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THE STRENGTH RESEARCH OF THE ADHESIVE JOINTS OF SHEET STRUCTURES

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ABSTRACT

The research results of stress-strained condition of constructional sheet materials are given in the article. The strength dependence on type, configuration and sizes of adhesive joints is analyzed. The research of the strength dependence was made on the samples from bakelite plywood with the main types of adhesive joints. The research results in the specified range of the bonding lengths of the adhesive joints are determined by the equation, which was derived by using the settlement of the problem of the tenses in the symmetric adhesive joints of different materials. The features of stress-strained condition of the specified adhesive joints, which were made from orthotropic material by stretching the samples, are shown in the article. The obtained results can be used for design of adhesive joints with two plates, overlapping and with one plate in the sheet structures.

Keywords: adhesive joint; stress-strained condition, orthotropic material, bakelite plywood.

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1. INTRODUCTION

Plywood, especially, bakelite plywood is a perspective material for lightweight adhesive structures [1]. It is characterized by high relative strength, bending stiffness and high resistance against the environmental influence. These advantages of bakelite plywood as structure material open a wide possibility of using it for large-span structures of buildings with various functions. It is especially important for agricultural construction, as well as construction in inaccessible and sparsely populated areas [2].

Insufficient knowledge of problems of strength and deformability of adhesive joints complicates an affective introduction of bakelite plywood in construction industry. The absence of feasible methodology of design of the adhesive joints also slows down the use of bakelite plywood. In this connection, the research of real work of the adhesive joints in various structures from bakelite plywood is a very important [3, 4].

It is necessary to take into account the strength dependence of the stretched adhesive joints of sheet materials in building structures on the number of factors during their design and construction. The main factors are type and configuration of the adhesive joints, their sizes [5-7].

The research work is devoted to experimental identify of this dependence and further using it for design of various types of adhesive joints. The main types of adhesive joints are symmetric joint with two plates, overlapping and with one plate in the structures from bakelite plywood.

2. RESEARCH METHODOLOGY

The experimental research of the adhesive joints samples (fig. 1) was made to study the strength dependence on type, configuration and sizes of the adhesive joints of bakelite plywood.

The samples were made from 9-layers bakelite plywood with the thickness of 10 mm. The minimum bonding length of the samples was accepted as the same and equal to four thicknesses of bakelite plywood (δ), it means 40 mm. This length is minimum possible length of adhesive joints in sheet materials. The ratio between the bonding length and the thickness of plywood (l/δ) was 4, 5, 6, 8, 9, 12 and 16 in the joints with two plates. This ratio was 4, 8, 12, 16, 19, 40 in the overlapping joints and 4, 8, 12, 16, 20, 30 in the joints with one plate. The length of bonded plywood plates outside the adhesive joint was 40δ for the all samples.

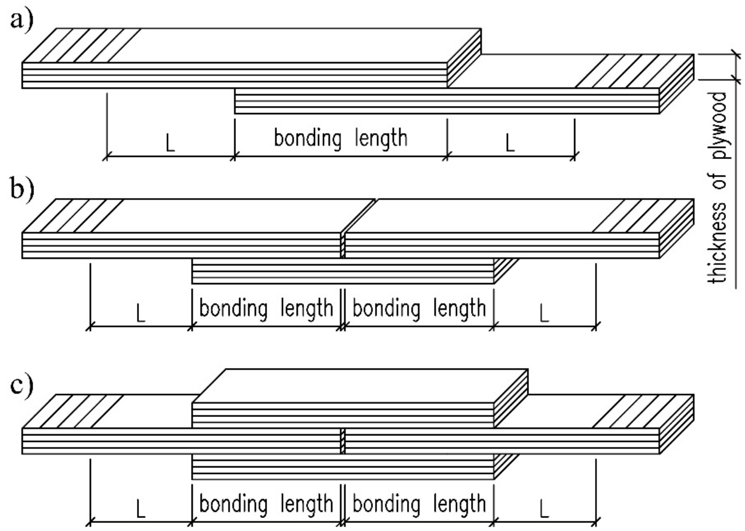

Fig.1. Types of adhesive joints

a) overlapping; b) with one plate; c) symmetric joint with two plates

The end sections of plywood plates with the length of 15δ are used for mounting samples in grips and keeping their center stretch. The distance from the grips to the beginning of bonding was equal to 25δ (L) as the minimum size, which allows avoiding the influence of bending stiffness of the bonded plates on stress-stained condition in the area of bonding in the asymmetric joints. The research results show that if $L/\delta \geqslant 25$ the stress in the joints depends only on the ratio l/δ in the overlapping joints subject to elastic features of bakelite plywood as orthotropic material [8].

The accepted value of size L also avoids risk of non-uniform distribution of normal stress for the width of bonding plates near the adhesive joint from possible uneven compression of the samples in the grips. The research of stress condition of anisotropic plate and the use of Saint-Venant's principle allow finding out that the normal stress is uniform for the width in the all sections of the sample even in case of stretching of orthotropic plate by focused forces. In this case, the distance from the point of applied forces to the all sections of the sample is more than $3b$, where b – the width of the samples, which is equal to 5δ.

The samples were bonded by synthetic phenol-formaldehyde adhesive. The preliminary treatment of the plywood samples was made by removing the resin layer from the sample surface. The pressing of the samples with pressure of 0.6-0.8 kN/cm^2 is kept during the bonding. The thickness of the adhesive joint was not more than 0.3 mm in those conditions. The adhesive joint is considered as unyielding because the equation (1) is kept.

$$\begin{cases} \dfrac{\delta}{10E} \geq \dfrac{\eta}{E_A} \\ \dfrac{\delta}{10G} \geq \dfrac{\eta}{G_A} \end{cases} \qquad (1)$$

where η – the thickness of the adhesive joint; E – elastic modulus of the plywood sample (E=75000 MPa); E_A – elastic modules of the adhesive joint (E_A=1100000 MPa); G – shear modulus of the plywood sample (G=62000 MPa); G_A – shear modulus of the adhesive joint (G_A=420000 MPa) [9].

The tests of the samples were carried out with speed of loading 5 kN/min. The samples with overlapping and one plate due to the asymmetry structure of the joints were exposed by the significant bending strains, which are schematically shown in fig. 2. These strains depend on the ratios L/δ and l/δ.

The samples destruction began with the appearance of cracks in the bonding tips, where shear and strength stress concentrated. The areas of the destruction beginning are pointed out by circles in fig. 2.

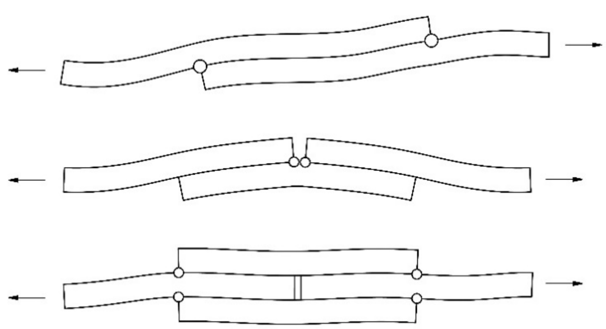

Fig.2. Deformation of the samples during the tests

As a rule, the samples destruction took place in the plywood, mainly, in the border "adhesive-plywood". In some cases, the destruction surface spread on internal layers of bonded plywood.

3. RESULTS AND DISCUSSION

The results of the tests are shown in table 1. The dependence graph has damping feature in the joints with two plates according to table 1.

Table 1. Results of the tests of the adhesive joint

Type of joint	Parameters							
	l	***n***	***N***	***σ***	***υ***	***m***	***p***	***τ***
Symmetric joint with two plates	4	10	2138	2.12	9.9	67	3.1	0.535
	5	5	2600	1.6	6.2	72	2.8	0.52
	6	13	2627	3.39	12.9	94	3.6	0.438
	8	12	2970	2.64	8.9	76	2.6	0.371
	9	5	3230	2.46	7.6	110	3.4	0.359
	12	10	3177	2.45	7.7	77	2.4	0.265
	16	10	3232	2.75	8.5	87	2.7	0.202
Overlapping	4	9	1218	1.19	9.7	40	3.2	0.609
	8	9	1346	1.23	9.1	41	3	0.337
	12	9	1438	1.48	10.3	49	3.4	0.24
	16	14	1922	2.21	11.5	59	3.1	0.24
	19	10	2014	2.67	13.3	85	4.2	0.212
	40	9	2443	1.82	7.5	61	2.5	0.122
Joint with one plate	4	9	798	0.73	9.1	24	3	0.399
	8	9	861	0.99	11.5	33	3.8	0.215
	12	11	1052	1.17	11.1	35	3.4	0.175
	16	10	1360	1.58	11.6	50	3.7	0.17
	20	8	1420	1.6	11.3	57	4	0.142
	30	7	1577	1.42	9	54	3.4	0.105

Note: l – the bonding length (cm); n – the number of samples; N – the average arithmetic value of destructive force (kN); σ – the average arithmetic variation (kN/cm^2); υ – variation coefficient (%); m – the average error of the average arithmetic value; p – accuracy rate (%); τ – the average value of the shear stress during the destruction (kN/cm^2).

Starting, approximately, with l=12 *cm* N tends to constant value. Taking into account such feature of N, we can identify the following approximate dependence of τ on l or, in view of geometric similarity, l/δ (2).

$$\begin{cases} \tau = 75.2\exp(-0.084 l/\delta)\left[4 \le l/\delta \le 12\right] \\ \tau = 330\delta/l\left[l/\delta > 12\right] \end{cases} \quad (2)$$

Almost the same results in the completely analyzed range of bonding lengths of the joints are approximated by equation (3).

$$\tau = \frac{336sh(0.286 \cdot l/\delta)}{l/\delta(0.5 + ch(0.286l/\delta))} \quad (3)$$

Equation (3) is determined by using the settlement of the problem of the stress in the symmetric adhesive joints of different materials. Equations (2) and (3) can be used for design of adhesive joints of bakelite plywood with two plates in sheet structures.

If we design the adhesive joints according to current standard documentation as a joint, working for shear, it is necessary to keep the load capacity of the joint under minimum length l=4δ. In this case, it is important that the average value of shearing stress does not exceed the estimated strength of plywood (R_p).

If this condition is satisfied, the joint strength will be kept in view of long-term load. If it is short-term load the reserve of the strength will be threefold. If l>4δ the change of load capacity of the joint can be taken into account by introducing correction coefficient, which reflects the influence of the adhesive joint length on the strength of the joint [10]. In this case, the estimated load capacity of the adhesive joint can be determined by formula (4).

$$T = m \cdot R_{sh}^{av} \cdot F_{sh} \quad (4)$$

where m – coefficient of working conditions, taking into account quality, the technology features and other characteristics of the adhesive joints in particular building structures (in the first approximation m=1); F_{sh} – the estimated shearing area of the adhesive joint; R_{sh}^{av} – the average estimated resistance of shear, which can be determined by formula (5).

$$R_{sh}^{av} = m_j \cdot R_{sh} \quad (5)$$

where m_j – the correction coefficient, which depends on type of the adhesive joint and ratio l/δ; R – the estimated resistance of shear, which can be determined by using table 2.

The correction coefficient can be determined from the condition of proportionality R_{sh}^{av} to the average shear stress τ in equations (2) and (3).

It is determined by formula (6) in the joints with two plates in sheet structures from bakelite plywood.

$$\begin{cases} m_j = \exp(0.084(4 - l/\delta))[4 \le l/\delta \le 12] \\ m_j = 6.13\delta/l[l/\delta > 12] \end{cases} \quad (6)$$

Based on the research results, we can use equation, which is almost equal equation (5) for determination of load capacity of symmetric joints.

Table 2. The estimated resistance of plywood

Type of plywood	**The estimated resistance, MPa**				
	Stretching in the plane of the plywood sheet	**Compression in the plane of the plywood sheet**	**Bending from the plane of the plywood sheet**	**Shearing in the plane of the plywood sheet**	**Slice perpendicular to the plane of the plywood sheet**
Bakelite plywood with thickness of 7 mm and more:					
▪ along the fibers of outer layers	32	28	33	1.8	11
▪ across the fibers of outer layers	24	23	25	1.8	12
▪ under angle of 45° to the fibers	16.5	21	-	1.8	16
Laminated birch plywood:					
a) thickness of 8 mm and more:					
▪ along the fibers of outer layers	14	12	16	0.8	6
▪ across the fibers of outer layers	9	8.5	6.5	0.8	6
▪ under angle of 45° to the fibers	4.5	7	-	0.8	9
б) thickness of 5-7 mm					
▪ along the fibers of outer layers	14	13	18	0.8	5
▪ across the fibers of outer layers	6	7	3	0.8	6
▪ under angle of 45° to the fibers	4	6	-	0.8	9

Equation (7) is valid if the thicknesses of plates and plywood are the same, but it allows taking into account the difference of these thicknesses [8].

$$T = mR_{sh} \times \frac{10.3b\delta\left(1+\frac{\delta}{2\delta_p}\right)sh\left(0.233\frac{l}{\delta}\sqrt{1+\frac{\delta}{2\delta_p}}\right)}{\sqrt{1+\frac{\delta}{2\delta_p}}\left(\frac{\delta}{2\delta_p}+ch\left(0.233\frac{l}{\delta}\sqrt{1+\frac{\delta}{2\delta_p}}\right)\right)} \quad (7)$$

where b – width of the joint (cm); δ – thickness of plywood (cm); δ_p – thickness of plates (cm). This equation is valid under condition $\delta_p \geqslant \delta/2$. The calculations according to equation (7) show that if the thickness of plates decreases, the load capacity will increase, and vice versa. For example, if the thickness of plates is 2 times less than plywood sheet and l/δ=12, the load capacity will increase by 15% as compared with the joint with the same thickness of plates and plywood sheet. If the plates are 2 times more than plywood sheet, the load capacity will decrease by 11%.

The dependence of τ on l/δ, which approximates the tests results in table 1, can be determined by formula (8) for the overlapping joints.

$$\tau = 199\left(\frac{l}{\delta}\right)\exp\left(0.0375\frac{l}{\delta}\right)\left[4 \le l/\delta \le 20\right] \quad (8)$$

On the area of lengths 20<l/δ<40 we can assume without large error that N depending on l/δ changes under liner law (9).

$$\tau = 356(\delta/l) + 3.3\left[20 < l/\delta < 40\right] \quad (9)$$

It is necessary to determine m_j proportionally equations (8) and (9) taking into account features of stress condition of the overlapping joint, specifically that τ for the overlapping joint is more than for the joint with two plates (10).

$$\begin{cases} m_j = 4.28\left(\frac{\delta}{l}\right)\exp\left(0.0375\left(\frac{l}{\delta}-4\right)\right)\left[4 \le \frac{l}{\delta} \le 20\right] \\ m_j = 6.56\frac{\delta}{l} + 0.061\left[20 < \frac{l}{\delta} < 40\right] \end{cases} \quad (10)$$

The dependence of τ on l/δ, which approximates the tests results in table 1, can be determined by formula (11) for the joints with one plate.

$$\tau = 130.6\frac{l}{\delta}\exp\left(0.0392\frac{l}{\delta}\right)\left[4 \le \frac{l}{\delta} \le 20\right] \quad (11)$$

According to table 1, N increases only by 10% on the area of lengths 20<$l/\delta \leqslant$30. Taking into account that the joint with one plate works in heavier stress-strained conditions as compared with other joints, we can assume that N saves the constant value on this area. Therefore, in view of difference of τ, determined by equations (2) and (11), the correction coefficients are determined by formula (12).

$$\begin{cases} m_j = 2.84\left(\dfrac{\delta}{l}\right)\exp\left(0.0392\left(\dfrac{l}{\delta}-4\right)\right)\left[4 \le \dfrac{l}{\delta} \le 20\right] \\ m_j = 5.32\dfrac{\delta}{l}\left[20 < \dfrac{l}{\delta} < 30\right] \end{cases} \tag{12}$$

The correction coefficients, determined by equations (6), (10) and (12), are presented in table 3 to simplify design of the adhesive joints.

Table 3. The correction coefficients for various adhesive joints

Type of joint	***l/δ***							
	4	**8**	**12**	**14**	**16**	**20**	**25**	**30**
Symmetric joint with two plates	1	0.72	0.51	0.44	0.38	0.31	0.25	0.2
Overlapping	1.07	0.62	0.48	0.44	0.42	0.39	0.32	0.28
Joint with one plate	0.71	0.42	0.32	0.3	0.28	0.26	0.21	0.18

Thus, the design process of the adhesive joints bakelite plywood with two plates, overlapping and with one plate should be made according to equation (4) with the determination of the average estimated resistance of shear according to equation (5), where equations (6), (10) and (12) or table 3 determine the correction coefficients. Furthermore, the estimated load capacity of the joints with two plates can be determined by equation (7).

4. CONCLUSION

The obtained research result is the unification of the features number of real work of the adhesive joints in the stress-strained conditions. The main feature is the influence of the joint type on the strength of the bakelite plywood structure. It provides better approximation to work of real joints of sheet anisotropic materials under load.

The methodic of design of the adhesive joints, based on the obtained research results, takes into account their type and sizes. It can be used for design and construction of the adhesive joints in building structures from bakelite plywood.

The obtained research results allow calculating strength and deformation of the adhesive joints of anisotropic materials with flexible and inflexible adhesive layer.

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