

THESES OF THE PhD. DISSERTATION

Determination of the dangerous stress-states of glue laminated timber beams caused by external loads and manufacturing and climatic stresses and the statical dimensioning of beams on the basis of anisotropic strength theory

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1 Introduction

Glue laminated timber beams started to become widespread in Hungary as of the mid-1970-s, because they are lighter, more flexible and more economical than beam structures made of metal or reinforced concrete. There are currently innumerable firms in the construction industry involved in the construction of glue laminated timber beams and the manufacture of timber structures. Glue laminated beams are durable constructs if they are manufactured from adequate quality materials and if their installation and operation are performed to a high quality standard. There are however an increasing number of cases of glue laminated beams suffering damage and as a result entire roof structures becoming life-threatening (such as the swimming pool in Pécs, the swimming pool in Berettyóújfalu, pool No. III in Harkány, etc.). This problem is caused by the lack of targeted studies about the temporal behaviour of glue laminated timber beams exposed to changing climatic environmental effects, about the extent of residual stresses, and about the D4 glue being used.

2 Research Objective

It is my assignment and topic to present the stresses of glue laminated timber beams and their calculation methods. Timber being an anisotropic material (i.e., its properties have different values for each direction) I also performed the stress calculations on an anisotropic basis in order to obtain a more realistic view of the processes that take place within the wood. Separate calculations have already been made (albeit only in academia and not in the practice) of the stresses induced by external loads in straight and arched glue laminated timber beams, of the residual stresses generated during the manufacture

of glue laminated arched beams, and of the residual stresses generated by climatic conditions, but their combined effects have hitherto never been studied. It is my objective to be able to demonstrate the combined effect of the stresses that result from the three different loads, a method for the combination of the partial stress-state fields, and knowing those, a method to determine the dangerous cross section and the critical points of the beam as well as its critical stress states. Knowing the critical stress states it is possible to perform the statical dimensioning of the entire structural element, but rather on an anisotropic basis, using the theory of anisotropic strength, which has been proven to be the most appropriate for this purpose.

The calculation procedures presented and developed can also be used to make statements about beams already built, which can be of great use for the practice. Namely, in Hungary as well as in Europe an increasing number of glue laminated beams are being used, and the installed base is increasingly ageing. Nevertheless, the ex-post investigation of load bearing structures has always been relegated to the background. I would like to use my doctoral thesis to change this.

Many partial issues have already been solved regarding the statical dimensioning, design and verification of glue laminated timber beams, but a generic, systemic approach for the dimensioning of these structures has not yet been developed. One of the main objectives of my work is therefore to enable the dimensioning procedure that I have developed to become widespread as soon as possible in the everyday common practice for the statical design of glue laminated timber structures.

3 Methods Used

The Institute of Engineering Mechanics and Beam Structures of the Faculty of Wood Sciences at the University of West Hungary has received a project grant (Gábor Baross RRTARTO1 OMFB-00398/2010). I had the chance to participate in this project and within it I studied the combined effects of the stresses acting on glue laminated beams. Knowing these I dimensioned the critical points of the dangerous cross-sections using the newly developed dimensioning procedure.

In this grant I worked together with Péter Rabb, a certified civil engineer, and his colleagues, who have been surveying beams already built. We attempted to use our calculations to justify and to explain these real problems.

I presented the calculation of stresses induced by external loads in glue laminated arched timber beams, as defined by von Roth (1975), and of the residual stresses generated during manufacturing and as a result of climatic effects, as deducted by Szalai (2001), on an anisotropic basis. I developed separate examples for the calculation of all three stresses considering various geometry and load cases, and finally - something no-one has ever done so far - I defined and summarized the combined stress-state field of the three effects for a glue laminated arched timber beam. I have used the original notations in all of the three calculations and I have opted for a uniform notation only for the summation and for the statical dimensioning. I performed the calculations using Microsoft Excel.

We prepared an Excel-based program within the Gábor Baross grant, for the purposes of the engineering practice, to enable design engineers to consider external load-induced stresses that can be calculated on an anisotropic basis, as well as the residual stresses

(manufacturing and climatic stresses) that have been neglected so far. Using this we can summarize the stresses that originate from the manufacturing process and from climatic loads within the dangerous cross-sections. The software program still requires further development to also incorporate stresses due to external loads, to thus provide the stress states that indeed act in the critical points of the dangerous cross-sections. A separate Excel program has been completed for the definition of the stresses induced by external loads, and now only the integration of the two programs is outstanding with the need for some IT assistance. Once this program will be completed, we will be able to say that we have developed an easy-to-use calculation format for the engineering practice for the statical dimensioning of glue laminated timber beams on an anisotropic basis.

3.1 Presentation of the specification of the various types of stresses

The analytical specification of stresses induced by external loads in arched glue laminated timber beams was deduced by Walter von Roth (1975). The stresses are calculated using the following formulae:

$$\sigma_{rr} = \frac{M_0 + N_0 \cdot R}{W} \cdot K_{rr}^M + \frac{Q_0}{F} \cdot \sin\varphi \cdot K_{rr}^Q + \frac{N_0}{F} \cdot \cos\varphi \cdot K_{rr}^N, \quad (1)$$

$$\sigma_{\varphi\varphi} = \frac{M_0 + N_0 \cdot R}{W} \cdot K_{\varphi\varphi}^M + \frac{Q_0}{F} \cdot \sin\varphi \cdot K_{\varphi\varphi}^Q + \frac{N_0}{F} \cdot \cos\varphi \cdot K_{\varphi\varphi}^N, \quad (2)$$

$$\sigma_{r\varphi} = \frac{N_0}{F} \cdot \sin\varphi \cdot K_{r\varphi}^N + \frac{Q_0}{F} \cdot \cos\varphi \cdot K_{r\varphi}^Q, \quad (3)$$

where: $\sigma_{\varphi\varphi}$ – is the normal stress parallel to the grains,

σ_{rr} – is the normal stress perpendicular to the grains,

$\sigma_{r\varphi}$ – is the shearing stress,

W – is the section modulus,

F – is the surface of the cross-section,

N_0, Q_0, M_0 – are the internal forces of the beam in the initial cross-section of the examined section,

R – is the radius of curvature of the beam's centroid thread,

φ – is the angle of the location of the cross-section to be calculated, from the initial calculation point,

$K_{rr}^M, K_{rr}^N, K_{\varphi\varphi}^M, K_{\varphi\varphi}^N$ – are factors that can be calculated from the geometric characteristics and from the material properties, and

$$K_{rr}^Q = -K_{rr}^N, K_{r\varphi}^N = K_{rr}^N, K_{r\varphi}^Q = K_{rr}^N, K_{\varphi\varphi}^Q = -K_{\varphi\varphi}^N.$$

Using these relationships we can calculate the three components of the planar stress state induced by the external load, for any point of the beam cross-section defined by φ . The solution enables us to take the ortotropic material properties of any chosen tree species as the elastic constants.

According to Szalai (2011) residual stresses generated during the manufacture of glue laminated arched timber beams can be determined as follows:

Within lamella i:

$$\sigma_{zzi}(z, y_i) = \frac{M_i(z)}{I_i} y_i + \frac{N_i(z)}{F_i}, \quad (4)$$

in the vicinity of the beam ends within glue layer i:

$$\sigma_{yyi}(\xi) = \frac{2}{bh^2 f(\xi=1)} [2 \sum_{j=1}^i M_j + \sum_{j=1}^i h_j \sum_{k=1}^i N_k - N_j] f''(\xi), \quad (5)$$

$$\tau_i(\xi) = -\frac{2 \sum_{j=1}^i N_j}{bh f(\xi=1)} f'(\xi), \quad (6)$$

where: σ_{zzi} – is the normal stress parallel to the grains,

σ_{yyi} – is the normal stress perpendicular to the grains,

τ_i – is the shearing stress,

$I_i = \frac{bh_i^3}{12}$ – is the secondary moment of inertia of lamella i , for its own centroid x axis,

$F_i = bh_i$ – is the cross-section area of lamella i ,

b – is the width of the lamellas,

h_i – is the thickness of lamella i ,

$N_i(z) = A_i \frac{M_0(z)}{AJ-S^2} (Aa_i - S)$ – is the normal stress of lamella i in location z ,

$M_i(z) = M_{0i}(z) - J_i \frac{M_0(z)A}{AJ-S^2}$ – is the transverse stress of lamella i in location z ,

$$S = \sum_{i=1}^n A_i a_i$$

A_i – is the area of the modified cross-section of lamella i ,

a_i – is the distance of the centre of gravity of lamella i from the centre of gravity of the first lamella in location z ,

J_i – is the modified secondary moment of inertia of lamella i ,

$M_{0i}(z)$ – is the momentum required to bend the lamellas into the press shape.

Of the stresses generated we need to know that the normal stress σ_{zzi} that is parallel to the grains applies to the entire section of the beam (with the exception of a disturbed section), while the normal stresses σ_{yyi} that are perpendicular to the grains and the shearing stresses τ_i act only in the vicinity of the beam ends. The so-called disturbed section develops at the end of the beam in a length of $h/2$; The maximum values of the stresses arise in the end point of the beam, and in the cross-sections located at distances of $h/6$ and $2h/6$ from the

end of the beam. The σ_{zzi} stress gradually drops to 0 on the disturbed section in accordance with function $f(\xi)$ (see Diagram No. 1).

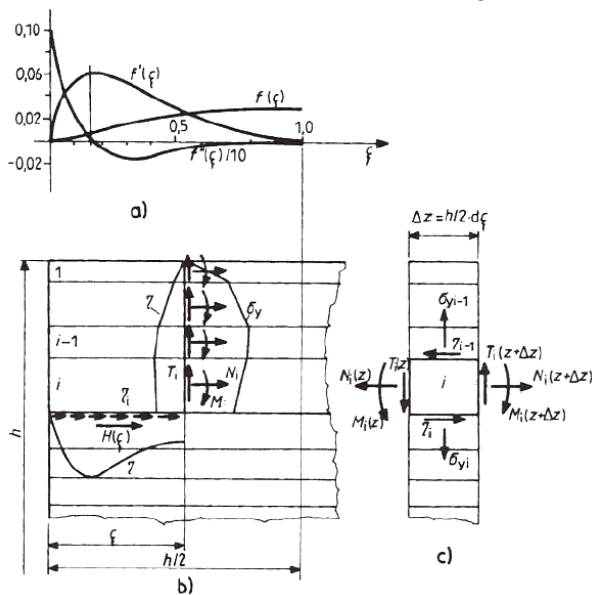


Diagram No. 1: Distribution of internal forces and residual stresses in the vicinity of the beam ends within the glue layer and within the lamellas: a – are the functions defined by Y. Guyon; b – are the internal forces and stresses arising in the vicinity of the lamella ends; c – are the internal forces and stresses acting on lamella i of a length of Δz .

The residual stress states generated by climatic loads may be determined in an analogous way. The fundamental difference is in the calculation of the heat dilatation and of the moisture dilatation of the lamellas due to climatic changes.

3.2 Method to Summarize the Stress States

In accordance with the three kinds of action (external, manufacturing and climatic) there are three corresponding kinds of stress tensor fields generated within the beam. In reality beam structures experi-

ence the combined effects of these, i.e., the resultant stress tensor field, and behave accordingly, i.e., they are either fractured or remain intact.

To summarize the tensors we perform a scalar addition of the corresponding tensor components. This ability to sum is conditional on the three kinds of stress tensor fields for a specific point to be provided in the same co-ordinate system (in relation to timber materials the axes of this co-ordinate system are parallel to the main anatomical orientations of the timber material). If this condition is not met, then the tensor components are to be transformed into the most appropriate common co-ordinate system using the appropriate tensor transformations. If the appropriate conditions are met, then the summation formula is as follows:

$$\begin{aligned}
 \sigma_{ered\acute{o}}^{ij} &= \sigma_{k\ddot{u}l\acute{s}\acute{o}}^{ij} + \sigma_{gy\acute{a}rt\acute{a}si}^{ij} + \sigma_{klimatikus}^{ij} = \\
 &= \begin{bmatrix} \sigma_{k\ddot{u}}^{LL} & \sigma_{k\ddot{u}}^{RL} & \sigma_{k\ddot{u}}^{TL} \\ \sigma_{k\ddot{u}}^{LR} & \sigma_{k\ddot{u}}^{RR} & \sigma_{k\ddot{u}}^{TR} \\ \sigma_{k\ddot{u}}^{LT} & \sigma_{k\ddot{u}}^{RT} & \sigma_{k\ddot{u}}^{TT} \end{bmatrix} + \begin{bmatrix} \sigma_{gy}^{LL} & \sigma_{gy}^{RL} & \sigma_{gy}^{TL} \\ \sigma_{gy}^{LR} & \sigma_{gy}^{RR} & \sigma_{gy}^{TR} \\ \sigma_{gy}^{LT} & \sigma_{gy}^{RT} & \sigma_{gy}^{TT} \end{bmatrix} + \begin{bmatrix} \sigma_{kl}^{LL} & \sigma_{kl}^{RL} & \sigma_{kl}^{TL} \\ \sigma_{kl}^{LR} & \sigma_{kl}^{RR} & \sigma_{kl}^{TR} \\ \sigma_{kl}^{LT} & \sigma_{kl}^{RT} & \sigma_{kl}^{TT} \end{bmatrix} = \\
 &= \begin{bmatrix} \sigma_{k\ddot{u}}^{LL} + \sigma_{gy}^{LL} + \sigma_{kl}^{LL} & \sigma_{k\ddot{u}}^{RL} + \sigma_{gy}^{RL} + \sigma_{kl}^{RL} & \sigma_{k\ddot{u}}^{TL} + \sigma_{gy}^{TL} + \sigma_{kl}^{TL} \\ \sigma_{k\ddot{u}}^{LR} + \sigma_{gy}^{LR} + \sigma_{kl}^{LR} & \sigma_{k\ddot{u}}^{RR} + \sigma_{gy}^{RR} + \sigma_{kl}^{RR} & \sigma_{k\ddot{u}}^{TR} + \sigma_{gy}^{TR} + \sigma_{kl}^{TR} \\ \sigma_{k\ddot{u}}^{LT} + \sigma_{gy}^{LT} + \sigma_{kl}^{LT} & \sigma_{k\ddot{u}}^{RT} + \sigma_{gy}^{RT} + \sigma_{kl}^{RT} & \sigma_{k\ddot{u}}^{TT} + \sigma_{gy}^{TT} + \sigma_{kl}^{TT} \end{bmatrix}.
 \end{aligned}$$

The most frequent case for the stress state generated in straight or arched axis glue laminated timber beams, is a planar stress state in a plane parallel to the plane of the beam. I.e., the stress states will have three non-zero components in every point of the beam. We have seen under subsection 3.1 that these stress components can be determined from each of the three different load types, namely as a function of the location of the points chosen on the theoretical median plane of the beam. By summing these in accordance with the rules of

tensor calculus we obtain the resultant stress state field of the planar model of the beam. Knowing the resultant stress tensor function we can in principle calculate the corresponding stress state for any point. From a fracture point of view the location of the most dangerous stress state tensor will be the critical point of the beam, and the corresponding cross-section will be its dangerous cross-section. Of course there could be several such points on a beam at the same time. Using a computer we can formulate these tensor field functions and we can relatively simply determine the critical points and stress states (even an Excel program may be suitable for this).

It results from the nature of the task that we can only design a beam structure indirectly, i.e., - on the basis of practical experience - we record the cross-sectional dimensions of the beam and subsequently perform a verification. When considering also the requirements of economy we may even reduce the dimensions of the cross-section and perform a repeated verification.

With some practice we may even save ourselves the effort of formulating the stress tensor functions. Once we have solved an adequate number of problems the selection of the dangerous cross-sections and of their critical points becomes almost automatic. In this case it is not necessary to determine the stress state field of the entire beam, it is sufficient to calculate the resultant stress states for the points considered as critical. The maximum values of the stresses due to external loads are to be expected in the cross-sections where the maximum strains arise. These cross-sections must be examined by all means from the point of view of whether the stresses generated by climatic effects or in manufacturing exert a favourable effect, or an extra burden on the specific cross-section. Using the same principle the cross-sections of the extreme values of the residual stresses

are to be examined, to determine the extreme values that result from the combination of the three stresses.

Unfortunately the interference of the three stresses within the structure may result in extreme stress values arising in other places than where the extreme values of the individual stresses are located, i.e., within cross-sections where the three kinds of stresses are not so large, but where they still interfere with each other in a detrimental way. We must be very prudent in selecting the cross-sections and their critical points that we intend to examine. In the case of simpler structures this can be determined very rapidly, but in the case of complicated loads and/or beam geometries we may have to subdivide the beam into small sections outside the locations of the extreme values and we may have to summarize the stress tensors for the cross-section of each longitudinal section to be able to see where the critical values of the stress states resulting from the diverse effects will be.

3.3 Statical dimensioning with consideration to anisotropy

We perform the statical dimensioning of glue laminated timber beams - in line with the provisions of the Hungarian Standard and of EUROCODE - using the limit state method with the addition of probability calculus. I.e., we calculate stresses from the standard load, and we calculate limit stresses as the 0.1% transgression level value of the distribution function for the given type of material strength. For the problem related to the complex stress state of the anisotropic material we used the Ashkenazi strength theory, which proved to be the most successful on the basis of the research conducted in the recent decades. According to this the structural element is acceptable in the examined point if its standard equivalent stress

calculated using the Ashkenazi theory is lower than the limit tensile strength of the employed timber material in the direction of the grains. As a formula:

$$\sigma_{egy}^M = \frac{1}{t_{LLLL}^H} \frac{t_{ijkl}^H \sigma_M^{ij} \sigma_M^{kl}}{\sqrt{I_1^2 - I_2}} \leq \sigma_e = f_L^{H+}, \quad i,j,k,l = L, R, T, \quad (7)$$

where: σ_{egy}^M – is the Ashkenazi equivalent stress corresponding to the standard load,

f_L^{H+} – is the limit tensile stress in the direction of the grains,

t_{ijkl}^n – are tensor components calculated using the limit value of the technical strengths (for the 0.1% probability level),

σ_M^{ij} – is the tensor of the acting stress state (calculated using the standard load of the beam) in the co-ordinate system corresponding to the main anatomical orientations of the timber material,

I_1, I_2 – are the first and second invariants of the stress state.

As a result of the complex stress state the procedure cannot be used for design (dimensioning), but only for verification purposes. Thus, using the pre-recorded geometric dimensions and the standard load we calculate the standard stress state in the critical point. We calculate the standard equivalent strength and we compare it to the limit tensile strength of the timber material in the direction of the grains.

4 Summary of the results

It can be clearly stated from the results that in the practice glued and laminated timber beams are not being dimensioned for the actual, true strains and stresses. It is thus no coincidence in the light of the calculation results that glue laminated timber beams become dam-

aged and ruined ahead of time. It is also visible that considerably smaller stresses are generated in beams consisting of thin lamellas.

If we accept that stresses induced during manufacturing can be reduced significantly by allowing the beams to rest, and that climatic stresses may be reduced by changing the effects of the climate change by mechanical or physical, or by chemical means, then the dimensioning procedure that has been used in the practice so far may be said to be almost correct. We must add, that in the dimensioning methods that were employed earlier, predominantly isotropic, homogeneous material models were used. This view can no longer hold today, because there exists a dimensioning procedure in the technical literature that has been proven to provide an outstanding reflection of the strength properties of timber materials and of timber-based materials.

While preparing the Gábor Baross grant application we have already realised that the study of the fracture of glue laminated beams is a very complex task, and a lot of research is still required to obtain a full picture of this field. There can be many factors involved in the fracture of glue laminated beams and structures. Many cumulative problems (non adequate manufacturing process, design, construction and operation) can cause very big damages to glue laminated timber beam structures, as we have already seen in the overview of the literature.

In my doctoral thesis, out of the cumulated problems I wanted to prove the dimensioning errors of practical design, to make them known also for the engineering practice. The calculated stresses and their summation have shown that there are strains and stresses that could be calculated, that considerably contribute to fracture, and that are currently not being considered in the engineering practice. Of

course the extent of these could be reduced through adequate operation (by providing a steady climate) and with the protection of the timber material, but these are usually neglected in the practice, and thus the effects that cause additional strains must be considered already in the design phase.

In my theses I have summarized the specific scientific results that I have obtained during my doctoral work and which I have described and proven in my paper.

5 Theses

Thesis No. 1: I have presented the statical dimensioning of glue laminated, arched and straight-axis timber beams by having considered both manufacturing and climatic loads in addition to external loads.

People have been manufacturing, building and dimensioning glue laminated timber beams for nearly 100 years already. However, so far only external loads were considered in the dimensioning. Other effects have not, or have rarely been considered. Often designers have even neglected the anisotropic characteristics of the timber material, and have treated it as a straight or curved-axis beam made of an isotropic and homogeneous material. I have found the most generic analytical model calculation that could be found in the technical literature, that allows for the anisotropic nature of the timber material and the curvature of the beam to be accurately considered, as well as the model calculations that can be used to determine both manufacturing stresses and climatic stresses (the latter subject to certain conditions). I have summarized these calculation procedures in a way to enable users to perform the calculations by themselves

and to be able to use my paper as an outline and as a collection of examples.

Thesis No. 2: I have developed a method to sum the stress tensor fields that originate from the various types of loads, i.e., to specify the resultant tensor field. With this - in principle - I have specified the combined (resultant) stress state resulting from the three kinds of loads, for any point of the timber beam. I have developed a way to specify the dangerous cross-sections of the timber beam and the critical points within these cross-sections. In addition, I have also presented the calculated stress state for these points, for which the statical dimensioning can be performed on an anisotropic basis.

Thesis No. 3: As a result of the preceding theoretical and experimental research I have presented the anisotropic statical dimensioning (verification) of glue laminated timber structures with the application of the Ashkenazi strength theory, as a method that can be processed and implemented in the design practice.

Although strength theories have already been used earlier for the statical dimensioning of timber structures and other composites, their suitability for assessing the strength of anisotropic materials is demonstrably only approximative. It is one of the unconcealed objectives of my paper to allow this strength theory, examined and proven from several points of view, to become widespread in the everyday design practice as soon as possible. The dimensioning and the design can be performed in the same way for simpler and for more complex loads.

Thesis No. 4: I have found that in the case of arched glue laminated timber beams, for identical external geometries and radii of curvature, an identical external load will result in an identical stress tensor field.

I.e., the extent and the distribution of the stresses resulting from an external load are not affected by the lamella-thickness, or by the number of lamellas, or not even by the Young modulus of the individual lamellas, i.e., not even by the tree species that is being used. In principle each lamella could be made of a different tree species. Only the manufacturing technology sets a limit for the number of tree species used. In the practice - in the case of a beam made of timber - it is not worth using more than two (or occasionally three) tree species. Suitability for gluing is one of the most important technological factors. The combined beam cross-section - in a layout that conforms to the approach and to the EN standard - follows well, in the dangerous cross-sections, the height distribution of the normal stresses that are parallel to the grains (the maximum stresses arise near the bottom and the top fibres). Lamellas of greater strength that are placed here can easily withstand these stresses.

Thesis No. 5: My findings for the manufacturing stresses of arched glue laminated timber beams are as follows:

5.1 The stresses that originate from the manufacturing are comparable to those that originate from external loads. These are often of an identical magnitude, and thus by all means the manufacturing stresses must be considered in the statical dimensioning of the beams.

5.2 The lower the R/H ratio (i.e., the smaller the radius of curvature for an identical beam height), the greater the manufac-

turing stresses will be, especially the normal stresses that are parallel to the grains. However, an R/H value of 200 should not be considered as a limit value here (in similar to the calculation of stresses that originate from external loads), because the stresses will not change significantly if this value is exceeded. The model calculation is suitable for considering the specific R/H ratio.

5.3 For identical external geometries the manufacturing stresses will be smaller where the individual lamellas are thinner.

In the case of the two beams presented, the normal stresses that are parallel to the grains have dropped to a third, while the normal stresses that are perpendicular to the grains and the shearing stresses have both dropped by an order of magnitude when the lamella thickness was one third.

5.4 In the case of a combined beam, lamellas having a higher Young modulus, i.e., more rigid lamellas, carry greater normal stresses in parallel to the grains, than the middle lamellas that are less rigid.

This is also optimal for load bearing, as the more rigid timber material is presumably also stronger in the direction parallel to the grains, than the timber material that has a lower Young modulus. There is no significant difference with an impact on the dimensioning in the distribution of shearing stresses. Neither are there significant differences in the values of the normal stresses perpendicular to the grains, but the maximum values of the normal stresses are significant in the vicinity of the transitions (lamellas 4-5 and 15-16 in a beam with 20 layers) and the risk of tearing perpendicularly to the grains directly after removal from the shape is greater with these mixed arched beams with diverse

Young modulus values. This phenomenon also serves as a warning to correctly observe the gluing technology.

Thesis 6: My general findings for the stresses induced in glue laminated timber beams by climatic changes are as follows:

6.1 In the case of an unfavourable climatic change (that could also be due to an inadequate manufacturing technology) the normal stress perpendicular to the grains at the beam ends and the shearing stress could reach values that could by themselves (without the external load or the manufacturing stresses) cause fracture, which could result in the tearing and shearing of the beam ends. In this regard there are no differences between straight and arched-axis beams.

This statement primarily serves as a warning to strictly observe the manufacturing technology. If the moisture contents of the lamellas to be glued together are not identical (i.e., the material of the beam is not homogeneous), this could have catastrophic consequences for the entire beam structure.

6.2 For identical external geometries, stresses due to climatic changes will be lower for lamellas that are thinner. Changes in normal stresses in parallel to the grains were not significant in the internal area that makes up a large portion of the beam, while normal stresses perpendicular to the grains and shearing stresses at the beam ends have dropped by almost half in comparison to the stresses for lamellas with three times the thickness.

6.3 In beams with a combined lamella construct, similar climatic changes will practically create identical stress state fields as in

the case of a homogeneous beam, but the maximum stress values will be 20-30% lower.

A combined construct therefore has a favourable effect on the extent of climatic stresses in glue laminated timber beams.

6.4 If the moisture content of the lamellas changes randomly at the start of the manufacturing process, but never in excess of ± 1 %, then the climatic stress curves along the height are similar for the homogeneous and for the combined cross-sections. For deviations in moisture content not exceeding ± 1 % the climatic stresses will not be of a sufficient extent to fracture the construction, but in accumulation with the other types of stresses there will be a significantly higher probability of fracture.

6.5 In glue laminated beams anomalies in temperature changes create climatic stresses that are lower by an order of magnitude than stresses caused by changes in moisture content (with climatic changes observed in the practice).

6.6 During the life-span of a glue laminated timber beam an asymmetric moistening by 12 % could generate climatic stresses that could in themselves fracture the construct.

While paragraph 6.1 of this thesis calls attention to precisely observing the manufacturing technology, this section indicates that the specifications of the assembly and construction technology (and even its design) are also of extraordinary importance. Incidental leaks or the constant precipitation of moisture could cause significant climatic stresses that could lead to the fracturing of the structure.

Thesis No. 7: I have shown and have performed calculations to validate that after combining and considering all stresses, for two identical glue laminated timber beams (with identical external geometries and loads) there will be considerably lower stresses generated in the one consisting of thin lamellas, then in the one consisting of thick lamellas.

At the beginning of the dissertation while surveying 16 buildings we have encountered structures consisting of both thin and thick lamellas. During the survey it was found that cross-sections consisting of thin lamellas are less likely to crack than those consisting of thick lamellas. I have used calculations to validate the cause of this.

Although it is more expensive to manufacture beams that consist of thinner lamellas (as more waste is generated and more glue is required, and these are also more sensitive to manufacturing specifications), but their higher safety in terms of fracture still justifies their use, especially for structures characterised by more uncertain external loads and climate exposures.

Thesis No. 8: On the basis of my research the dimensioning of glue laminated straight and arched-axis timber beams is to be performed as follows:

- I. Select a type of timber structure that conforms to the objective and the task.**
- II. Choose the tree species and the external and internal geometry for the main beam (radius of curvature, spread, lamella thickness, the cross-sectional dimensions of the lamellas and of the support beam).**
- III. Specify the standard load.**

- IV. Specify the reaction forces and the strains on the basis of the standard load.
- V. Specify the stress state field resulting from the external standard load (von Roth model).
- VI. Specify the residual stress state field corresponding to the manufacturing technology (Szalai model).
- VII. Specify the residual stress state field corresponding to the foreseeable climatic changes (Szalai model).
- VIII. Specify the critical points of the beam (based on the practice that corresponds to the approach, or using an adequately chosen computer program).
- IX. Specify the equivalent stresses of the critical points on the basis of the standard stresses and the anisotropic limit stresses in accordance with the Ashkenazi strength theory.
- X. Compare the values of the equivalent stress(es) to the limit stress value. If

$$\sigma_{egy}^M < f_L^{H+},$$
 then the critical point of the structure is acceptable. Of course all critical points must be verified.
- XI. If for some critical point the relation does not hold, then go back to Section 2 and repeat the verification with adequately increased cross-sections.

6 Technical literature references list

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