Bonded wooden balks

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ABSTRACT: The paper describes the basic type models of wooden balk structures, their use and typical dimensions of balks. Further the calculation of bonded wooden balks is described. The paper also contains the summary of basic type models with bonded wooden balks. Finally the orientation values for the design of construction elements are described.

Keywords: force diagram; balks; metal fittings; bonded joints; wooden structure

In the last years wooden structures with bonded balks have been used for the construction of halls, riding halls, sports stadiums and similar facilities more and more frequently. The bonded wooden balks are characterized by the lower mass than the steel ones, the width of the span of balks is not limited by the real length of the grown tree, by the ecology – the regenerative natural raw material is processed with lower costs of the building structure and erection. At the roofed building the service life of wooden parts is 100 to 150 years.

The shape of the structure with bonded wooden balks depends not only on the building parameters (width of span, spacing, depth, slope) but also on the service conditions (sports hall, riding hall, assembly hall, exposition hall, etc.). The excellent chemical resistance of bonded wooden balks and the proved distortion resistance during fires are the reasons for the increased interest of hall designers and their customers. The wide shape variety of structures also meets the requirements of architects (Berka, Lederer 1978; Breyer 2003; Zachariáš 2005) (Table 2).

CONSTRUCTION OF BONDED WOODEN BALKS

The balk section is bonded using *n* lamella layers. Lamellas are made from selected clean planed boards (without visual perceptible pulps with knots of maximal diameter 6 mm in balks of t_L = 32 mm thickness, in selected lamellas of t_L = 18 mm thickness the allowed knot diameter is 3.5 mm). The balk material is usually spruce (*Picea*) or pine (*Pinus*).

The applied arrangement of two joint arches from bonded wooden balks of rectangular section is used according to the following rules.

The minimal curve radius shall not be smaller than 200times thickness of the lamella. With regard to the lamella standard thickness 32 mm the curve radius shall not be smaller than 6 m, at the lamella thickness 18 mm the minimum curve radius of 3.60 m is possible, but at higher production costs.

Bonded wooden balks used as supporting members e.g. in the hall structure (Figs. 1 and 2) are most often of rectangular section (Berka, Lederer 1978; Zachariáš 2005).

WOOD BONDING

Wood is one of the renewable raw materials. The wood processing belongs to low energy intensive fields of engineering. In contrast to metals wood is a porous, non-homogeneous, water absorbing and volume instable material, consisting of cellulose and other substances according to the class of wood. Wood has a number of excellent properties and therefore it is used as a construction material from the beginning of our civilization.

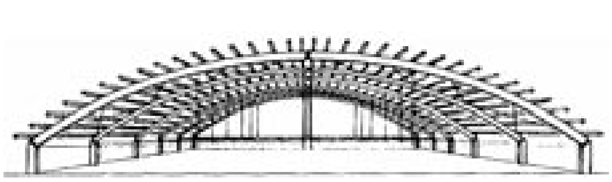

Fig. 1. Real diagram of the arched balk

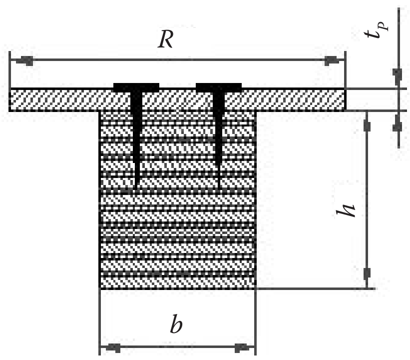

Fig. 2. Balk section

For the constructional utilization the wood bonding is advantageous.

Bonded wooden structures have become the high-class and reputable construction material with many advantages. The bonded lamellar wood loses the spurious geometrical changes and it is possible to make the infinitely long balks from only a few decades long lamellas. This balk can be shortened to the requested length according to the hall size. The possibility of the wood bonding from short lamellas makes it possible to cut out the blends and so to reach higher strength and cost savings than at the use of massive wood. Using short logs the overall higher mass yield is reached in this way.

But among all wooden structure joints the bonded joints are technologically demanding. They request the high-class dry (humidity 15–20%) wood. The wood surface must be adapted before bonding. The surfaces of bonded wood should be even and tight abutting. For the bonding the smooth surface is the best (the unevenness should be max. ± 2 mm), which can be reached e.g. by planing, moulding or grinding. After grinding the surface must be cleared from the abrasion dust. At hardwood refacing the surface must be more precise than at softwood refacing. When rough surfaces are bonded, it is necessary to extend the filler into the adhesive.

The adhesive must be humidity and chemical resisting and resistant to the other acting influences.

Bonded joints can be used for the production of bonded plain girders or balks.

The main advantages of bonded joints are that they do not reduce the joints, they are tough, they are humidity and water resisting and above all the allowable stress can be about a quarter higher than the specified stress (Ambrose 1996; Newman 1993).

Wooden balks

Wooden balks are made from softwood, as a rule from spruce, fir or pine wood. Especially the pine wood is suitable for many structures, because it contains a considerable amount of resin and therefore it is more humidity resistant than the spruce wood. Wooden balks are from various sections.

Wooden beams are bonded. The upper part (upper boom) is bonded using the good heart lamellas which are more pressure resistant. The lower beam part (lower boom) is bonded from sapwood which is more tension resistant. The stalk (the intermediate part), which is minimally stressed, is bonded from the common spruce. The lamellas are bonded using the splayed heading joint which is tougher than the abutment joint. For bonding the resins are used (Ambrose 1996; Newman 1993).

Bonding of lamellas

Lamellas are lengthened using the indented or the scarf joint (Fig. 3). The abutment joint is admissible only in the internal part of the bonded lamellar elements.

The bonded indented joints are made using the special set and at their production the inspection of the wood, resin and finished product quality must be ensured. In the bonded place the knots and cracks are not allowable. The central distance between the indented joints of one blank (lamella) should not be smaller than 1 m.

The maximal allowed slope of bonded scarf joints is 1:10 for tensile stress and 1:6 for compressive stress. The central distance between the joints must be minimally 20 times the major thickness of ad-

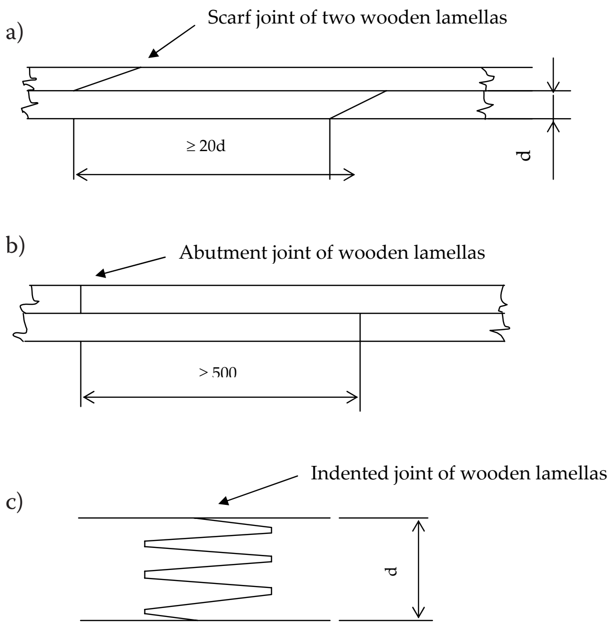

Fig. 3. Bonded joints of lamellas: a) scarf joint, b) abutment joint, c) indented joint

joining lamellas. The abutment joints are not used today.

Adhesives used for wooden elements must secure the strength and preservability for the whole structure life.

The types of adhesives and their properties still evolve and their utility properties are improved. Above all, the factors which affect the spread of the adhesive, the environment of processing (temperature, humidity) and the curing time are supervised. Therefore the trend of improvement of adhesive properties and of product diversification is clear (AMBROSE 1996; NEWMAN 1993).

Bonding method

Adhesive bonded joints are the most resistant and progressive method of all methods of wooden joints, they give the most constructional possibilities. But they require to be carried out carefully, in definite conditions and manufacturing processes, and the worked surface.

The temperature of the environment and of the wood in the space where the bonded wooden elements are made should be above 15°C and the relative water content should amount to 40 to 70%. In the space where the curing takes place the minimum temperature should be 20°C and the minimum air humidity 30%. The thickness of single wooden lamellas in the direction perpendicular to the bonded surface must be 35 to 50 mm. The relative water content of the sawn wood may be maximally 15%. The glue line can be to 0.3 mm thickness, therefore the bonded wood is planed. The plastic glues are used under many commercial names.

The working pressure is determined by the manufacturer of the adhesive. The conventional pressure related to the bonded surface is 0.4 MPa to 0.5 MPa for softwood and 0.9 MPa to 1.0 MPa for hardwood. Further this pressure depends on the adhesive type, on the surface quality and naturally on the lamella thickness. At curved lamellas the higher pressure and pressure time are demanded. After the pressure relief the bonded elements must be deposited in the space of 15°C temperature for approximately 72 h for the adhesive ripening.

The glue line should be predominantly shear stressed, the stress perpendicular to the glue line substantially decreases the load capacity, not only owing to the stress caused by the load but also to that caused by the relative water content – therefore the constructional rules should be observed.

Epoxide adhesives – are cured in the same way as polyurethane adhesives in the course of chemical reaction. They consist of resins which are used in combination with setting agents for the bonding of metals each to other and to other substances. The bonded joints made using epoxy adhesives for metal bonding are characterized by high strength. Epoxy resins have advantageous properties, e.g. high surface activity, wettability for a great assortment of materials, high cohesive strength of cured adhesive. They contain no volatile substances which are the reason of shrinkage after curing. In the cured state epoxy resins reach excellent physical and chemical properties. They are cold water resisting. The long-term action of hot water evokes milkiness and a decrease in their cohesive parameters (impact resistance, tensile strength).

Polyurethane adhesives – the one- and two-component adhesives have the same quality as epoxy adhesives. Compared with the epoxy adhesives they have higher elasticity and heat resistance which is in the range of –40 to +130°C. The advantage of polyurethane adhesives is that they can be grinded and lacquered, they are very resistant to UV radiation, they have extraordinarily long service life and excellent adherence almost to all materials.

Solvent-type adhesives – the film-forming compound is solved in a suitable liquid solvent (water, alcohol, acetone, etc.). Casein glues – adhesives from milk casein in a powder form. Before use they

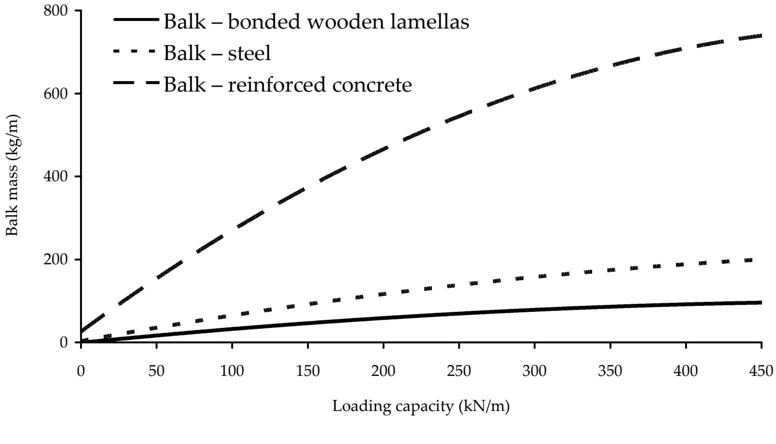

Fig. 4. Loading capacity of various types of structures

are solved in water (2 to 3 weight parts of water, 1 weight). Bonding is possible at low temperatures below 0°C. Joints are tough but low resistant to fungi.

High-temperature curing adhesives – are delivered as liquid or pastelike substances on the basis of epoxy, phenolic, urea or melamine resins as one-component (the setting agent in so-called latent form is homogenized with the resin on the point of manufacturing) or two-component with so-called semilatent setting agent which is homogenized with the resin before application and this composition is treatable for several days. These adhesives cure only at higher temperatures, usually at 80°C to 200°C. They are used almost exclusively for industrial applications (Ian et al. 2003; Faherty, Williamson 1995).

BALK DESIGN

Wood is a non-homogeneous material; its cells dilute at tensile stress while they compress at compression stress. Therefore the stress of the balk should be only compressive. To reach the compression stress only the balk must be formed in the form of the inverted catenary curve.

$$y = -2B\left[\cosh\left(\frac{x}{B}\right) - 1\right] \qquad (1)$$

where: $B = 2\sigma_o/\rho g$; the stress σ_o is the pressure stress at the highest place of the arch, $\rho = (620 \div 700)$ kg/m^3 is the density of the balk (wood + adhesive), $g = 9.81$ m/s^2 is the gravity acceleration.

Practically the inverted catenary curve arch is substituted by the circular arch. The width of the span L is chosen. The spacing between the balks is calculated using the equation

$$R = 7.5\, e^{-y}, \text{ where } y = \frac{L}{m}$$

The ratio of $\dfrac{h}{b} = 1.3\left(\dfrac{L\,[m]}{15\,[m]} - 1\right) + 2.2$

The uniformly distributed load

$$q = 0.01 \times R \times L \times \rho \times g\,(1 + R/R_z) \qquad \text{(N/m)} \qquad (2)$$

For 10 m ≤ L ≤ 40 m R_z= 8 m; for 40 m < L ≤ 60 m R_z= 6 m.

The depth of the rectangular balk is calculated using the relation

$$h = \sqrt[4]{\frac{9.6 \times l^2 \times R_A \times \left(\frac{h}{b}\right)}{3{,}100\,\sigma_{Dd}}} \qquad (3)$$

At $H < 0.25\,L$ the arch AOB at q = const. The arch has a form of quadratic parabola. For the arch length AOB is true

$$l = \frac{L}{2}\left(\sqrt{1+\left(\frac{4H}{L}\right)^2} + \frac{L}{4H} \times \ln\left(\frac{4H}{4} + \sqrt{1+\left(\frac{4H}{L}\right)^2}\right)\right) \qquad (4)$$

σ_{Dd} is the allowable compressive stress. For the balk material (spruce, pine) σ_{Dd} = 7.5 MPa.

$$U = \frac{1}{R}\left(\frac{g}{\rho} - S_c \times \rho \times g \times \frac{l}{L}\right) \qquad \text{(kg/m}^2\text{)} \qquad (5)$$

The total section surface (Fig. 2) $S_c = R \times t_p + b \times h$ where t_p is the board thickness of the cover ceiling (Berka, Lederer 1978; Zachariáš 2005; Faires 1955).

FORCES IN THE BALK

Uniformly distributed load

$$q = R \times (F_{kl} + F_{pl} + F_{NI}) + F_V/L \qquad (6)$$

q (N/m) is the uniformly distributed load of the balk (at the arch $H/L \leq 0.25$ it is possible to take q = const.), H (m) is the arch height, L (m) is the width of the span, R (m) is the spacing between the balks, F_{kl} (N/m^2) is the weight of one square meter of the roofing, F_{pl} (N/m^2) is the weight of one square meter of the boards and the elements of the hall lower ceiling, F_V (N) is the weight of the whole balk – it is estimated and in the course of the calculation it will be defined with more precision, F_{NI} (N/m^2) is the

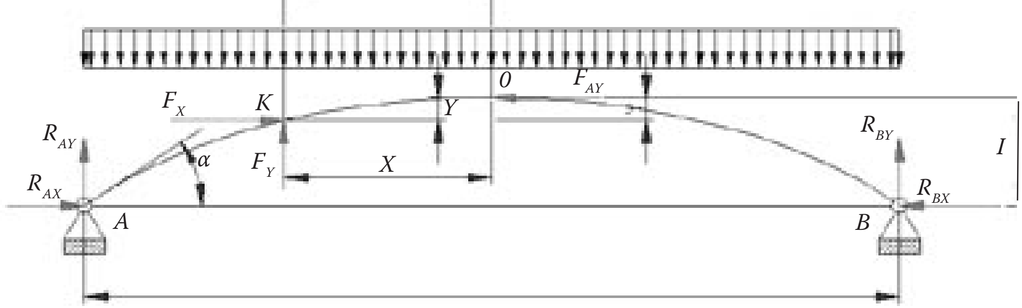

Fig. 5. Force diagram of the arched balk

weight caused by external phenomena (rain, snow, etc.), N – number of balks, n – number of lamellas in the rectangular section of the balk, t_L (mm) thickness of one lamella, t_p (mm) thickness of lower ceiling boards, h/b the ratio of height h to width b at the rectangular section of the balk (Fig. 2) (Breyer 2003; Gagliano, Frazier 2001; Zachariáš 2005).

For the pure pressure in the balk (Fig. 5) the forces F_0 and F_x being situated on the tangent to the balk bended axis must act on the unfastened balk arch OK (Fig. 5). From the force-equilibrium condition of three forces which act on the unfastened arch OK it results for the reaction forces components R_A:R_{AX} = F_0:R_{AY} = Q.

The concentrated force $Q = q \times L/2$, the force

$$F_o = Q/\text{tg}(\alpha),\ \text{tg}(\alpha) = H/(L/4) = 4H/L \qquad (7)$$

Consequently

$$F_o = Q \times L/(4H) = q \times L^2/8H = R_{AX} \qquad (8)$$

After substitution and arrangement it is

$$R_A = \sqrt{R_{AX}^2 + R_{AY}^2} = 0.5 \times q \times L \times \sqrt{(L/4H)^2 + l} = R_B$$

$$R_{Ax} = \frac{q \times L^2}{8H}; \quad R_{Ay} = \frac{q \times L}{2} \qquad (9)$$

CHECKING OF THE DESIGNED BALK SECTION

The designed balk section is checked as the straight bar subjected to compression (buckling). From the Eulerian equation of the critical buckling force it is logic that the I-section is the most suitable balk section. The I-section is suitable from the aspect of lateral stiffness, but from the aspect of the balk gripping and its fittings the rectangular section is more suitable. Therefore the next calculation will be made for the rectangular section.

The centroidal moment of inertia to the horizontal axis running through the mass centre is

$$J_x = \frac{b \times h^3}{12} \qquad (10)$$

For the reason of the strengthening with ceilings fitted by means of nails (Fig. 2) we use the experimentally determined centroidal moment of inertia for the stiffened rectangular section of the bonded wooden balk.

$$J_x^{/} = \frac{b \times h^3}{9.6} \qquad (11)$$

The mechanical weakness by the use of nails is insignificant. Entering into the wood the nails replace the fibres aside and therefore the fibres are intact.

The gyration radius is determined by substitution of (11) into equation (12)

$$i = \sqrt{\frac{J_x^{/}}{S}} = \sqrt{\frac{b \times h^3}{9.6 \times b \times h}} = \frac{h}{\sqrt{9.6}} \qquad (12)$$

The slenderness ratio is determined by substitution from (1) into (13)

$$\lambda = \frac{l}{i} = \frac{l \times \sqrt{9.6}}{h} \qquad (13)$$

We calculate the checking of compressive stress using the buckling coefficient and in this way we transfer the buckling stress to the compressive stress.

$$c \times \sigma_D \leq \sigma_{Dd} \qquad (14)$$

Table 1. Buckling coefficient values

λ	c	λ	c	λ	c	λ	c
0	0.00	55	1.32	110	3.90	165	8.78
5	0.00	60	1.40	115	4.27	170	9.32
10	1.01	65	1.51	120	4.64	175	9.88
15	1.02	70	1.64	125	5.04	180	10.45
20	1.03	75	1.82	130	5.45	185	11.04
25	1.05	80	2.06	135	5.88	190	11.64
30	1.08	85	2.33	140	6.32	195	12.27
35	1.11	90	2.61	145	6.78	200	12.90
40	1.15	95	2.91	150	7.26	205	13.56
45	1.19	100	3.23	155	7.75	210	14.23
50	1.25	105	3.56	160	8.26	220	15.61

The buckling coefficient values for wood are determined by the standard ČSN 73 1701. The buckling coefficient values c depend on the slenderness ratio λ (Table 1) (Berka, Lederer 1978; Zachariáš 2005; Faires 1955).

By approximation of the values from Table 1 we determine the $c = f(\lambda)$ relations (Fig. 6).

$$c_T = \frac{1}{1 - 0.8 \times \left(\frac{\lambda}{100}\right)^2} \qquad (15)$$

For the elastic column – the Euler's zone (Fig. 6)

$$c_E = \frac{\lambda^2}{3{,}100} \qquad (16)$$

where the limiting slenderness for spruce and pine wood is $\lambda_m = 75$.

For the preliminary design of the balk rectangular section we use the well-known Euler's theory of the plane column.

$$c_E \times \frac{R_A}{S} \le \sigma_{Dd} \qquad (17)$$

Substituting (16) into equation (17) and expressing $S = b \times h$ we obtain

$$\frac{\lambda^2}{3{,}100} \times \frac{R_A}{b \times h} \le \sigma_{Dd} \qquad (18)$$

Expressing h from equation (18) we obtain the equation for the balk depth

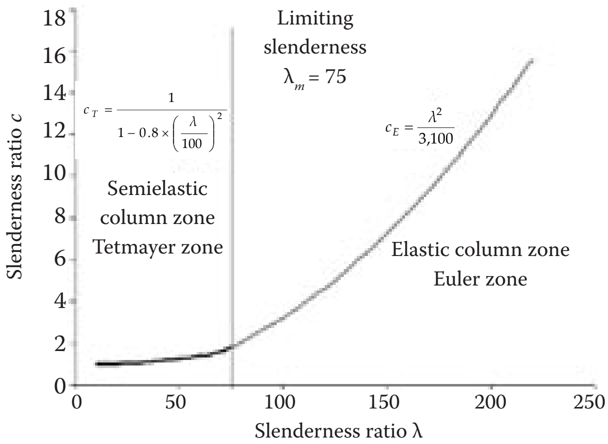

Fig. 6. The buckling coefficient – slenderness ratio relationship

$$h = \sqrt[3]{\frac{9.6 \times l^2 \times R_A}{3{,}100 \times b \times \sigma_{Dd}}} \qquad (19)$$

For practical use equation (19) may be expressed as the relation for the ratio of h/b. By solution of the equation we obtain the already well-known relation (3) (Ball 1980; Faherty, Williamson 1995; Ronald 1963).

$$h = \sqrt[4]{\frac{9.6 \times l^2 \times R_A \times \left(\frac{h}{b}\right)}{3{,}100 \times \sigma_{Dd}}} \qquad (20)$$

Table 2. Orientation values for the design of bonded wooden balks

Shape of construction	Description	Span [m]	Spacing [m]	Approximate high	Bevel of roof	Shape of construction	Description	Span [m]	Spacing [m]	Approximate high	Bevel of roof
	Joining balk	5 – 20	0.7 – 1.5	$h \approx \frac{l}{25}$	-		Three joint frame	15 - 50	3,6 - 6	$h \approx \frac{l}{15 \div 20}$	0 – 40°
	Continuous joining balk	6 – 30	0.7 – 1.5	$h \approx \frac{l}{50}$	-		Three joint frame	15 - 40	3,6 - 6	$h \approx \frac{l}{20 \div 25}$	0 – 60°
	Truss	10 – 30	3,6 – 9	$h \approx \frac{l}{12 \div 17}$	-		Three joint frame with mettalic link	12 - 30	3,6 - 6	$h_1 \approx \frac{l}{40 \div 50}$ $h_2 \approx \frac{l}{15 \div 20}$	3° - 15°
	Saddle truss	10 – 30	3,6 – 9	$h_1 \approx \frac{l}{20 \div 30}$ $h_2 \approx \frac{l}{10 \div 15}$	3° - 12°		Two joint arch	21 - 100	4,5 - 9	$f \approx \frac{l}{6 \div 7}$ $h \approx \frac{l}{50}$	-
	Saddle truss with higher bottom	10 – 30	3,6 – 9	$h_1 \approx \frac{l}{20 \div 30}$ $h_2 \approx \frac{l}{13 \div 17}$	3° - 15°		Three joint arch	21 -100	4,5 - 9	$f \approx \frac{l}{6 \div 7}$ $h \approx \frac{l}{50}$	-
	Leanto truss	10 – 30	3,6 – 9	$h \approx \frac{l}{12 \div 17}$	3° - 6°		Three joint arch with higher sagitta	21 - 100	4,5 - 9	$h \approx \frac{l}{35}$	-
	Three joint beam with rod	15 – 40	3.6 – 7.2	$f \approx \frac{l}{6 \div 7}$ $h \approx \frac{l}{20 \div 30}$	15°		Two joint frame	15 - 30	3,6 – 7,2	$h \approx \frac{l}{15 \div 20}$	-

ORIENTATION VALUES FOR THE DESIGN OF BONDED WOODEN BALKS

For the bonded wooden balks other constructions than the arched ones are also used. Orientation values for the wooden constructions are presented in Table 2.

CONCLUSIONS

Newly developed adhesives make possible the new, more perfect utilization of the traditional natural material – wood – positive properties. Constructions with bonded wooden balks are used in the structures of halls, riding halls, tribunes, sports halls and churches and in the last years in the structures of production shops and storehouses of industrial enterprises. It is evident that the growing demand calls for the introduction of metal fittings production for balk ends independently of their concrete use.

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Dřevěné lepené vazníky

ABSTRAKT: Článek popisuje základní typy dřevěných lepených konstrukcí, jejich použití a charakteristické rozměry lepených vazníků. Je detailně popsán výpočet dřevěných lepených vazníků. Článek obsahuje souhrn základních druhů konstrukcí s dřevěnými lepenými vazníky. V závěru jsou popsány orientační hodnoty pro návrh prvků konstrukcí.

Klíčová slova: silové schéma; vazníky; kování; lepené spoje; dřevěné konstrukce

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