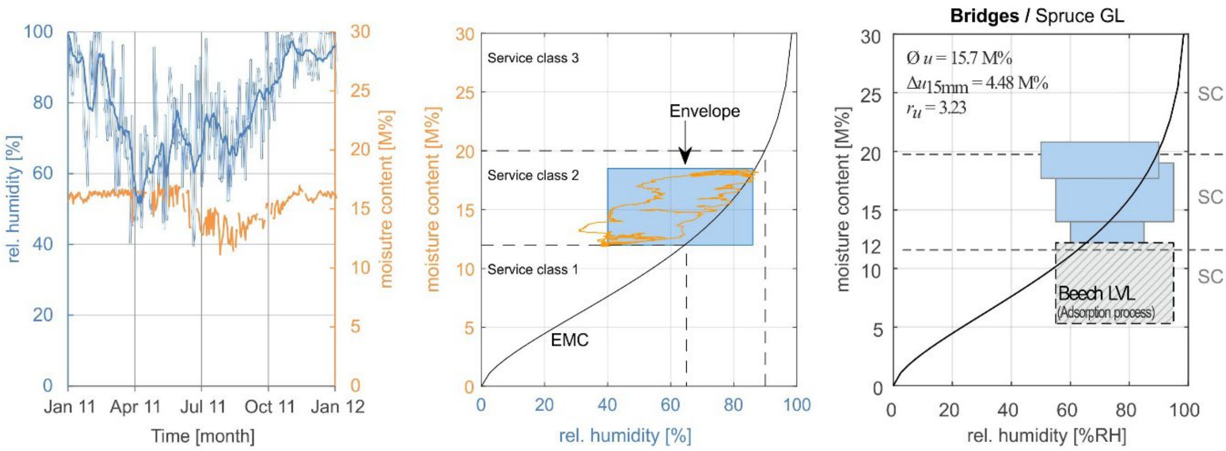

Figure 2: Evaluation of envelope of ambient climate and moisture content for timber bridges, left: moisture content and relative humidity on a specific timber bridge, middle: analyses of data compared with equilibrium moisture content (EMC), right: summary of four analysed timber bridges monitored by BFH

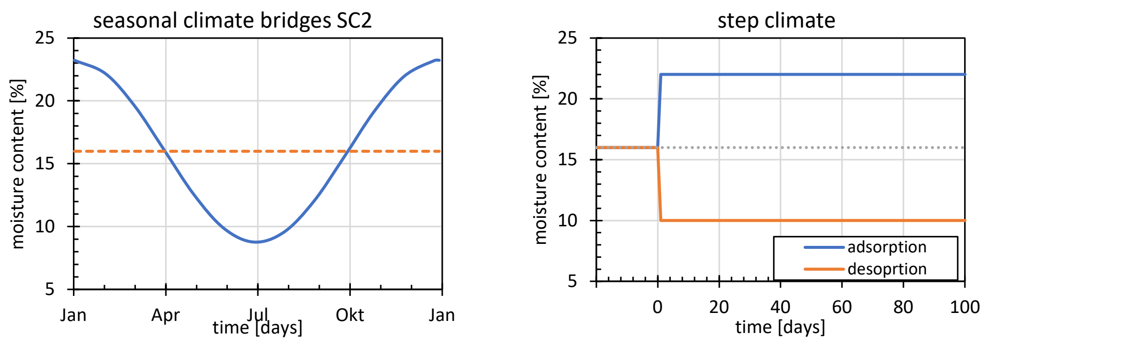

Figure 3: Simplified seasonal climate for bridges (left), stepwise climate change used for numerical simulation (right)

2.2 Numerical model

Numerical simulations were made to predict the effects of the moisture content changes on the structural health as the structures are subjected to ambient climate variations. The numerical finite element model was set up to simulate the moisture diffusion with focus on practical dimensions and applications and considers the calculation of moisture content distribution, deformations, and strain developments. Different numerical models to calculate the moisture content distribution and corresponding moisture induced stresses are available in literature: such as a 1D-model [5], 2D-model [6], and 3D-model [7]. For this research study, simulation of moisture content developments and following stress distributions were enabled through a 1D-model [5] and a 2D-model [6], as described in detail in [8]. Moisture transport was modelled through Ficks' second law observed in Eq. (1), in which u refers to moisture content, D to the diffusion coefficient, and t and x to time and position respectively.

$$\frac{\partial u}{\partial t} = D\frac{\partial^2 u}{\partial x^2} \tag{4}$$

A constant diffusion coefficient of $3.0\cdot10^{-10}$ m^2/s [6] was used in all simulations. The dependency of diffusion on moisture content in transverse direction is not as pronounced as in longitudinal direction, so a constant coefficient was assumed to be sufficient. Ambient relative humidity and temperature were used to calculate a theoretical equilibrium moisture content at the surface [9], [10]. This theoretical equilibrium moisture content was used as a driving force at the surface of the cross section. Surface emission factors were not used since the simulations concern sufficiently ventilated structures [6]. A list of the material parameters is given in Table 1.

Table 1: *List of material parameters used in the numerical model, obtained from [6], [7]*

Parameter	Value	Parameter	Value	Parameter	Value
E_r [N/mm^2]	467	α_r [%/M%]	0.13	m_r [mm^2/N]	0.07e-6
E_t [N/mm^2]	216	α_t [%/M%]	0.32	m_t [mm^2/N]	0.10e-6
G_{rt} [N/mm^2]	42	D [m^2/s]	3e-10	m_{rt} [mm^2/N]	0.40e-6
nu_{rt} [N/mm^2]	0.50	mu_{rt}	0.75	mu_{tr}	0.75

The time dependent stress-strain behaviour was considered by adding the elastic, hygro-expansive, mechano-sorptive and creep strains. Equation (6) and (7) show the total strain ε_t as the sum of the elastic strain ε_E, hygro-expansive strain ε_u, mechano-sorptive strain ε_{ms}, creep strain ε_φ. E represents the anisotropic elasticity matrix, α the vector with the hygro-expansive factors, and m the vector with the mechano-sorptive creep parameters. These are averaged over the cross-section height in the 1D-model, so the extra subscript *eff* (effective) is added to the parameter. In addition to the mechano-sorptive value m in the 1D-model, a parameter β is used to allow for different mechano-sorptive creep during wetting or drying processes. In the 2D-model, only one parameter for the mechano-sorptive creep was used since this concerned only wetting or drying cases. The time dependent creep strains in these dynamic conditions are often neglected, [11].

$$\dot{\varepsilon}_t = \dot{\varepsilon}_E + \dot{\varepsilon}_u + \dot{\varepsilon}_{ms} + \dot{\varepsilon}_\varphi \tag{5}$$

$$\dot{\varepsilon}_t = \frac{\dot{\sigma}}{E_{eff}} + \alpha_{eff}\dot{u} + \left(m\left|\dot{u}\right| - \beta\dot{u}\right)\sigma + 0 \tag{6}$$

The moisture distribution numerically modelled was compared with experimental investigations done by Jönsson, [14] as shown in Figure 4. The moisture content of a glued laminated member with a cross section of 90 mm in width and 270 mm in height was increased (wetting process) from 9 M% to 16 M%. Figure 5 shows the resulting stresses for an adsorption process investigated by Jönsson, [14] on the same glued laminated cross section of 90 mm in width and 270 mm in depth. The simulations show a good agreement with the experimental results and validates the model predictions. An influence of the glue lines of glued laminated timber on the moisture diffusion or moisture transport was not considered since the moisture transport took in a direction parallel to the glue lines.

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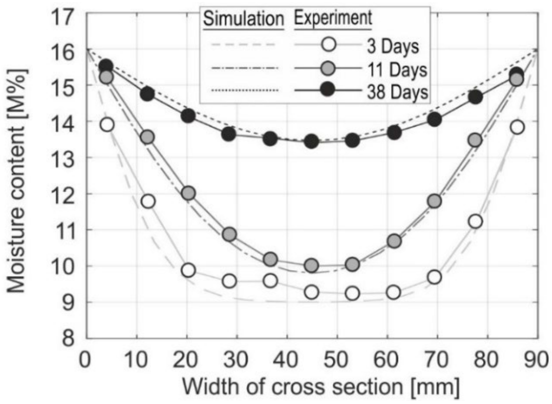

Figure 4: Numerical distribution of moisture content in comparison to experimental results on a glued laminated cross section of 90 x 270 x 16 mm^3 under adsorption process from 9 to 16 M% done by Jönsson [13]

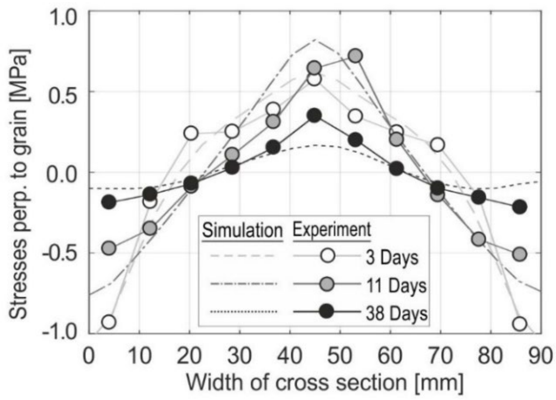

Figure 5: Numerical stress distribution and development in comparison to experimental results on a glued laminated cross section of 90 x 270 x 16 mm^3 under adsorption process from 9 to 16 M% done by Jönsson [13]

2.3 Glulam and investigation program

Figure 6 gives an overview of cross section sizes used over the last 50 years in more modern timber bridges. It shows that cross section widths are slowly increasing, until these are finally block glued into very large cross sections with a width of more than 1.5 m. These cross sections can be found in all types of timber bridges: arch bridges, truss bridges, etc. according to the information provided in [14].

The principal layout of one lamella of glulam including the annual ring orientation, pith location and distances are shown in Figure 7 as well as the defined aspect ratio and the sideways assembly of individual beams into a block glulam beam is also illustrated in Figure 7.

Block glulam beams were modelled in which the width over height relation was:

- 160 mm x 800 mm, and as multiple up to 800 mm x 800 mm
- 200 mm x 800 mm, and as multiple up to 800 mm x 800 mm
- 360 mm x 800 mm, in divisions of up to 9 beams

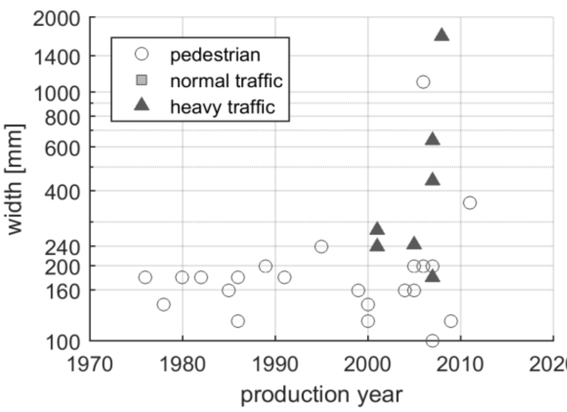

Figure 6: Illustration of increase of width of cross sections used in different types of bridges. Eventually, block glulam beams are used to transfer the high load traffic [14]

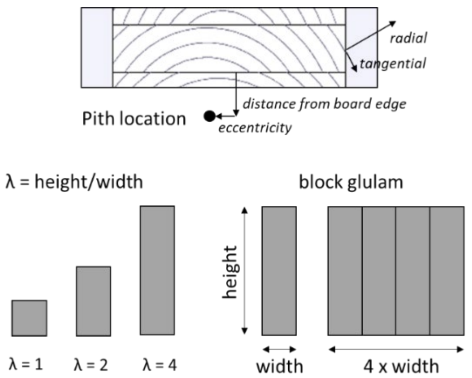

Figure 7: Illustration of a board in a glued laminated beam with the annual ring orientation, pith eccentricity and distance from the board edge (top), aspect ratio and assembly of individual beams into a block glulam beam (bottom).

3 Results

3.1 Moisture content distribution and cross-section deformations

The moisture content distribution and vertical deformations across the width of the two cross sections 160/800 mm and 200/800 mm corresponding to the applied step loads of + 6 M% are shown in Figure 8. The plotted deformations are obtained from the maximum duration of the simulations. This was set to 120 days on the smaller cross-sections and 360 days on the large cross-sections. The smaller cross-sections respond faster to moisture content increases, due to the smaller amount of constraint during swelling, and the faster increase in moisture. It takes a long time until the moisture content reaches equilibrium in the centre of the cross-section. Hence, building with wider cross-sections most likely results in smaller deformations.

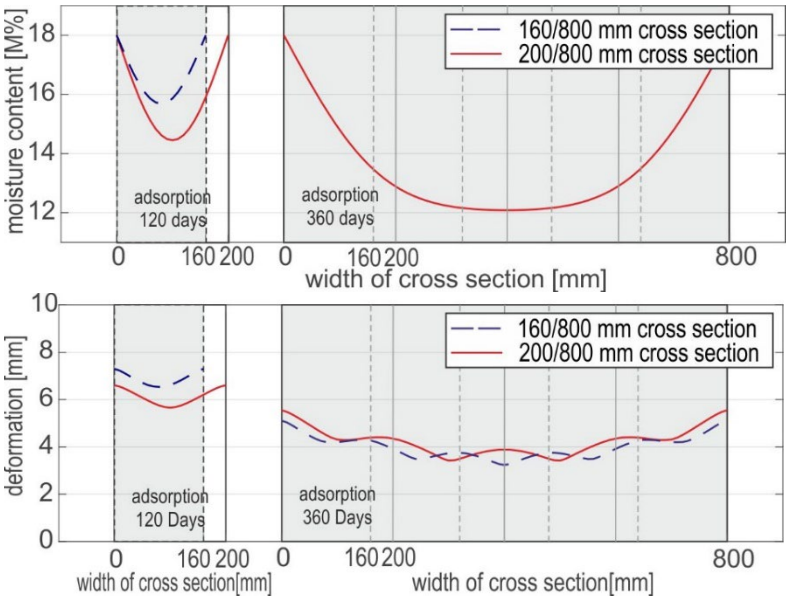

Figure 8: Moisture content distributions (top) and deformation across the width of the timber beams of different widths subjected to a step load of 6 M% moisture content increase. All beams have a height of 800 mm and the duration of the simulations is indicated in the figures.

3.2 Stress situation over the cross section

The magnitude of the climatic variations affects the generated moisture induced stresses in the cross-section. Results showed that the moisture induced stresses are also affected by cross section width. Low aspect ratios showed that the geometry also can affect the generated stress levels. The block glulam beams form wide cross-sections by gluing single glulam beams to each other. This is expected to affect the moisture induced stresses in two ways.

1. The ratio between the areas where the compressive stresses and the tensile stresses are present is different from those in slender beams. The tensile stresses are spread out over a larger portion of the cross section, resulting in smaller values.
2. Since the cross section is not slender anymore, effects of aspect ratio also start playing a role and reduce the total amount of generated stresses in the cross section.

This is however verified by setting up simulations where a stepwise climate is induced of $u = 12 \pm 6$ M%. The cross-section height is always maintained at 800 mm.

The calculated levels of moisture induced stresses in different widths of cross-sections is plotted in Figure 9. The stress distribution is plotted at the point where the maximum tensile stress levels are achieved. Two beam widths were used to calculate stress levels up to total block glulam beam widths of 800 mm:

- four beams of 200 mm were needed to form a block glulam of 800 mm, and
- five beams of 160 mm were assembled to form a block glulam beam of 800 mm.

Figure 9 shows that higher tress levels are found in block glulam beams with an uneven number of single beams when submitted to wetting loads. In the block glulam beams with an even number of single beams, maximum stress levels are lower than in the uneven number of single beams. Converged stress levels remain at around 0.5 MPa. The time needed for each of these beams to develop these stresses is different and all reach a maximum level long after the moisture loads were initially applied.

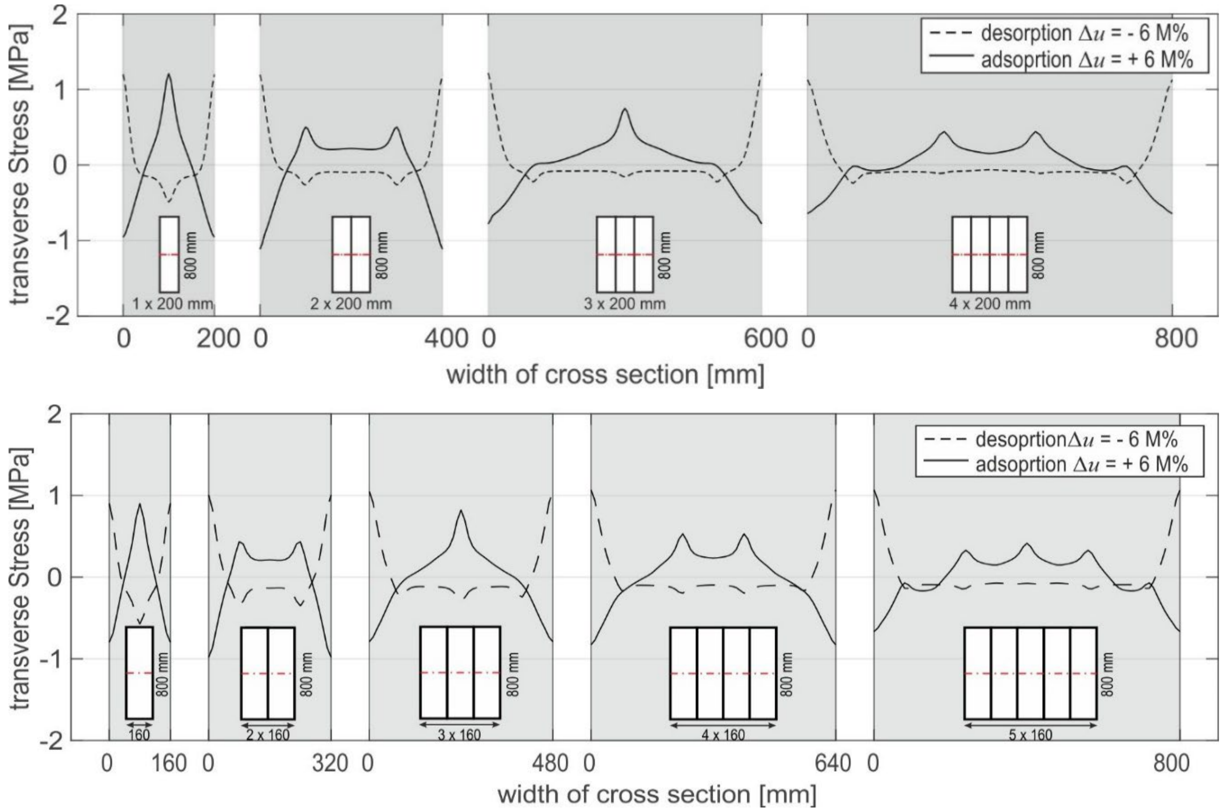

Figure 9: Transverse stresses due to moisture step-loading in block-laminated beams depending on the width of the cross-section

When the beams were subjected to drying loads, the width of the beams or the number of beams used does not affect the level of maximum tensile stresses. These simply occur shortly after the driving load has changed at the surface. This could be an explanation why almost every timber member in a structure shows at least some cracks. It is assumed that these stress levels depend on the angle the annual rings make with the surface of the beam.

To verify if the aspect ratio affected the reduction of strains only a simulation was done where the cross-section width and height were maintained constant, and the number of single beams was varied as shown in Figure 10. A beam with a cross section width of 360 mm is subdivided into two, three, four, six, and nine single beams. Here too, the stress distribution perpendicular to the grain converges once four beams or more are used in the cross section. It is noted that the cross sections simulated here are not necessarily economical for use in practical production lines or construction.

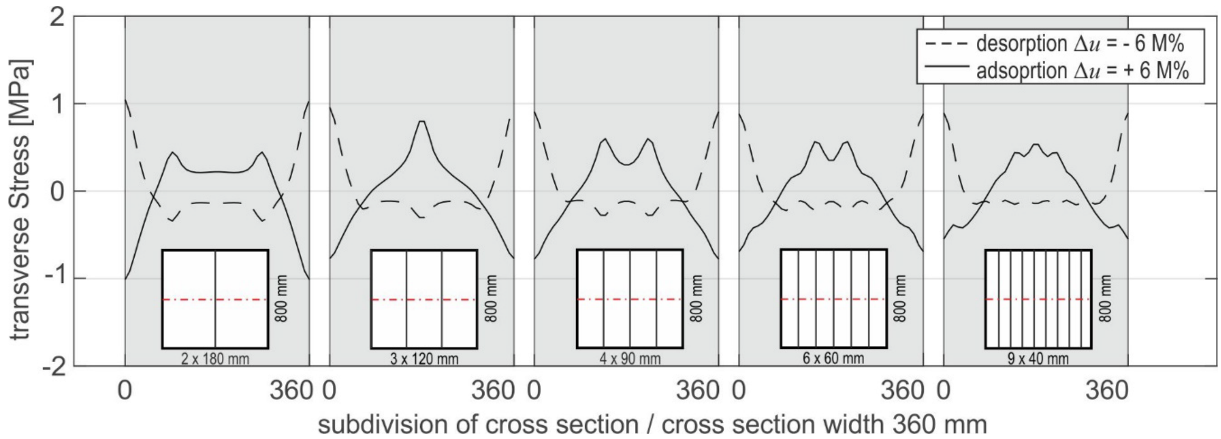

Figure 10: Transverse stresses due to moisture step loading in cross-laminated beams with identical cross-sections but different set-up regarding number of single beams.

4 Discussion and Conclusion

Monitoring results for timber structures and timber bridges are summarized through envelope diagrams that show the moisture content variation and the variation of the surrounding climate during service. The structural elements of bridges are mostly exposed to these variations. A moisture content below 20 M% can be assumed for timber bridges if adequate constructive wood protection is met. The risk of fungi is avoided effectively. Use of timber in bridges is not considered as a problem from the climate point of view, provided that enough ventilation is always available, also around structural details. Design of details, providing protection of structural elements against impact of rain and sun, and keeping a maintenance log is expected to be more important for the durability of the bridge structure. Whether it crosses a water body or road is likely to have an impact, but this is for the moment considered unmeasurable with regards to at least average moisture content, [4].

The numerical investigations concentrate on block glued glulam members. The numerical model includes moisture transport and the resulting stress distributions over various cross sections. The numerical simulations allowed insight in the dependency of moisture load and geometry on the generated moisture induced stresses. The results showed that moisture induced stresses in block-laminated beams depend on moisture load amplitude, geometry, and beam slenderness. Drying loads almost instantly lead to high tensile stresses and visible cracks at the surface, whereas wetting loads lead to gradual increase of tensile stresses in the midplane of the cross section. Cracks generated in the midplane are not visible but have however been observed during the demolition and inspection of timber structures. Drying stresses are much less affected by the geometry. Use of block-gluing shows a positive effect on the development of stresses in the cross-section. The number of glulam members should be two or more than three to reduce the transverse tensile stresses in block glued glulam members for wetting situations.

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