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EVALUATION OF GLULAM BEAMS' PERFORMANCE IN SPECIAL ENVIRONMENTAL CONDITIONS

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ABSTRACT

This paper describes a survey and damage assessments of glued, laminated wooden beams in the central European region (Hungary). Primarily, the effects of constant high humidity and temperature regulated environments on the structural adequacy of load supporting beams were the focal point of the investigation. Such conditions existin public swimming pools and thermal bathes, sometimes coupled with corrosive vapours. The observed deteriorations may be traced back to manufacturing errors and to the long term, changing environmental exposures. Both are attributable to internal stresses. Two models were developed to approximate the internal shear and tension stresses, particularly at the end of the beams. The shear model may aid designers and manufacturers to avoid delamination. Predicting the tension stresses perpendicular to the grain of the lamellas highlights the importance of proper drying to expected, in-service moisture content. Furthermore, with careful layering of the lamellas and improved design of connectors/joints the service time of glulam beams can be extended.

KEYWORDS: Glulam beams, internal stresses, moisture content, relative humidity.

INTRODUCTION

The structural application of glulam beams has started from the beginning of XXth century when Hetzer patented his technology. In 1920 in Europe there were 200 buildings with layered, wooden beam structures (Kovács 2011). Later, with the innovations of glulam technology, the span of the beams increased and their structure became more complex. Despite the advances in resin technology, at the wood to wood joints (lamella layering), as well as at the connectors or supports, strength of the glulam beams still decrease with ageing. These deteriorations attributed to the manifold fatigue progressions. The changing climatic conditions accelerate these phenomena that eventually results in structural failure.

Since the mid-1900s, works addressed strength and stability problems from different point of view. However, limited number of research projects in Europe dealt with the effects of environmental exposure on the shear and none parallel normal stress developments in layered wooden structures. Glued laminated members may experience about 0.3 MPa tension stresses perpendicular to the grain of the layers due to external loads. Coupled with the hygroscopic stresses it may exceed the average strength values (0.5 MPa) in that direction. Particularly it happens in outdoor structures, where the seasonal equilibrium moisture content changes are noteworthy.

Aicher et al. (1998) conducted an extensive investigation on the duration of load (DOL) effect in tension perpendicular to the grain under variable climate conditions. They found that the changing temperature and relative humidity may drastically increase the DOL effect. Alpo in 2001 showed that the effect of moisture content gradient usually was not considered in the past during the cross sectional design of the structures.

A recent tragic accident happened at the ice-arena of Bad Reichenhall in 2006 when the structure collapsed. Fifteen lives were lost, most of them children, and additionally thirty four injuries occurred. The reason of the collapse was partly due to the structural defects and partly by the deterioration of the general finger joints and glue lines on the lower girders (Winter 2006).

The ageing of infrastructure is a world-wide problem not only for wooden structures, but for any types of constructions. Thus, research on long term performance of load bearing elements should have high priority. The above tragic example clearly demonstrates that there are still many questions or problems to be solvedregarding the prolonged use of wood glulam-beams. The highlights of this research presented here may contribute to the better understanding and better design of load supporting, layered wooden structures.

Theoretical background

In general, for layered systems, elasticity theories provide good approximations for normal, shear and bending stresses generated by external loads in the cross section of a particular structural element. Than these stresses can be modified to incorporate the climate induced internal stresses. However, at the load free, end-cross sections, where theoretically no shear exists, the climate change induced internal stressesare still present. The state of equilibrium indicates some stress state distortion. At the end of the beam tension stresses, perpendicular to the glue layers, and shear stresses are also induced. These stresses may delaminate the layers and/or and cause cracks at the end of the beams.

Some forty years ago Henrici (1977) identified such distorting stresses on homogenous, isotropic poles andproved that the derived equations apply to glued laminated wooden beams as well.

Most recently (Szalai 2002, Szalai and Kánnár 2002, Kánnár 2011) developed equations to calculate normal stresses perpendicular to the grain along with shear stresses at the end of glued laminated beams. Without presenting the lengthy derivations, results of these analytical works can be summarized as follows:

At h/2 (h=depth of the beam) distance from the end cross section the shear distribution can be calculated by the given Eq. 1:

$$\tau(\xi,\eta)=\tau(\xi,y)=\tau_{i\max}f'(\xi)+\frac{12M_{i+1}}{bhh_{i+1}f(\xi=1)}\left(\frac{y^2}{h_{i+1}^2}-\frac{1}{4}\right)f'(\xi)-\frac{2N_{i+1}}{bhf(\xi=1)}\left(\frac{y}{h_{i+1}}+\frac{1}{2}\right)f'(\xi). \tag{1}$$

where: $\tau(\xi,\eta)=\tau(\xi,y)$ - shear stresses,

$f'(\xi)$ - shear distribution function near the end of the beam,
M - moment,
N - normal forces,
h and b - depth and width of the beam, respectively,
y - location of the layer,
(ξ,η) - global coordinates, for curved beams and arches, measured from the center of the curvature,
i - layer index.

Similarly, Eq. 2 provides the normal stresses at the end of the beam:

$$\sigma_{yy}(\xi,\eta)=\sigma_{yy}(\xi,y)=\sigma_{yyi}(\xi)+\frac{4h_{i+1}}{bh^2 f(\xi=1)}\left(\frac{y}{h_{i+1}}+\frac{1}{2}\right)\sum_{j=1}^{i}N_j f''(\xi)-$$
$$-\frac{2M_{i+1}}{bh^2 f(\xi=1)}\left(\frac{4y^3}{h_{i+1}^3}+\frac{3y}{h_{i+1}}\right)f''(\xi)+\frac{2N_{i+1}h_{i+1}}{bh^2 f(\xi=1)}\left(\frac{y^2}{h_{i+1}^2}+\frac{y}{h_{i+1}}+\frac{1}{4}\right)f''(\xi) \quad (2)$$

where the unknowns: σ_{y} - normal stresses perpendicular to the grain,
$f''(\xi)$ - normal stress distribution perpendicular to the grain at the end of the beam.

In details:

$$f(\xi)=\frac{a_1}{a_3^2}\left[1-(1+a_3\xi)\exp(-a_3\xi)\right],$$
$$f'(\xi)=\frac{df(\xi)}{d\xi}=a_1\xi\exp(-a_3\xi), \quad (3)$$
$$f''(\xi)=\frac{d^2f(\xi)}{d\xi^2}=a_1(1-a_3\xi)\exp(-a_3\xi)$$

where: a_1=16.3 and, a_3=6 empirical constants,
$\xi=\frac{2z}{h}$
z - polar coordinate of the radius of curvature for the beam.

Eqs. 1 and 2 provide opportunities to estimate the expected stress distortions in layered systems if the external and internal loads are defined.

MATERIAL AND METHODS

The locations of the surveyed constructions are scattered all over the Carpathian Basin. The first column of Tab. 1 provides information and identification of the structures. The location code A represents the Southern, hilly parts of the Basin. B stands for Sub-Alpine climate; C denotes the mountainous Northern region. Letters D to G and J mark miscellaneous locationsin different planes of the region. H had upper Mediterranean climate, while I denotes lakeside environment. Tab. 1 further compiles technical specifications and the year of constructions.

Tab. 1: Specifications of the surveyed structures.

Location & structure Code	Exposure categories	Span of the beam (m)	Type of the beam	Cross sectional size(s) (mm)	Number of layers	Year of constr.	Wood species
A – H1	Indoor/pool	37.0	Three-hinged, straight	200 x 1000	40	1975	Black locust
A – H2	Indoor/pool	12.5	Straight	160 x 700	40	1994	SPF*
A – H3	Indoor/pool	16.0	Curved, pitch - tapered	160 x 700 pc.	40	1994	SPF
A – H4	Indoor/pool	12.0	Curved	160 x 600	40	1994	SPF
A – H5	Indoor/heated	30.0	Curved	15 x (1000, 900, 600)*	35, 15	1997	SPF
A – H6	Indoor/pool	18.0	Curved	150 x 700	40	1986	SPF
B – S1	Indoor/pool	42.0	Curved arch	150 x 650	35	1978	Scots pine
B – S2	Indoor/pool	36.0	Three–hinged arch	150 x 800	30	1987	Spruce
B – S3	Indoor/heated	36.0	Three–hinged arch	150 x 800	35	1987	Spruce
C – E1	Indoor/pool	12.0	Curved	130 x (650, 700)	(35, 25)	2000	Spruce
C – E2	Indoor/pool	36.0	Three – hinged arch	160 x 1300	35	2000	Spruce
D – J1	Indoor/pool	30.0	Curved, pitch - tapered	180 x 800	25	2010	Spruce
D – J2	Indoor/pool	24.0	Three – hinged, curved	130 x (700, 800)	30	1992	Spruce
D – J3	Indoor/pool	18.0	Arch	140 x 800	10 - 20	2000	Eu. Larch
E – M1	Indoor/pool	16.0	Frame w. tie	100 x 570	40	2007	Scotch pine
F – P1	Prot. outdoor	18.0	Three–hinged, straight	120 x (800-250)	30	1980	Spruce
G – K1	Ind./unheated	--	Baroque roof structure	Variable cross sections	30	2000	Eu. Larch
H – C1	Indoor/heated	24.0	Curved	200 x 800	30	2006	Spruce
I – B1	Indoor/heated	12.0	Straight	120 x (700, 150)	22, 30	2100	Oak
I – B2	Indoor/heated	12.0	Straight	180 x 500	15	2100	Oak
I – B3	Prot. outdoor	18.0	Straight	140 x (500, 300)	35	2100	Oak

*-spruce, pine and fir

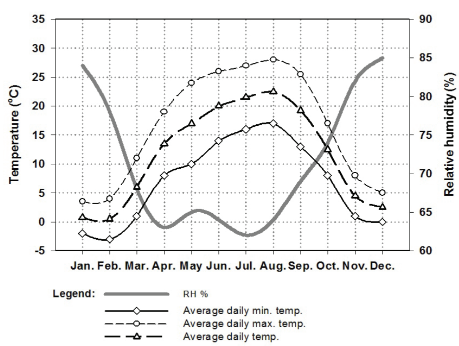
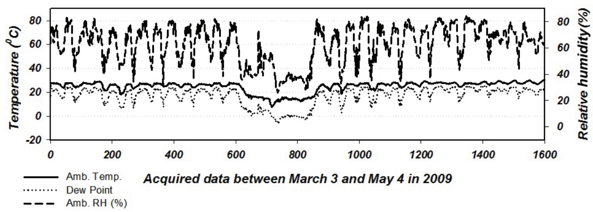


Fig. 1: Yearly average temperature and relative humidity in the Central European region. Source: National Weather Service of Hungary.

The survey included visual inspections four times a year. Fig. 1 provides information about the yearly average climate condition in the region. During the spring, summer, fall and winter seasons, the indoor temperature, dew point and relative humidity were recorded using a Volt craft DL-120T.H type data logger. Fig. 2a and b show partial recordings of an indoor pool's climate conditions.

a.)



b.)

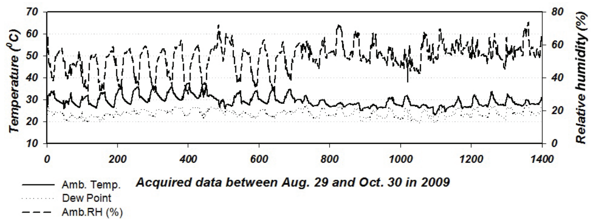


Fig. 2: Typical spring and fall recordings of T, RH and dew point of indoor pools.

The evaluation of strength properties happened thorough non-destructive testing. The used device was a FAKOPP- ultrasonic type apparatus that measures the ultrasound propagation along the length of the layers. The interested reader can find more information regarding this measuring method in the next publications (Divos 2011). During the inspections the length and width of cracks, the magnitude and location of cracks were evaluated and recorded. Additionally, stained and fungi infested areas were also assessed.

RESULTS AND DISCUSSION

Out of the 22 surveyed structures, all of them showed some deterioration; however, only five had severe damage. These inadequacies were treated post manufacture. In structure A-H3 the bottom layers were fixed with screws. The time and mode of delamination could not been identified.

Similarly, the bottom layers of the elements of structure C-E1 were also reinforced with screws. At the support of the three-hinged elements of D-J2 frame, severe delamination occurred, which was fastened with steel bands (Fig. 3).

The heated indoor climate conditions (A-H5) caused severe crack developments in members having thicker layers (Fig. 4). Surprisingly, members having thin (15 mm) lamellas did not crack.

Furthermore, as it was expected, the climate control in pools and other indoor structures resulted in fewer cracks and less delamination.

The survey revealed another observation regarding tapered beams. Due to the manufacturing processes, tapered beams always contain lamellas with sloping grain. Such members are more prone to crack development because any cross grain elements is weaker than that of its straight grained counterparts. Fig. 5 shows the likely failure of tapered beams due to the sloping grain occurrences (D –J1). Besides the sloping grain, the pith content is a significant factor for crack development. The weak parenchyma cells of the pith can trigger crack propagation during even slight ambient condition changes (Fig. 6). The ultrasonic measurement of the beams in

Fig. 3: Delamination of an indoor beam at the support; tied with metal brace (humid indoor environment).

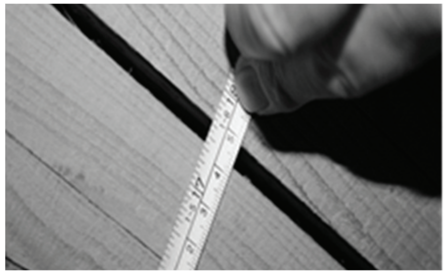


Fig. 4: Typical delamination of an indoor beam in dry environment.

structure A-H3 showed that the lamellas have significant variations in strength.Because strength properties directly related to the physical properties (shrinkage and swelling), highly inhomogeneous layering results in frequent defects. In some cases the changing environmental condition induced stresses may exceed stresses from external loads. Consequently, high variation in layer strength properties leads to delamination with certainty.

Based on the results of this survey and other theoretical considerations, the major general factors causing most of the inadequacies may be listed as follows:

- restrained swelling and shrinking;
- presence of sloping grain (tapered beams);
- different moisture content of the lamellas;
- stresses perpendicular to the grain;
- pith content of the lamellas;
- glue line failure;
- dissimilar anisotropic behaviour of the different lamellas.

Fig. 5: The effect of sloping grain in tapered beam (unheated indoor environment).

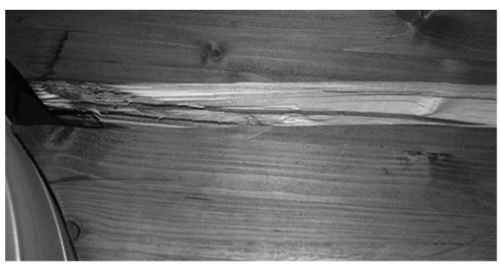


Fig. 6: Sever climate induced damage at the pit of the lamellas (unheated indoor environment).

To a certain extent restrained swelling and shrinkage is an inherent property of any layered wood structure. The restraining effect of the glue lines; however, are limited. Sever shrinkage and /or swelling certainly results in delamination, especially at the ends of the beams. The water uptake at the unprotected end-grains is much higher than at any side-grain surfaces, therefore the end-grain surfaces should be protected with water vapour berries. Restrained shrinkage and swelling can occur in steel band or plate reinforced members due to the hygroscopic neutrality of metal elements. Cross grained constituents in layered systems also cause crack developments as it was discussed earlier.

The uneven moisture content of the lamellas may have come from different sources that include improper drying of lamellas, inadequate roofing, asymmetric environmental exposure, etc. Similarly, stress development perpendicular to the grain of the lamellas can be the results of remaining internal stresses after manufacture, external load, climate induced internal stresses and/or the combination of the above.

Lamellas containing pith have higher rate of swelling-shrinkage properties and also show pure tension strength perpendicular to the grain, hence their application should be avoided.

Because evaluation showed that the cracks were usually developed at the glued plane, one can't exclude the glue-line failure. It was found by Vanya (2012) as well.

Although solid wood is more or less cylindrically orthotropic, it is treated as rectilinearly orthotropic material. In glued laminated beams the different ring orientations in the layers may cause inherent stresses due to the manufacturing processand/or due to the different anisotropic behaviour of the elements in changing environmental conditions. It was examined and concluded by Gustafsson (2009) and Niemz (2005) as well.

Based on the above arguments, the effective practice of design with wooden, glued, laminated structural elements should incorporate the followings:

~ The stresses, induced by changing relative humidity (RH) and temperature (T), should be included in the dimensioning process.
~ There is a need for development of new type of metal connectors, reinforcements; that alleviate the risk of crack developments and crack propagations.
~ To prevent failure, originated from manufacture, the construction rules of load supporting members should be revised. The revision should target the applied layers' quality, working quality of the resin, required surface finishing and end-grain protection.
~ Finally, to assure long term trouble free service, maintenance guide with suggested schedule must be established.

In the next section thorough a numerical example the effect of uneven moisture content (MC) of the layers are demonstrated. Note, that such discrepancies in the MC of layers may originate from different sources, such as uneven exposure, leaks, floods, etc.

Stress development in layered wooden systems by uneven MC

The general formula to calculate the extension of the i^{th} lamella takes the following form:

$$\varepsilon_{zzi}(y,z) = \frac{\sigma_{zzi}(y,z)}{E_i} + \alpha_{LLi} dT_i(y) + \beta_{LLi} du_i(y), \qquad (4)$$

where: σ_{zzi} - ensile stress caused by normal force and bending moment,
E_i - MOE of the i^{th} lamella parallel to the grain,
β_{LLi}- moisture expansion/contraction coefficient (1/ %),
α_{LLi} - temperature expansion/contraction coefficient (1/°C),
$dT_i(y)$, du_i - difference between the initial and final temperature and moisture content of the i^{th} lamella,
y,z - coordinates,
T_i - temperature of the i^{th} lamella.

Based on this strain model (Eq. 4) moments, normal and shear forces can be calculated according to the three equations below (Szalai and Kánnár 2002):

$$M_i(z) = J_i\left(\frac{\Delta_i}{h_i} - \frac{SD + AG}{AJ - S^2}\right)$$

$$N_i(z) = A_i\left[\frac{D(J - Sa_i) + G(S - Aa_i)}{AJ - S^2} - (\delta_i - \delta_1)\right], \quad (5)$$

$$T_i(z) = J_i\left[\frac{1}{h_i}\frac{d\Delta_i(z)}{dz} - \frac{S\frac{dD(z)}{dz} + A\frac{dG(z)}{dz}}{AJ - S^2}\right]$$

where:

$$A = \sum_{i=1}^{n} A_i, \quad J = \sum_{i=1}^{n} J_i + \sum_{i=1}^{n} A_i a_i^2, \quad S = \sum_{i=1}^{n} A_i a_i$$

$$D = \sum_{i=1}^{n} A_i(\delta_i - \delta_1); \; G = \sum_{i=1}^{n}\left[J_i\frac{\Delta_i}{h_i} - A_i a_i(\delta_i - \delta_1)\right];$$

$$\Delta_i = E[\alpha_i \Delta t_i(z) + \beta_i \Delta u_i(z)]; \; \delta_i = E[\alpha_i \delta t_i(z) + \beta_i \delta u_i(z)]$$

and where:
A - cross sectional area,
J - moment of inertia,
D;G - simplifications as given,
$a_i - a_i = \sum_{j=1}^{i} hj - \frac{h1+hi}{2}$; - distance of the centre of gravity (COG) of the i^th lamella form the COG of the first lamella,
S - 1st order of moment of inertia of the lamella,
$\Delta_i - \Delta_i = E(\alpha_{LLi}\Delta T_i + \beta_{LLi}\Delta u_i)$,
$\delta_i - \delta_i = E(\alpha_{LLi}\delta T_i + \beta_{LLi}\delta u_i)$,
ΔT_i- temperature gradient between the top and bottom of the i^th lamella at the initial and final conditions,
Δu_i- moisture content gradient between the top and bottom of the i^th lamella at the initial and final conditions,
δT_i- temperature differential at the centre of gravity of the i^th lamella at the initial and final condition ns,
δu_i- moisture content differential at the centre of gravity of the i^th lamella at the initial and final conditions.

Solving Eqs. 4 through 5, the uneven moisture content induced forces and moments can be calculated. Substituting the results in eqs. 1 and 2, give us the critical hygroscopic shear and normal stresses perpendicular to the grain direction at the specified end-distance of the beam. Note that this approach does not include any external loads; however, applying the principle of superposition a complete loading scenario should be analysable.

As a numerical example, let us consider a curved beam having 60 m span. The radius of curvature of the upper lamella is 40 m. The cross section is comprised of 40 lamellas, 140 x 40 mm in cross sections each. The assumed modulus of elasticity of the layers, E = 12.0 GPa, with U_0 = 12 % moisture content and T = 25°C initial conditions.

After a certain roof leakage the temperature remained constant and the measured MC of the top 1/3 of layersturned out to be U_1 = 20 %. Other layers preserved the constant 12 % MC. After identifying the uneven moisture content induced moments, normal, and shear forces (Eqs. 5), the solutions of Eqs. 1 and 2 provided stress distributions at the particular locations of the beam cross sections. Fig. 7 shows the results of these analyses for the given beam described above.

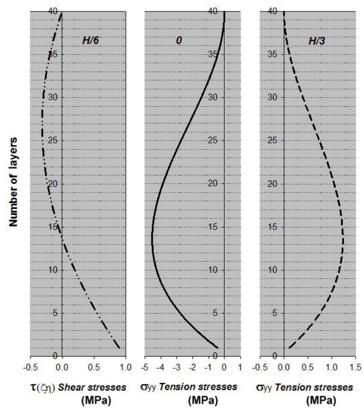


Fig. 7: Moisture content change induced shear, and perpendicular to the grain normal stresses at the end locations H/6, 0 and H/3, respectively.

From H/6 distance of the end of the beam, at the lower lamella, the maximum shear stress is positive with a value of ~0.9 MPa. Local positive maximum was detected at the bottom of wet layers (upper 13 lamellas). The normal stresses at both 0 and H/3 distance from the end had maximum values where the shear is nearly 0. As one can realise the positive normal (tension stresses) ~1.3 MPa may induce crack developments and failure, because the low strength properties in this anatomical directions. Note, that the computations were numerically executed for the glue layers; because most of the failures atthe end of the beams were delamination.

CONCLUSIONS

The ageing of infrastructures all over the world requires reconsideration of manufacturing, design and maintenance procedures. The comparatively new load supporting structural elements like glued-laminated wooden beams, girders and columns require particular attentions. The constituent for these in- and outdoor building elements is solid wood; which is very prone to changes in environmental conditions because of its hygroscopic nature. The results of survey and analytical work presented here, revealed seven major factors that may contribute to the structural inadequacy and/or failure.

Thorough a numerical example, it was demonstrated that the hygroscopic stresses alone can initiate delamination and crack development. Consequently, at the beginning of the design procedure, such moisture content changes induced stress development must be considered. Furthermore, the quality control over manufacture and the appropriate maintenance guides are also imperative for the long, trouble free, servicelife of glued laminated beams.

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