Qualification tests of adhesive systems, the assessment of the durability of glued wooden structures

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Abstract. The question of the use of qualification tests of adhesive systems to determine their residual life is considered. The purpose of the study. Testing the hypothesis about the possibility of applying qualification tests of adhesive systems and regression equations to predict the residual life. Methods. Experimental studies of water resistance of adhesive joints, tensile strength along fibers, heat and frost resistance of adhesive joints, and resistance of adhesive joints to delamination were carried out. Results. Based on the test results, data were obtained on the water resistance of adhesive joints, the tensile strength along fibers, the heat and frost resistance of adhesive joints and the resistance of adhesive joints to delamination. The dependences of the limit on the strength of time are obtained. The residual life was calculated using the obtained equations. Discussion. Based on the studies, it was found that the qualification test data of adhesive systems can be used to determine their durability (residual life). In the future, the results of these studies can be applied for widespread implementation and for inclusion in regulatory documents.

1. Introduction
Glued wood and timber used in building structures has been studied in the works of various authors [1-12]. Physical and mechanical characteristics of glued wooden structures depend equally on the properties of the wood and the adhesive system. The influence of the glue system on glued wooden structures is analyzed in various aspects [13-15].

In the production of glued wooden structures, the choice of the type of glue is determined by the class of functional purpose of the structures and operating conditions. Compliance of the glue type with the functional class of the wooden structure and operating conditions according to State Standard GOST 20850-2014 “Wooden glued load bearing structures. General specifications” and EN 14080:2013 “Timber structures. Glued laminated timber. Requirements”.

State Standard GOST 33122-2014 “Glue for load bearing structures. General specifications” sets the classification, general technical requirements, test methods, rules for acceptance and quality assessment of adhesives at the entrance control at the KDC manufacturing plants, and also defines the requirements for the performance characteristics of adhesives for wooden load-bearing structures. Requirements for performance characteristics of adhesives for load-bearing wooden structures are presented in table 1.
Table 1. Requirements for performance characteristics of adhesives for load-bearing wooden structures

| Water-resistant | Heat-resistant | Frost-resistance | Indicator of the total bundle, %, no more than | Tensile strength axial, MPa | Glue joints long-term strength, years |
|-----------------|----------------|------------------|---------------------------------------------|----------------------------|-------------------------------------|
| I Higher        | Higher or normal | Normal           | 5                                           | 9                          | 100                                 |
| II Higher       | Higher or normal | Normal           | 5                                           | 9                          | 50                                  |
| III Higher      | Normal          | Normal           | 10                                          | 9                          | -                                   |

The study tested the hypothesis of the possibility of applying qualification tests for EPI-adhesive systems and calculating regression equations for predicting the long-term strength of EPI-adhesive compounds (residual life), since currently in accordance with State Standard GOST 20850-2014 (table 4) EPI-glue systems belong to the III type of glue.

It is possible to predict the maximum service life of adhesive systems which will allow you to estimate the remaining life in the future. To do this, set the minimum value of the parameter (strength) and consider the intersection point with the distribution curve of the specified parameter. This point corresponds to the time when the system reaches the limit state (fig. 1). Taking away the time that the system has already served, we get a residual resource.

![Figure 1](image-url)

**Figure 1.** Determining the duration of operation by the long-term strength of EPI-adhesive systems: 1 – the design strength of EPI-adhesive systems; 2 – the predicted change in strength in real conditions; 3 – the strength of EPI-adhesive systems, corresponding to the time of the survey.

In order to identify the dependence of one value on another, regression analysis is used. This method is used when working with various types of building structures [16-22].

The most commonly used regression equations are:

1) Multiple linear regression:

\[ y = a_0 + a_1 \cdot x_1 + \cdots + a_n \cdot x_n + \varepsilon \]  

A special case is paired linear regression:

\[ y = a_0 + a_1 \cdot x + \varepsilon \]  

2) Polynomial regression:

\[ y = a_0 + a_1 \cdot x + a_2 \cdot x^2 + \cdots + a_n \cdot x^n + \varepsilon \]
3) A power regression:
\[ y = \alpha_0 \cdot x_1^{\alpha_1} \cdot \ldots \cdot x_n^{\alpha_n} + \varepsilon \]  
(4)

4) A power regression:
\[ y = \alpha_0 \cdot x_1^{\alpha_0} \cdot \alpha_1^{x_1} \cdot \ldots \cdot \alpha_n^{x_n} + \varepsilon \]  
(5)

5) Exponential regression:
\[ y = e^{(\alpha_0 + \alpha_1 x_1 + \ldots + \alpha_n x_n)} + \varepsilon \]  
(6)

6) Logarithmic regression:
\[ y = \alpha_0 + \alpha_1 \cdot \ln x_1 + \ldots + \alpha_n \cdot \ln x_n + \varepsilon \]  
(7)

7) Hyperbolic regression:
\[ y = \alpha_0 + \frac{\alpha_1}{x_1} + \ldots + \frac{\alpha_n}{x_n} + \varepsilon \]  
(8)

where \( \alpha_0, \alpha_1, \ldots, \alpha_n \) – parameters of the regression equation; 
\( x_0, x_1, \ldots, x_n \) – independent variable; 
\( \varepsilon \) – the discrepancy (error) of approximation; 
\( y \) – a dependent variable that is found by the regression equation. 
These equations can be used to estimate the durability using tensile tests along the fibers.

2. Methods
The qualification tests for adhesives include studies to evaluate the following characteristics of glued wood:
1. Water-resistant;
2. Tensile strength axial;
3. Heat-resistance;
4. Frost-resistance;
5. Indicator of the total bundle.
Studies are performed on small samples made from pine wood (fig. 2) or beech (fig. 3) (to assess the tensile strength along the fibers) using a two-component EPI (Emulsion Polymer Isocyanate) – adhesive system.

Figure 2. The test specimen to shear along the grain of the wood.
In addition to the qualification tests, the long-term strength of adhesive joints was assessed in accordance with the requirements of State Standard GOST 34349-2017 “Glued timber structures. Methods for determining of glue joints long-term strength”.

2.1. Determination of water resistance of adhesive joints
The method for determining the water resistance of adhesive joints is based on determining the cleavage strength along the fibers after holding samples in water and boiling them, in a wet and dry state, respectively.

Testing includes the following steps:
- mechanical testing of control samples;
- soaking with subsequent mechanical tests in wet and dry form and assessment of the need for further tests;
- boiling with subsequent mechanical tests in wet and dry form.

Mechanical tests are performed according to the scheme of cleaving along the fibers (samples from pine).

The relative strength of the adhesive joints of samples (for wet, dried, cooled wet and dried after boiling, respectively) is calculated using the formulas:

\[ A_1 = \frac{M_{\text{ave}}^v}{M_{\text{ave}}} \cdot 100\% \]  \hspace{1cm} (9)

\[ A_2 = \frac{M_{\text{ave}}^{vs}}{M_{\text{ave}}} \cdot 100\% \]  \hspace{1cm} (10)

\[ A_3 = \frac{M_{\text{ave}}^k}{M_{\text{ave}}} \cdot 100\% \]  \hspace{1cm} (11)

\[ A_4 = \frac{M_{\text{ave}}^{ks}}{M_{\text{ave}}} \cdot 100\% \]  \hspace{1cm} (12)

where \( M_{\text{ave}} \) – arithmetic mean of test results of control samples;
\( M_{\text{ave}}^v \) – arithmetic mean of test results for wet samples after soaking;
\( M_{\text{ave}}^{vs} \) – arithmetic mean of test results of dried samples after soaking;
\( M_{\text{ave}}^k \) – arithmetic mean of test results for wet samples after boiling;
\( M_{\text{ave}}^{ks} \) – arithmetic mean of test results of dried samples after boiling.

The group of water resistance of adhesive joints of adhesives for load-bearing structures is set according to the arithmetic mean values of the strength of samples according to table 2.
Table 2. Arithmetic mean values of the strength of samples.

| A group of water resistance of the adhesive joints | Relative strength of adhesive joints, % |
|-----------------------------------------------|--------------------------------------|
|                                               | after soaking | after boiling |
| wet A1                                       |             |             |
| dried A2                                      |             |             |
| wet A3                                       |             |             |
| dried A4                                      |             |             |
| Low                                          | Less 60     | Less 70     |
| Average                                      | More than 60| More than 70|
| Elevated                                     | More than 60| More than 90|

2.2. Determination of the tensile strength of adhesive joints along the fibers.

The method is based on applying force to a single adhesive joint, made in lap, when stretched along the wood fibers.

Tests are performed on small samples made of beech.

The strength limit of the adhesive joint is calculated using the formula:

$$\sigma = \frac{P}{F}$$  \hspace{1cm} (13)

where

- $P$ – breaking load, H;
- $F$ – area of the adhesive joint, m$^2$.

In addition, the nature of destruction of the adhesive joint is recorded.

2.3. Determination of heat and frost resistance of adhesive joints.

The research method is based on determining the strength index when testing samples for cleavage along the fibers.

The heat resistance test is performed by holding samples in a test chamber for two weeks at a temperature of 90±3°C.

For frost resistance tests, samples with humidity above the hygroscopic limit (W≥30%), i.e. soaked in water at a temperature of 20±2°C, for 48 hours, are kept in the chamber for two weeks at a temperature of minus 30°C.

After testing for heat resistance and cold resistance samples were tested for shear parallel to the grain to failure.

The relative strength of the adhesive joint is calculated using the formula:

$$A^I(A^{II}) = \frac{M^{m}_{ave}}{M^{k}_{ave}} \cdot 100\%$$  \hspace{1cm} (14)

where

- $A^I$ – relative strength of the adhesive joint after temperature influences (for samples tested at a given temperature);
- $A^{II}$ – relative strength of the adhesive joint after the samples reach the temperature and humidity of the control samples;
- $M^{m}_{ave}$ – arithmetic mean of test results of samples subjected to temperature and humidity influences;
- $M^{k}_{ave}$ – arithmetic mean of test results of control samples.

The group of heat and frost resistance is determined depending on their relative strength in accordance with table 3.
Table 3. Groups of heat and frost resistance

| Indicators       | Heat or frost resistance group | Relative strength of adhesive joints, % | $A'$ | $A''$ |
|------------------|-------------------------------|----------------------------------------|------|------|
| Heat resistance  | normal                        | ≥75                                    | ≥90  |      |
|                  | reduced                       | <75                                    | <90  |      |
| Frost resistance | normal                        | -                                      | ≥100 | <100 |
|                  | reduced                       | -                                      |      |      |

2.4. Determination of the resistance of adhesive joints to delamination.
The test method is based on the formation of internal stresses in samples of glued wood due to the pressure drop in the vessel, humidity, which reduce the strength of the adhesive joint.

Samples are made by sawing from a batch of glued wood (fig. 4) so that each of them has 4 adhesive seams.

![Figure 4. Schematic diagram of cutting out samples for testing.]

As indicators of the durability of adhesive joints to peeling take: total delamination of adhesive joints and the maximum separation of the individual weld, as well as evaluating reducing the strength of adhesive joints in stratified shear samples tested.

2.5. Determination of the resistance of adhesive joints to delamination.
For testing, four series of samples of wooden glued structures are produced for testing for cleavage under tension (from beech). Samples from series 1 are subjected to control tests to determine short-term strength (breaking load).

Samples of series 2, 3, and 4 are subjected to prolonged static loading with a load equal to 0.9, 0.8, and 0.7 of the average destructive load of control samples, respectively.

For conducting long-term tests, an experimental installation was designed and constructed, the principle of operation of which is based on a system of levers. The general scheme of the experimental installation is shown in fig. 5.
Figure 5. Scheme of an experimental installation for conducting long-term tests of adhesive joints of wooden glued structures.

The duration of long tests, i.e. the time from the beginning of loading of samples to their destruction, was recorded using special video recording devices with a timer. The time was controlled with an accuracy of 1 min.

The long-term strength assessment is performed graphically in accordance with the specified service life. On the x-axis postpone the time until the specimen breaks, expressed in logarithm on the vertical axis is the relative load, where 100% take the results of the control tests.

If the schedule of long-term strength of adhesive joints 2 is above the graph of long-term strength of wood shear 1 (the construction of which is based on data from scientific and technical literature, for example, Regulations SP 64.13330.2017), long bonding strength meets the requirements for adhesives type I. Based on the obtained graph, a graphical method is used to predict the coefficient of long-term strength for a certain service life.

3. Results and Discussion

3.1. The results of qualification tests of adhesive joints.

Tested:
- 80 samples for cleavage along the fibers (control and after various influences);
- 10 specimens for cleavage when stretched along the fibers (beech);
- 4 large samples for resistance to delamination;
- 20 samples for layered cleavage (10 control and 10 made from samples that have passed the test for resistance to delamination).

The test results are summarized in tables 4 and 5.

| No. of sample | Name of characteristic                        | Unit | Indicators |
|---------------|-----------------------------------------------|------|------------|
| 1K-10K        | Shear strength along the fibers (spruce)      | MPa  | 6.3        |
| 1V-10V        | The strength of the samples in the wet state  | MPa  | 4.1        |
|               |                                               | %    | 65.7       |
| 11V-20V       | The strength of the dried samples             | MPa  | 6.4        |
|               |                                               | %    | 103        |
| 21V-30V       | The strength of the samples in the wet state  | MPa  | 3.9        |
|               |                                               | %    | 61.9       |
Table 5. Results.

| No. of sample | No. of glue line in a bar | Delaminations, mm | Delaminations, % |
|---------------|----------------------------|-------------------|------------------|
| 1             | 7+5                        |                   | 2.8              |
| 2             | 17+0                       |                   |                  |
| 3             | 0+0                        |                   |                  |
| 4             | 11+0                       |                   |                  |
| In total:     |                            |                   | 40               |
| 1             | 0+0                        |                   | 1.6              |
| 2             | 17+0                       |                   |                  |
| 3             | 0+0                        |                   |                  |
| 4             | 4+2                        |                   |                  |
| In total:     |                            |                   | 23               |
| 1             | 0+0                        |                   | 2.5              |
| 2             | 0+0                        |                   |                  |
| 3             | 0+3                        |                   |                  |
| 4             | 16+16                      |                   |                  |
| In total:     |                            |                   | 35               |
| 1             | 11+0                       |                   | 5.3              |
| 2             | 0+0                        |                   |                  |
| 3             | 0+3                        |                   |                  |
| 4             | 33+7+20                    |                   |                  |
| In total:     |                            |                   | 74               |

Long-Term Strength Assessment Results

Qualification tests of the tested adhesive for glued wooden building structures revealed the following:

1. Water resistance – increased.
2. The tensile shear tensile strength along the fibers is 14.5 MPa.
3. Heat resistance – normal.
4. Frost resistance – normal.
5. The index of the total bundle – 5.3%.

The obtained results of the test complex indicate that the EPI-adhesive system in terms of water resistance, frost resistance, tensile strength corresponds to the parameters established for adhesives I,
II, III type for load-bearing wooden structures. Moreover, in terms of thermal conductivity, in terms of total stratification, it corresponds to the parameters for type III adhesives. The long-term strength index for type III glues is not standardized, which causes the greatest interest in research.

3.2. Long-Term Strength Assessment Results.

40 samples of glued wood compounds were tested (10 samples for each batch). The average value of the fracture time for each load value is calculated. The results for the tested samples are presented in the graph (fig. 6).

![Graph](image)

**Figure 6.** The graph of the time dependence of strength on the value of the applied load.

Knowing the minimum (design) strength of adhesive systems and the known regression equation, where the parameters of the regression equation are defined, you can determine the maximum service life of this system. Subtracting from it the actual period that the glue system has already served, we get the remaining resource. The service life limits will be equal.

**For linear regression:**

\[ R_{\text{min}} = a_1 \cdot t + a_0 \rightarrow t = \frac{R_{\text{min}} - a_0}{a_1} \tag{15} \]

**For the logarithmic regression:**

\[ R_{\text{min}} = a_1 \cdot \ln t + a_0 \rightarrow \ln t = \frac{R_{\text{min}} - a_0}{a_1} \rightarrow t = \exp \left[ \frac{R_{\text{min}} - a_0}{a_1} \right] \tag{16} \]

**For polynomial regression.** Since the second-order equations (parabolic regression) are presented, the answer will be in the form of a solution of the square equation:

\[ R_{\text{min}} = a_2 \cdot t^2 + a_1 \cdot t + a_0 \rightarrow a_2 \cdot t^2 + a_1 \cdot t + (a_0 - R_{\text{min}}) = 0 \tag{17} \]

\[ t = \frac{-a_1 \pm \sqrt{a_1^2 - 4 \cdot a_2 \cdot (a_0 - R_{\text{min})}}}{2 \cdot a_2} \tag{18} \]

The restriction on the resulting solution will be that the time should not be negative. **For power regression:**

\[ R_{\text{min}} = a_0 \cdot t^{a_1} \rightarrow t^{a_1} = \frac{R_{\text{min}}}{a_0} \rightarrow t = \left( \frac{R_{\text{min}}}{a_0} \right)^{1/a_1} \tag{19} \]
The restriction will be as follows $\alpha_1 > 1$.
If $\alpha_1$ is a negative number, then the unit must be divided by the resulting value of $t$ in equation 11.
The restriction on the resulting solution will be that the time should not be negative.
For the exponential regression there are two possible options:

$$R_{min} = a_0 \cdot e^{a_1 \cdot t} \rightarrow e^{a_1 \cdot t} = \frac{R_{min}}{a_0} \rightarrow a_1 \cdot t = \ln \frac{R_{min}}{a_0}$$
(20)

$$R_{min} = e^{(a_1 \cdot t + a_0)} \rightarrow a_1 \cdot t + a_0 = \ln R_{min} \rightarrow t = \frac{1}{a_1} \cdot (\ln R_{min} - a_0)$$
(21)

For the power regression:

$$R_{min} = a_0 \cdot a_1^t \rightarrow a_1^t = \frac{R_{min}}{a_0} \rightarrow t = \log_{a_1} \frac{R_{min}}{a_0}$$
(22)

The restrictions will be as follows: $\alpha_1 > 0$ and $\alpha_1 \neq 1$.
For hyperbolic regression:

$$R_{min} = a_0 + \frac{a_1}{t} \rightarrow \frac{a_1}{t} = R_{min} - a_0 \rightarrow t = \frac{a_1}{R_{min} - a_0}$$
(23)

where $\alpha_0$ — initial value of the parameter (strength), MPa;
$\alpha_1$ — speed of change of the parameter (strength) MPa/s;
$\alpha_2$ — acceleration of parameter change (strength), MPa/s$^2$;
$R_{min}$ — minimum value of the parameter (strength), MPa.
$t$ — the maximum service life or time at which the minimum value of the parameter (strength) is reached.

Since several regression equations can be applied at once for some breeds, the final value of the service life limit in this case must be taken as an arithmetic mean. You can also take the average value when setting the final value, if the discrepancy relative to the average does not exceed 10%.

$$t_{average} = \frac{1}{n} \cdot \sum_{i=1}^{n} t_i$$
(24)

If the stress-strain state is complex, it is necessary to estimate the service life limit for several States at once. The final value should be taken as the smallest of the received values. Also, the smallest value is selected if the values range from 10 to 20%.

$$T_{ult} = \min \{T_{ult 1}, ..., T_{ult i}\}$$
(25)

It should be noted that the derived equations for estimating the service life of wooden structures can be applied to any operating conditions, because these regression equations use abstract parameters $a$ and $b$.

These equations can also be applied when several factors work together at the same time.
Then in this case the remaining resource will be calculated using the formula:

$$T_{res} = A \cdot \left[-\frac{1}{B} \cdot t_{expt} + T_{ult}\right]$$
(26)

The physical meaning of coefficient $A$ is that it reduces the initial (set) residual resource of building structures due to imperfections in manufacturing technology, device, installation, design errors, etc. The physical meaning of the coefficient $B$ is that it reduces the remaining resource of building structures during their operation.

Therefore, coefficients $A$ and $B$ can be considered as stock coefficients (lowering coefficients). In general, they will take values from 0 to 1.
4. Conclusions

Qualification tests of glued joints of glued wooden structures make it possible to determine whether it is permissible to determine the long-term strength, as well as to predict the durability of glued wooden structures.

As a method for predicting the durability of structures, it is permissible to use regression equations. Since it is possible to estimate the long-term strength of adhesive systems using one-factor regression equations (only one factor is used - the operating time), the same equations can be used to estimate the remaining life of buildings and structures made of glued wooden structures. In this case, the assumption is introduced that the operating conditions remain unchanged throughout the entire service life of the structures.

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