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Csilla Vanya

DAMAGE PROBLEMS IN GLUED LAMINATED TIMBER

On a number of occasions glued laminated timber breaks apart before the end of their service life. Examples in Germany (Frese M., Blaß H. J. [2011]) and Denmark (Hansson, Larsen [2005]) show that this problem is real. In order to find the causes of the problem, extensive tests were conducted: 16 buildings with glued laminated timber were examined on the spot, calculations and laboratory work were carried out. These examinations told us that not only did the properties of the wooden material cause the damage, but the problems were also due to the wood used and the method of construction. In the calculations, the external load and residual stresses occurring in the glued laminated timber were included. Residual tensions in this timber were generated by climatic stresses and also due to the method of construction. These stresses also accumulated along with the stresses of the external load. Laboratory work was carried out to measure the delamination. We examined whether these analyses and calculations prove or disprove the results of the on- the- spot examinations.

Keywords: stresses in glued laminated timber, internal stresses, manufacturing stresses, climatic stresses, damage of glued laminated timber, reasons for damage

Introduction

The first step to finding the reasons for damage in arched glulam timber is deciding on what constitutes an external load and how to calculate the stresses caused by this load. The calculation of the external stresses in glulam arches has been carried by a number of researchers. Many scientists have published their solutions: Heimeshoff [1973], Routh and Epple [1981a, 1981b], Schelling [1981], Möhler [1976a, 1976b], Möhler and Hemmer [1980]. They calculated the stresses and examined the relationships between the shape of the construction, the statical model, the cross section and the load distribution types. Most of these calculations applied isotropic material models.

Noack and Roth [1972] published a calculation method for arched glulam beams loaded with normal forces, shear forces and bending moment. Their work is

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Csilla Vanya, University of Pécs, Hungary
e-mail: vanya.csilla@gmail.com

one of the most ambitious research projects ever carried out because they applied an anisotropic material model. They proved that we can use an ideal elastic and isotropic model if the radius of the curvature and the height of the beam correspond to some determined conditions. A smaller radius and changing height (non-prismatic beam) caused inaccurate results, therefore we have to use the accurate anisotropic model in special cases.

In arched glulam beams, internal stresses can be born near the stresses caused by the external load. This situation was studied in Szalai [1985, 1984, 1985, 2001], Garab, Tóth, Szalai, Bejó, Dívós [2010]. He separatelythe stresses caused by the gluing process and those caused by the climatic changes.

Several authors have examined the correlation between climatic and residual stresses from different points of view. For example Niemz, Bärtschi, Howald [2005], Angst, Malo [2012], Häglunk [2009], Gustafsson, Hoffmeyer, Valentin [1998], Olejniczak, Gustafsson [1994], D'Amico, Hrabalova, Müller, Berghofer [2012].

These three types of stresses are the most important if we want to create a complete picture of the reasons for damage in glulam beams. To summarise, three stresses in glulam beams can help us uncover and understand most of the problems of damage in Hungarian glulam constructions.

Test methodology

Background of the research.

Due to general practical knowledge and the report from our research [Bartal, Rabb 2010], we can say that the reasons for cracking in glulam beams can be the following:

- change in air humidity,
- cyclic changing in climatic conditions,
- hindered shrinking and bulking (mainly at connections),
- outrunning grain,
- endgrain lamellas without surface protection,
- different moisture content in the lamellas,
- different thickness of the lamellas,
- perpendicular normal stresses,
- incorrect gluing (pressure, adhesive application etc.),
- low quality adhesive,
- other kinds of technological problems.

Small cracks are not rare in glulam beams. One reason for this is changes in humidity. Wood is an orthogonal anisotropic material, thus the absorption of water – as its other physical properties – depends on the grain direction. The absorbed volume of water is higher in the direction of the grain than perpendicular to it. The absorbed water builds between the fibers and causes bulking. For the same reason, loss of water causes shrinking. When air humidity changes too quickly, this bulking and shrinking cannot follow this process, and the developing internal stresses cause deformations and cracking in the wood.

Cyclic climatic changes decrease the strength of the wood. After 25 full periods of change, this weakening can be confirmed through measuring, therefore cyclic climatic changes have the fatigue effect. (A full period is when the moisture content of wood changes from 30% to 0% and back. This full period cannot occur in real life, just in part).

Metal connectors such as steel-plates and bolts do not change size due to climatic changes, thus this constructional hardware hinders the bulking and shrinking of the wood elements. This effect is called hindered deformation.

When the height of the beam changes along the length, it is unavoidable that the grains will run out from the beam. These outrunning grains are more intensive in the absorption and desorption of water than any other part of the beam surface. Lamellas with higher moisture content want to bulk, while others with lower moisture content want to shrink. This difference causes relevant inner stresses. Those beams which have a triangular shape (because of the sloping of the roof) have outrunning lamellas on the top side and full lamellas on the bottom side. This means that the upper side of the beam is much more hygroscopic than the lower side.

Unprotected end grains are the next problem to be mentioned. A crack can easily develop when the end of the beam is not closed, because the opened fibers swallow the humidity very quickly. The adhesive layers have a moisture barrier effect, but this effect does not protect the outside lamellas.

When there is a difference between the moisture content of the single lamellas, delamination can develop even if D4 adhesive is used during the gluing process. This can be explained by the fact that inner stresses caused by shrinking are sometimes larger than the strength of any adhered connection.

Stresses which are perpendicular to the length axis of the beam can be a basic reason for damage of the construction. Some types of external load can cause these kinds of stresses, and these are added to the inner stresses caused by the changing moisture content.

General technological rules in Hungary dictate that the moisture content of the lamellas must be 12 ± 2%. This means that the difference can be almost 4%, and this difference is not even considered a quality fault. However, it can be proved through calculations that a 4% difference can cause delamination itself, without any external load. In our opinion, this ± 2% tolerance must be decreased.

Different lamella thickness is not recommended because the inner stresses are smaller in thinner lamellas than in thicker ones. Therefore, different lamellas are not able to deform together, and delamination of the adhesive layer between a thick and a thin lamella is predicted.

If we focus on some aspects of the calculation results, we can say that internal stresses are always smaller in glulam beams made of thin lamellas than the beams made of thick lamellas. Thick lamellas cause further bending stresses in arched glulam beams. This thesis was proved in our earlier research [Kánnár 2012].

Other parameters, not only the moisture content and the thickness, must also be the same in the single lamellas. Every kind of inhomogeneity decreases the strength of the beam. Lamellas with pith can cause general damage of the construction, because part of the wood around the pith has various hygroscopic or bulking-shrinking properties. This part of wood is called juvenile-wood and it is recommended that it is excluded from any kind of timber construction.

16 buildings with glued laminated timbers were examined on the spot. The damage noticed during these examinations was partially proved by our calculations and laboratory work.

List of the observed buildings in Hungary:

1. Harkány Medical Bath Centre pool Nr. III.,
2. Eger Swimming Pool,
3. Hajdúszoboszló City Swimming Pool,
4. Hajdúszoboszló City Training Swimming Pool,
5. Harkány High School,
6. Eger Water Adventure Park,
7. Mohács City Swimming Pool,
8. Kisharsány Church,
9. Bennet Business Centre, Comacchio Italy,
10. Harkány Medical Bath Centre Water Adventure Pool,
11. Hajdúszoboszló Water Adventure Pool,
12. Tapolca Event Hall,
13. Harkány Medical Bath Centre pool ‘B’,
14. Pécs Market Hall,
15. Sopron City Swimming Pool,
16. Sopron City Sport Arena.

Our “on site” experiments were the following: We examined 16 buildings altogether, and we found manufacturing or building faults in 4 cases. The lamellas in the beams of pool Nr. III. in Harkány (1) were screwed together, because maintenance personnelfound delamination problems during building control. The beams of the swimming pool in Eger (2) were strengthened with bolts, perhaps to repairfaults in manufacturing. The bolts were sinked and covered with the outside lamellas. The beams of the swimming pool in Hajdúszoboszló (3) had been standing in the rain for years, before the building was ready, and this outdoor climate caused delamination in the adhesive layers. The builders made steel bandage elements to strengthen the construction (fig. 1). The oak glulam beams of the yacht-club were seriously damaged, which can be explained by the use there of an unusual and quite unknown hardwood material, non-structural purpose PUR adhesive and the unregulated manufacturing process.
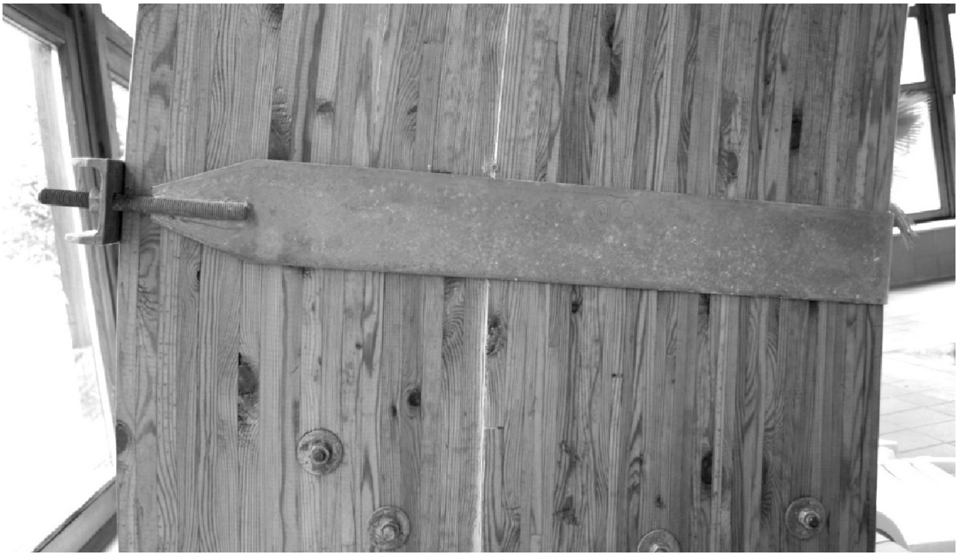
Fig. 1. Steel bandage element on the frame column in the pool at Hajdúszoboszló
Rys. 1. Stalowa opaska na kolumnie szkieletu konstrukcji – basen w Hajdúszoboszló

Typical problems were cracks on the ends of the beams, and delamination at the metal connectors. The bolted connections were hindering the shrinking and bulking, and the beam showed splits between the bolts. The effect of the hindered deformation was also examined at the University of West Hungary Testlab.

It also became clear during the on- site inspections that thin lamellas are favorable for glulam beams. For example, the 3 beams of the High School in Harkány (5) – which were made from thick lamellas – were all damaged, whilst the only one made of thin lamellas was in good condition.

Thin lamellas are ideal for glulam beams but this may not be enough in every case to prevent damage. The water-adventure-park in Eger (6) had a special valley beam between two spherical domes made of thin lamellas. These beams were also cracked because the two different roofs caused a large load on the beams.

The glulam columns of the city pool Mohács (7) were oversized but these elements were in good condition. The glulam purlins had quite large shear forces at the ends, and the steel bolts hindered the deformation, therefore cracks and delamination developed.

Concentrated forces raise the inclination of the cracks. The beams of the roof construction of the church in Kisharsány (8) were delaminated at the connection point of the tie rod. The Comacchio Bennet business house (9) had a special construction, the beams were hanged up at the points which divide the span into three equal parts, and the connection could cause cracking. The bearing plate spread the concentrated force and the damage was avoided.

We also took climate changes into consideration. Where the climate properties were uniform, the beams were generally in a better condition. The adventure pool in Harkány (10) had a retractable roof, and the delamination incidents were significant. In Eger (6) and Hajdúszoboszló (11), the air conditioning was continuous, and the climatic properties were uniform, therefore the beams were in a good condition. The sportshall in Tapolca (12) had no air conditioning or airing equipment, the building was just heated during the winter. The climate properties changed with the seasons of the year. The climate properties were more favorable with continuous air conditioning than in a seasonly heated building.

End grains and outrunning lamellas caused delamination hazards in glulam beams. The beams over pool Nr. III. in Harkány (1) also had outrunning lamellas, and this part of the beams cracked. The newly built pool "B" (13) had a glulam frame construction with outrunning lamellas at the corner, which were also delaminated. The beams in the roof construction of the market hall in Pécs (14) were cracked at the end grains, but the outrunning lamellas did not cause any damage. The columns and beams of the city pool in Mohács (7) were both oversized, and the risk of delamination was very low.

Inhomogeneity of the beams can also cause problems. Wood is an inhomogeneous anisotropic material, but gluing lamination decreases this inhomogeneity, because the glulam beam is made of thin lamellas. Ultrasound measuring on the controlled buildings was carried out, and large inhomogeneity in the beams was found. The theory of the relatively high homogeneity of glulam beams cannot be proved. For example, beam Nr. 3. in the roof of pool "B" (13) was measured, and the difference in the values is shown in table 1.

Table 1. Harkány, pool "B", beam no. 3 – strength classification of the lamellas
Tabela 1. Harkány, basen "B", belka nr 3 – wytrzymałościowa klasyfikacja lamelli

Lamella no. *Lamella nr*	Strength class MSZ 15025 (left end) *Klasa wytrzymałości MSZ 15025 (lewy koniec)*	Strength class MSZ 15025 (right end) *Klasa wytrzymałości MSZ 15025 (prawy koniec)*	Homogeneous beam *Belka homogeniczna*	Strength class of the static design *Klasa wytrzymałości statycznej konstrukcji*	MI-04.183--81 Technological directive 3.1.1. *Dyrektywa technologiczna MI--04.183-81, 3.1.1.*	Valuation *Ocena*
1	2	3	4	5	6	*7*
1	III	I		I	I	does not meet the requirements *nie spełnia wymogów*

Table 1. Continued
Tabela 1. Ciąg dalszy

1	2	3	4	5	6	*7*
2	III	I		I	I	does not meet the requirements *nie spełnia wymogów*
3	II	II		I	I	does not meet the requirements *nie spełnia wymogów*
4	II	I		I	I	does not meet the requirements *nie spełnia wymogów*
5	II	I		I	II	does not meet the requirements *nie spełnia wymogów*
6	II	II		I	II	does not meet the requirements *nie spełnia wymogów*
7	III	I		I	II	does not meet the requirements *nie spełnia wymogów*
8	II	II		I	II	meets the requirements *spełnia wymogi*
9	I	II		I	II	meets the requirements *spełnia wymogi*
10	II	I		I	II	meets the requirements *spełnia wymogi*
11	III	II		I	II	does not meet the requirements *nie spełnia wymogów*
12	III	III		I	II	does not meet the requirements *nie spełnia wymogów*
13	III	II		I	II	does not meet the requirements *nie spełnia wymogów*
14	II	II		I	II	meets the requirements *spełnia wymogi*
15	I	II		I	II	meets the requirements *spełnia wymogi*
16	I	II		I	II	meets the requirements *spełnia wymogi*
17	II	II		I	II	meets the requirements *spełnia wymogi*
18	I	I	X	I	II	meets the requirements *spełnia wymogi*
19	II	I		I	I	does not meet the requirements *nie spełnia wymogów*
20	II	III		I	I	does not meet the requirements *nie spełnia wymogów*
21	III	III		I	I	does not meet the requirements *nie spełnia wymogów*
22	II	II		I	I	does not meet the requirements *nie spełnia wymogów*
23	I	II		I	I	does not meet the requirements *nie spełnia wymogów*

The difference was significant, and certain parts of the beam did not meet either the new norms, or the old ones. The orthotropic behaviour of the wood was increased by the different MOE of the lamellas. This inhomogeneity had significant influence upon the timber service life of the whole construction. The lamellas with different MOE behaved unpredictably during climatic changes, and inner stresses developed. These inner stresses were sometimes as large as the stresses caused by the external load. These two kinds of stresses combined, and delamination or complete damage occured.

The width of the lamellas was also problematic. The beams were made of 20 cm wide lamellas for the roof construction of the Comacchio Bennet (9) building. This uncustomary width could cause delamination even when the utilization rate was low. Delamination of inhomogeneic lamellas was predictable.

The wood species also has an effect on the end product. It is our general experience that the gluing process of hardwoods is always more complicated than the gluing of softwoods. The beams of the yacht club were made of oak and the gluing was imperfect, therefore delamination was observable.

Table 2. Calculated cases glulam beams
Tabela 2. Obliczone przypadki belek typu glulam

Glulam type *Typ elementów klejonych warstwowo (glulam)*	Climatic load (moisture content of the lamellas) *Obciążenie klimatyczne (wilgotność lamelli)*	Lamella thickness *Grubość lamelli*
1	2	3
Homogeneous glulam beam (GL28h) *Homogeniczna belka glulam (GL28h)*	Whole beam u = 12% (no climatic load) *Cała belka u = 12% (brak obciążenia klimatycznego)*	10 mm 30 mm
	Top side lamella: u = 16% All other lamellas: u = 12% *Lamella na górnej stronie: u = 16%* *Wszystkie inne lamelle: u = 12%*	10 mm 30 mm
	Lamella no. 1, 3., 7., 9., 13., 15., 18., 21., 22., 24., 27.,30.: u = 13% all other lamellas: u = 12% *Lamella nr 1, 3., 7., 9., 13., 15., 18., 21., 22., 24., 27.,30.: u = 13%* *wszystkie inne lamelle: u = 12%*	10 mm
	Lamella no. 1., 5., 7., 9.: u = 13% all other lamellas: u = 12% *Lamella nr 1., 5., 7., 9.: u = 13%* *wszystkie inne lamelle: u = 12%*	30 mm
	Starting moisture content in lamella no. 1, 3., 7., 9., 13., 15., 18., 21., 22., 24., 27.,30.: u = 13% all other lamellas: u = 12%, ending moisture content of the whole beam u = 12% *Początkowa wilgotność lamelli nr 1, 3., 7., 9., 13., 15., 18., 21., 22., 24., 27.,30.: u = 13%* *wszystkie inne lamelle: u = 12%,* *końcowa wilgotność całej belki u = 12%*	10 mm
	Starting moisture content in lamella no. 1., 5., 7., 9.: u = 13% all other lamellas: u = 12% ending moisture content of the whole beam u = 12% *Początkowa wilgotność lamelli nr 1., 5., 7., 9.: u = 13%* *wszystkie inne lamelle: u = 12%* *końcowa wilgotność całej belki u = 12%*	30 mm

Table 2. Continued
Tabela 2. Ciąg dalszy

1	2	3
Combined glulam beam (GL28c) *Łączona belka glulam (GL28c)*	Whole beam u = 12% (no climatic load) *Cała belka u = 12% (brak obciążenia klimatycznego)*	10 mm
		30 mm
	Top side lamella: u = 16% All other lamellas: u = 12% *Lamella na górnej stronie: u = 16%* *Wszystkie inne lamelle: u = 12%*	10 mm
		30 mm
	Lamella no. 1, 3., 7., 9., 13., 15., 18., 21., 22., 24., 27.,30.: u = 13% all other lamellas: u = 12% *Lamella nr 1, 3., 7., 9., 13., 15., 18., 21., 22., 24., 27.,30.: u = 13%* *wszystkie inne lamelle: u = 12%*	10 mm
	Lamella no. 1., 5., 7., 9.: u = 13% all other lamellas: u = 12% *Lamella nr 1., 5., 7., 9.: u = 13%* *wszystkie inne lamelle: u = 12%*	30 mm
	Starting moisture content in lamella no. 1, 3., 7., 9., 13., 15., 18., 21., 22., 24., 27.,30.: u = 13% all other lamellas: u=12%, ending moisture content of the whole beam u = 12% *Początkowa wilgotność lamelli nr 1, 3., 7., 9., 13., 15., 18., 21., 22., 24., 27.,30.: u = 13%* *wszystkie inne lamelle: u = 12%,* *końcowa wilgotność całej belki u = 12%*	10 mm
	Starting moisture content in lamella no. 1., 5., 7., 9.: u = 13% all other lamellas: u = 12% ending moisture content of the whole beam u = 12% *Początkowa wilgotność lamelli nr 1., 5., 7., 9.: u = 13%* *wszystkie inne lamelle: u = 12%* *końcowa wilgotność całej belki u = 12%*	30 mm

Control examination with calculation

A detailed calculation was made to determine the residual (inner) stresses of different kinds of glulam beams. Moreover, the calculation determined the external load and a summary of the two kinds of stresses.
To model the real climatic properties, various cases were calculated.
For the examined cases see table 2.

Control examination with laboratory work

The laboratory work was carried out at the University of West Hungary. The first and most important result is that climatic loads reduced the shear strength and the module of shear elasticity by about 15%. The reduction could be observed after just 20 days of cyclic changing. The effect of longer-lasting changes could be much larger.

The examinations proved our calculated theory that thin lamella beams have better resistance against delamination. It is important to mention that the MSZ EN 391 Norm describes the method but does not stipulate a limit value, therefore we had to decide if the results met our expectations or not. In our opinion, this is a serious deficiency, and we will initiate the introduction of a classification value, at least in Hungary.

Following our research, theoretical analysis and our skilled experience, we propose a 5% delamination limit on the whole glulam beam and a 15% limit on one adhesive layer.

If delamination stays within this limit, the load-bearing capacity of the glulam beams will meet the expectations, meaning that the adhesive quality, the pressure and the whole production process is correct.

To compare, we carried out a delamination test on the oak glulam terrace elements at the yacht club. The lamella thickness was 20 mm, and the adhesive was PUR (for joinery application, not for load-bearing constructions). The testing process was the same as previously (fig. 2). After the test, delamination was almost 100%, and the glulam elements could be separated by hand.

In addition, railway sleepers made of oak were examined. The test specimens were made by Lignum Európa Ltd. with the Swedish Cascomin 1247 adhesive. Delamination was more extensive than our proposed limit. Therefore, we can conclude that glulam blocks are not applicable for railway sleepers, even if they are made of oak.

The results and industrial experience indicate 3 basic rules:

1. Only qualified constructional adhesives are permitted for fabrication of glulam beams.
2. The chemical industry develops adhesives for fir and spruce, because 90–95% of glulam constructions are made of these 2 wood species. Gluing other species of wood can cause various problems. Fabrication of hardwood glulams with common adhesives is not recommended.
3. Outdoor climatic conditions can damage even the most resistant adhesives, therefore unprotected beams or beam parts shall be avoided [Kánnár 2012].

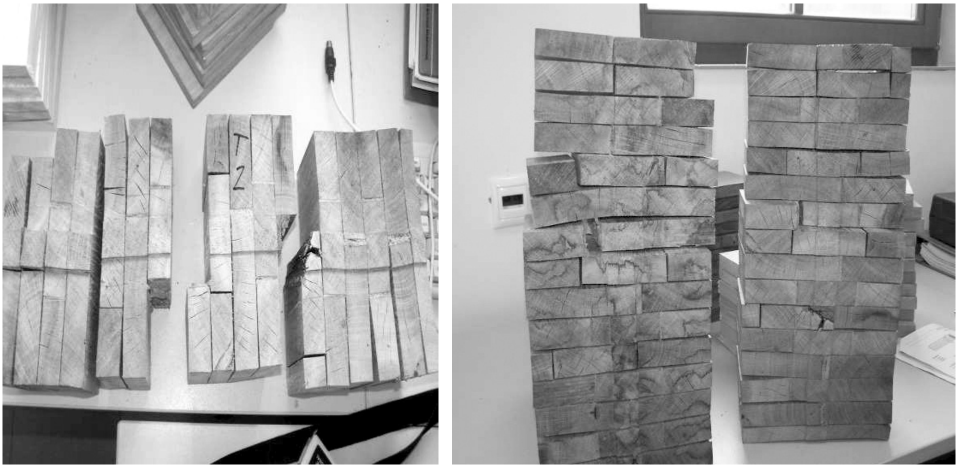

Fig. 2. Delamination on oak test specimens
Rys. 2. Rozwarstwienie na próbkach dębu

Test results

Conclusion of the calculations

Normal stresses can be superposed on any kind of inner stresses. It does not matter which kind of climatic stress or which kind of lamella arrangement we calculate, the summarized stresses are larger than the stresses caused only by the external load.

In beams glued using thick lamellas, the summed stresses can be many times larger than the external stresses. In beams glued using thin lamellas, this effect is not so significant, because the inner stresses are smaller in thin lamellas. The stresses are larger in beams which are made of wood from different strength categories (so-called combined glulam) than in the homogeneous ones, but the difference is not significant.

In arched glulam beams, inner stresses perpendicular to the grain can only develop during manufacture and due to climatic parameters. These stresses can be called residual stresses, because they are there in the beam after manufacture, without any external loading. Combined lamella quality beams show results approx. 10% worse than the homogeneous ones. The worst situation is when the upper lamella is wet (u = 16%) but the beam is dry (u = 12%). This situation can occur in real life: when there is no airing equipment in the building, air humidity can condense on the bottom side of the roofing, and the condensed liquid water can soak through the upper side of the beam. Beams made of thick lamellas are more unfavorable in this case than thin lamella beams.

Greater parts of shear stresses develop from residual stresses. Dependence on climatic properties is not so significant as in the case of the other kinds of stresses. The shear-stress distribution is varied and unusual. Combined and homogeneous glulam beams are more or less the same, but the effect of lamella thickness is important. Lamellas which are three-times thicker cause shear stresses three times as large. Thin lamella beams are favorable.

If the moisture content of the glulam beam is homogenous, there are no inner stresses. This phenomenon is irrespective of the value of the moisture content. In new built glued laminated wooden construction, there is no homogeneity in the moisture content of the lamellas, at least not before a certain time elapses. Wood endeavors to be equal in humidity, but this takes time, and during this equalization process, the superposition of the inner and external stresses can cause damage.

The new EN Norms decrease the strength of wood (safety factor 1.25, environmental damage factor 0.5–0.6 for permanent loads). If we calculate the design value of strength, and compare with the summarized inner and external stresses, we can see that the beams are not safe or in some cases the beams do not meet the requirements of the Norms. It is no wonder that glulam beam constructions become damaged or collapse before the service life of the timber, if manufacturing regulations or climatic changes are disregarded.

As a summary, it can be said that engineers do not make correct static calculations, if they do not calculate the residual stresses. If the manufacturer uses lamellas which are as thin as possible, the effect of the climatic or manufacturing stresses can be reduced significantly.

Conclusion of the laboratory work

It is prohibited to use non-certified adhesives for gluing load-bearing construction.

Manufacturing of hardwood glulams using common adhesives, which were developed for fir or spruce wood, is not recommended.

Outdoor climatic properties can damage even the most resistant adhesives, therefore unprotected beams or beam parts should be avoided [Kánnár 2012].

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PROBLEMY USZKODZEŃ W TARCICY KLEJONEJ WARSTWOWO

Streszczenie

Wyniki obliczeń potwierdzają obserwacje dokonane w warunkach naturalnych. Naprężenia wewnętrzne spowodowane właściwościami klimatycznymi muszą być uwzględniane przy projektowaniu, w procesie produkcyjnym oraz użytkowaniu. Badania laboratoryjne potwierdzają zjawiska widoczne w rzeczywistej konstrukcji budowlanej.

Badania powinny być kontynuowane w celu uzyskania większej ilości informacji na temat rozwarstwiania oraz opracowania rozwiązań dla projektantów, producentów drewna typu glulam lub właścicieli budynków.

Słowa kluczowe: naprężenia w tarcicy klejonej warstwowo, naprężenia wewnętrzne, naprężenia podczas procesu produkcyjnego, naprężenia klimatyczne, uszkodzenia tarcicy klejonej warstwowo, przyczyny uszkodzeń