

ЭКСПЕРИМЕНТАЛЬНЫЕ ИССЛЕДОВАНИЯ  
EXPERIMENTAL RESEARCH

DOI: 10.22363/1815-5235-2025-21-4-346-357

EDN: CKYDNO

Research article / Научная статья

Predictive Modeling Methods for Estimating the Residual Strength  
of Wooden Structures Based on Experimental DataSergey I. Abrakhin<sup>1</sup>, Anastasiya V. Lukina<sup>2</sup>, Mikhail S. Lisyatnikov<sup>1</sup>, Danila A. Chibrikin<sup>1</sup><sup>1</sup> Vladimir State University named after Alexander and Nikolay Stoletovs, Vladimir, Russian Federation<sup>2</sup> Moscow State University of Civil Engineering (National Research University), Moscow, Russian Federation pismo.33@yandex.ru

Received: April 29, 2025

Revised: July 21, 2025

Accepted: July 27, 2025

**Abstract.** Estimating the load-bearing capacity and predicting the residual strength of existing structures is one of the most difficult tasks. Such prediction is usually performed on the basis of experimental destructive testing of samples. A methodology for predicting the residual strength of wooden structures is proposed, based on the results of experimental studies to determine the short-term resistance of pure wood. Wooden rafter systems of residential buildings built in the 1950s and early 1960s in Vladimir were chosen as objects of research. Interpolation and extrapolation methods were used to build a predictive model of the residual life of a structure. Detailed calculations are given, which clearly show the possibility of using these methods. It is determined that the autoregression method (Burg method) shows good predictive results, correlating with experimental data from other studies and theoretical assumptions. Forecasting the remaining life of a structure is a key factor in ensuring the reliability and safety of buildings, as well as reducing future operating costs.

**Keywords:** buildings, wooden structures, forecasting, strength, durability, interpolation, extrapolation

**Conflicts of interest.** The authors declare that there is no conflict of interest.

**Authors' contribution:** *Abrakhin S.I.* — calculation and construction of predictive models; *Lukina A.V.* — development of a research program for obtaining experimental data, setting the goal and objectives of the research, writing, formulation of conclusions; *Lisyatnikov M.S.* — analysis of the current state of the use of wooden structures, literature review; *Chibrikin D.A.* — design of graphic material, translation into English. All authors read and approved the final version of the article.

**Funding.** The work was carried out with the financial support of the Ministry of Science and Higher Education of the Russian Federation within the state assignment in the field of scientific activity (theme FZUN-2024-0004, state assignment of the VISU).

**For citation:** Abrakhin S.I., Lukina A.V., Lisyatnikov M.S., Chibrikin D.A. Predictive modeling methods for estimating the residual strength of wooden structures based on experimental data. *Structural Mechanics of Engineering Constructions and Buildings*. 2025;21(4):346–357. <http://doi.org/10.22363/1815-5235-2025-21-4-346-357>

**Sergey I. Abrakhin**, Candidate of Technical Sciences, Associate Professor of the Department of Building Structures, Institute of Architecture, Civil Engineering and Energy, Vladimir State University named after Alexander and Nikolay Stoletovs, 87 Gorky St, Vladimir, 600000, Russian Federation; eLIBRARY SPIN-code: 2121-2007, ORCID: 0009-0002-8589-4826; e-mail: abrahin\_s@vlsu.ru

**Anastasiya V. Lukina**, Candidate of Technical Sciences, Associate Professor of the Department of Architectural and Construction Design and Environmental Physics, Institute of Architecture and Urban Planning, Moscow State University of Civil Engineering (National Research University), 26 Yaroslavskoye highway, Moscow, 129337, Russian Federation; eLIBRARY SPIN-code: 8745-0004; ORCID: 0000-0001-6065-678X; e-mail: pismo.33@yandex.ru

**Mikhail S. Lisyatnikov**, Candidate of Technical Sciences, Associate Professor of the Department of Building Structures, Institute of Architecture, Civil Engineering and Energy, Vladimir State University named after Alexander and Nikolay Stoletovs, 87 Gorky St, Vladimir, 600000, Russian Federation; eLIBRARY SPIN-code: 4089-7216, ORCID: 0000-0002-5262-6609; e-mail: mlsiyatnikov@mail.ru

**Danila A. Chibrikin**, Candidate of Technical Sciences, Associate Professor of the Department of Building Structures, Institute of Architecture, Civil Engineering and Energy, Vladimir State University named after Alexander and Nikolay Stoletovs, 87 Gorky St, Vladimir, 600000, Russian Federation; eLIBRARY SPIN-code: 1809-6997, ORCID: 0000-0001-9278-4559; e-mail: dachibrikin@outlook.com

© Abrakhin S.I., Lukina A.V., Lisyatnikov M.S., Chibrikin D.A., 2025

This work is licensed under a Creative Commons Attribution-NonCommercial 4.0 International License  
<https://creativecommons.org/licenses/by-nc/4.0/legalcode>

## Методы предсказательного моделирования для оценки остаточной прочности деревянных конструкций на основе экспериментальных данных

С.И. Абрахин<sup>1</sup>, А.В. Лукина<sup>2</sup>✉, М.С. Лисятников<sup>1</sup>, Д.А. Чибрикин<sup>1</sup>

<sup>1</sup> Владимирский государственный университет имени Александра Григорьевича и Николая Григорьевича Столетовых, Владимир, Российская Федерация

<sup>2</sup> Национальный исследовательский Московский государственный строительный университет, Москва, Российская Федерация  
✉ pismo.33@yandex.ru

Поступила в редакцию: 29 апреля 2025 г.

Доработана: 21 июля 2025 г.

Принята к публикации: 27 июля 2025 г.

**Аннотация.** Оценка несущей способности и прогнозирование остаточной прочности существующих конструкций является одной из самых сложных задач. Такое прогнозирование обычно выполняется на основе экспериментальных разрушающих испытаний образцов. Предложена методология прогнозирования остаточной прочности деревянных конструкций, основанная на результатах экспериментальных исследований по определению кратковременного сопротивления чистой древесины. В качестве объектов исследования были выбраны деревянные стропильные системы жилых домов 1950-х и начала 1960-х гг. постройки в г. Владимире. Для построения предсказательной модели остаточного ресурса конструкции были применены методы интерполяции и экстраполяции. Приведены подробные расчеты, наглядно показывающие возможность применения этих методов. Определено, что метод авторегрессии (метод Берга) показывает хорошие предсказательные результаты, коррелирующий с экспериментальными данными других исследований и теоретическими предположениями. Прогнозирование остаточного ресурса конструкции является ключевым фактором в обеспечении надежности и безопасности зданий, а также уменьшении эксплуатационных расходов в будущем.

**Ключевые слова:** здания, деревянные конструкции, прогнозирование, прочность, долговечность, интерполяция, экстраполяция

**Заявление о конфликте интересов.** Авторы заявляют об отсутствии конфликта интересов.

**Вклад авторов:** Абрахин С.И. — расчет и построение прогнозных моделей; Лукина А.В. — разработка программы исследований для получения экспериментальных данных, постановка цели и задачи исследования, написание текста, формулировка выводов; Лисятников М.С. — анализ современного состояния применения деревянных конструкций, литературный обзор; Чибрикин Д.А. — оформление графического материала, перевод на английский язык. Все авторы ознакомлены с окончательной версией статьи и одобрили ее.

**Финансирование.** Работа выполнена при финансовой поддержке Министерства науки и высшего образования Российской Федерации в рамках государственного задания в области научной деятельности (тема FZUN-2024-0004, государственное задание ВлГУ).

**Для цитирования:** Абрахин С.И., Лукина А.В., Лисятников М.С., Чибрикин Д.А. Методы предсказательного моделирования для оценки остаточной прочности деревянных конструкций на основе экспериментальных данных // Строительная механика инженерных конструкций и сооружений. 2025. Т. 21. № 4. С. 346–357. <http://doi.org/10.22363/1815-5235-2025-21-4-346-357>

### 1. Introduction

It is well known that the construction industry is the main wood consumer [1; 2]. Any building can be considered as a system, each element of which has its own operational lifespan. According to the Russian building code SP 64.13330<sup>1</sup>, the operational life of wooden elements and structures of buildings of large-scale construction under normal operating conditions (residential and industrial buildings) is at least 50 years. Scientific literature review shows that wooden structures are often operated outside the service standards [3; 4]. The available operational life of wood allows it to be used in the elements of wooden structures of unique buildings [4; 5].

From the analysis of the studies on the strength of operating wooden structures, it can be noted that there are practically no data and recommendations for estimating and predicting their strength capacity, in particular beyond the limits of the service life standards [7].

<sup>1</sup> SP 64.13330. *SNiP II-25-80 Timber structures*. Moscow, 2017.

To ensure the safety and durability of the structure, it is necessary to consider the factors affecting the reliability of wooden structures: internal stresses in structures that do not correspond to their design values; external effects; maintenance system (preventive and systematic); technical qualifications of maintenance and repair personnel [7; 8].

During operation, the physical and mechanical properties of wood change, which leads to the emergence of imperfections [10]. Many imperfections are gradual in character: the system parameters gradually deteriorate during operation and at some point in time they reach values, at which further operation becomes impossible or impractical [9].

The study and development of recommendations to substantiate the remaining life for wooden structures will allow to correctly predict the necessary material resources for repairs, as well as to justify the feasibility of constructing a new building or structure to replace an existing one, if necessary. Thus, the creation of a reliable model for predicting the residual strength of wooden structures is a key task.

The purpose of this methodology is to perform predictive modeling to estimate the residual strength of wooden structures using the example of a rafter system (spar) based solely on the results of experimental studies of samples, which is the main novelty of this study.

## 2. Methods

For establishing the experimental study program, it is necessary to identify the factors that affect the reliability of the obtained results and the number of performed experiments [12]. An insufficient number of the affecting factors will lead to mediocre results that cannot be accepted as reliable without additional investigation [13]. An increased number of influencing factors will increase the accuracy of the work results, however, this will simultaneously lead to an increase in the number of experiments and a decrease in the economic effect of the study.

The following factors are considered optimal for estimating the residual strength of load-bearing wooden structures beyond the limits of the service life:

- service class;
- operating conditions;
- service life of construction objects;
- availability of information on current/total repairs;
- physical deterioration of structural elements;
- load-bearing structure type based on strength;
- cross-section design features;
- loading mode of structural elements.

Taking into account the above factors made it possible to prepare the necessary experimental research program and ensure the reliability of the obtained results [14].

Residential buildings built in Vladimir, Russia, in the 50s and early 60s were selected as the sites where standard wood samples were taken for the study of the physical and mechanical properties (Table 1).

Table 1

**Results of experimental studies of wood samples under compression along the fibers**

| Type of structure                              | Rafter spar          |      |       |       |       |
|------------------------------------------------|----------------------|------|-------|-------|-------|
| Purpose of the building                        | Residential building |      |       |       |       |
| Age of the structure ( <i>t</i> )              | New                  | 49   | 60    | 64    | 65    |
| Year of construction                           | –                    | 1974 | 1963  | 1959  | 1958  |
| Test year                                      | 2023                 | 2023 | 2023  | 2023  | 2023  |
| Short-term resistance of pure wood $R^n$ , MPA | 30                   | 29.6 | 27.87 | 25.38 | 24.13 |
| Physical deterioration, %                      | –                    | 37   | 43    | 46    | 46    |

Source: made by A.V. Lukina

The samples were selected from structural elements in the same stress-strain state — rafter spars. Blanks for the manufacture of standard samples were selected from the structural elements that had no visible defects or damage. Then, small reference samples were made from blanks cut from structures in laboratory conditions to determine the ultimate strength of the wood under compression along the fibers according to the interstate standard GOST 16483.10-73<sup>2</sup>. Statistical data processing was carried out using the test results.

The physical deterioration of wooden structures of residential buildings was determined by the Delphi method [15]. The obtained experimental results of short-term resistance of pure wood (Table 1) served as the initial data for predictive modeling to estimate the residual strength of wooden structures (Table 2).

Table 2

**Experimental results of short-term resistance  
of pure wood for interpolation and extrapolation**

| №                     | 1  | 2    | 3     | 4     | 5     |
|-----------------------|----|------|-------|-------|-------|
| <i>t</i>              | 0  | 49   | 60    | 64    | 65    |
| <i>R</i> <sup>n</sup> | 30 | 29.6 | 27.87 | 25.38 | 24.13 |

Source: made by A.V. Lukina

For more accurate predictive modeling of the residual strength of wooden structures, the design resistance values ( $R^{des}$ ) for the service life of 75 and 100 years according to SP 64.13330 are determined as:

$$R^{des} = R^A m_{it} \Pi m_i.$$

Then, the design resistance for the grade II wood  $R^{des}$  (bending, compression and crushing along the fibers) for the service life of 75 years is:  $R^{des} = 19.5 \times 0.66 \times 0.9 = 11.5 \text{ MPa}$ , for 100 years and more:

$$R^{des} = 19.5 \times 0.66 \times 0.8 = 10.3 \text{ MPa}.$$

Thus, the minimum value of the design resistance cannot be less than 10.3 MPa. This value takes into account the decrease in the strength characteristics of wood over time due to prolonged exposure to loads and environmental factors.

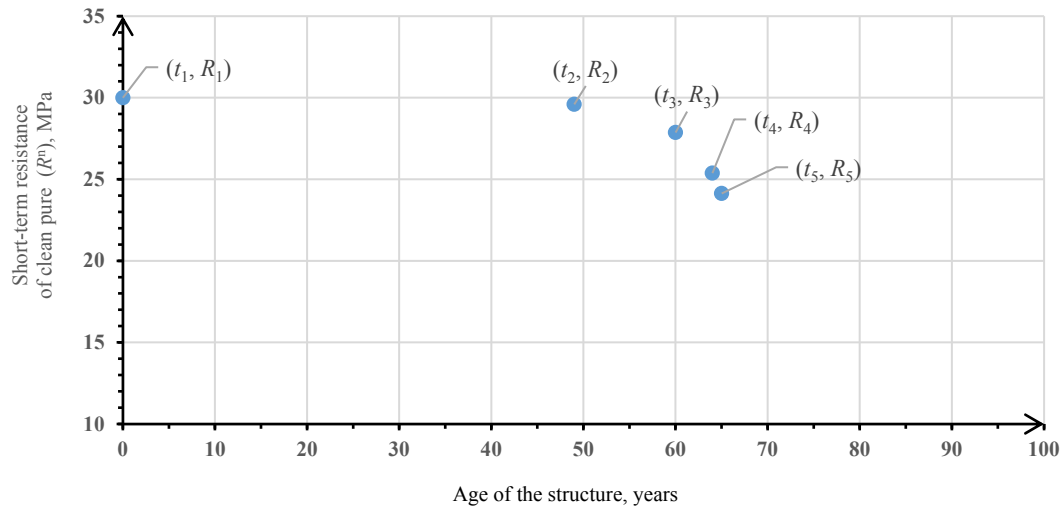
The experimental results of short-term resistance of pure wood are recorded in tabular form in Table 2 for interpolation and extrapolation.

The experimental values of the short-term resistance of wood are presented in the form of nodal points on the graph (Figure 1).

To represent patterns, as well as in the process of scientific and engineering calculations, relationships in the form  $y(x)$  are often used, and the number of specified points (hereinafter nodal) of these relationships is limited. The task of approximate computation of the function values in the intervals between the nodal points (interpolation) and beyond (extrapolation) inevitably arises. This task is solved by replacing it with some fairly simple function. Thus, it is necessary to use the methods of interpolation and extrapolation to estimate the value of short-term resistance of pure wood of wooden structures over the observed, historical, time period (0–65 years) and predict their future behavior (forecast period 66–200 years).

A decrease in the strength of wooden structures can occur as a result of bioerosion or physical deterioration [16]. It should be noted that the task of predictive modeling was not to identify the causes of the decrease in strength. The authors perform the simulation, assuming that the wooden structures were in normal operating conditions.

<sup>2</sup> GOST 16483.10-73. *Wood. Methods for determining the compressive strength along fibers*. Moscow: IPK Publishing House of Standards. 1999.



**Figure 1.** Nodal points of experimental data

Source: made by A.V. Lukina

### 2.1. Interpolation of Experimental Data

Interpolation allows to estimate resistance values for conditions, for which there are no direct measurements, but the interpolated values will accurately match the available experimental data. The results of interpolation beyond the limits of the range of available experimental data are not considered.

The most widely used interpolation methods are:

- piecewise-linear interpolation;
- polynomial interpolation;
- spline interpolation.

■ **Piecewise-linear Interpolation.** Piecewise-linear interpolation is a simple method that assumes that the parameter value changes linearly between two known points in the experimental data.

Piecewise-linear interpolation involves representing a tabulated function on each interval between the horizontal coordinates of the nodal points by a linear relationship:  $R(t) = a_1 + a_2t$ . Coefficients  $a_1$  and  $a_2$  are determined for each interval  $[t_{i-1}, t_i]$  separately according to conditions: 
$$\begin{cases} R(t_{i-1}) = R_{i-1}; \\ R(t_i) = R_i. \end{cases}$$

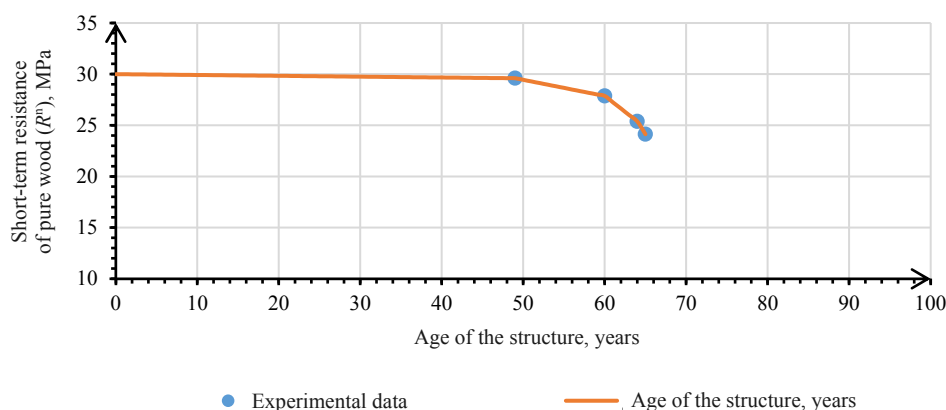
As a result, the piecewise-linear approximating function on the interval of  $[t_{i-1}, t_i]$  has the form:

$$R_{(i-1)...i}(t) = R_{i-1} + \frac{R_i - R_{i-1}}{t_i - t_{i-1}}(t - t_{i-1}), \text{ and is continuous.}$$

For the experimental data presented in Table 2, the piecewise-linear function will take the form:

$$R(t) = \begin{cases} 30 - 0.00816t, & \text{when } t \in [0; 49]; \\ 37.30636 - 0.15727t, & \text{when } t \in [49; 60]; \\ 65.22 - 0.6225t, & \text{when } t \in [60; 64]; \\ 105.38 - 1.25t, & \text{when } t \in [64; 65]. \end{cases} \quad (1)$$

The graph of the piecewise-linear interpolation is shown in Figure 2. The interpolated values of short-term resistance of pure wood obtained over a historical time interval with piecewise-linear interpolation will be used to predict their future behavior during extrapolation.



**Figure 2.** Piecewise linear interpolation of short-term resistance of pure wood

Source: made by S.I. Abrakhin

■ **Polynomial Interpolation Short-term resistance of pure wood ( $R^n$ ), MPa.** Polynomial interpolation uses power polynomials to interpolate the relationships between points. A more accurate method than linear interpolation, especially when the relationship is nonlinear. Such polynomials are the Newton and Lagrange polynomials. They are the same polynomial, but its coefficients are calculated in different ways [17]. The interpretation of experimental data by the Lagrange polynomial is considered below.

The Lagrange interpolation polynomial is a method of constructing a power polynomial that passes exactly through the given set of points (interpolation nodes)  $(t_1, R_1), \dots, (t_5, R_5)$ . The Lagrange interpolation polynomial  $P(t)$  is such that  $P(t_i) = R_i$  for all  $i = 1, \dots, 5$ .

This method belongs to a class of interpolation methods that allow to reconstruct (approximate) function values at points that are not explicitly specified, based on a known set of function values at other points.

The Lagrange interpolation polynomial has the following form:

$$P(t) = \sum_i R_i \cdot L_i(t), \quad (2)$$

where  $P(t)$  is the interpolation polynomial of degree no higher than the number of interpolation nodes;  $R_i$  is the function value at the interpolation node  $t_i$ .  $L_i(t)$  is the fundamental Lagrange polynomial, which has the form of:

$$L_i(t) = \prod_{\substack{j=1 \\ j \neq i}}^5 \frac{(t - t_j)}{(t_i - t_j)}, \quad (3)$$

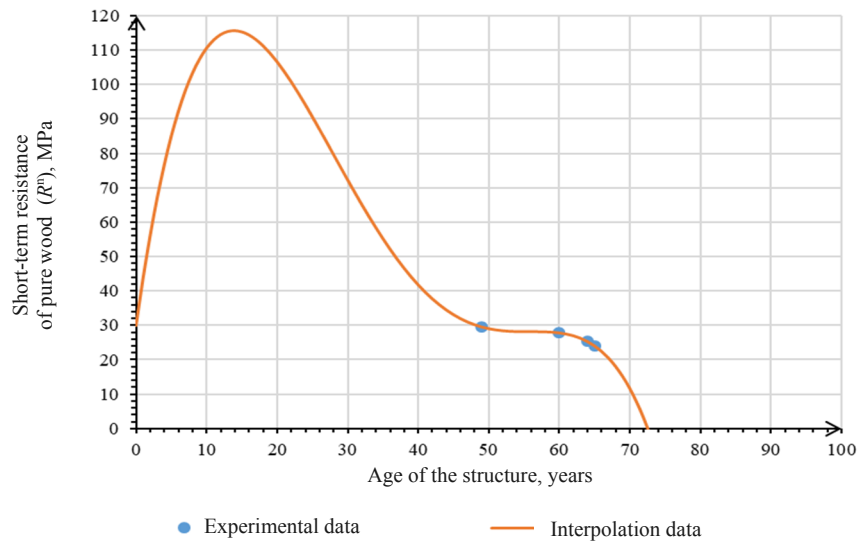
where  $t$  is the variable, for which the polynomial is evaluated;  $t_i$  is the horizontal coordinate of the  $i$ -th interpolation node;  $t_j$  is the horizontal coordinate of the  $j$ -th interpolation node.

As a result of substituting the experimental data and performing calculations in the Mathcad software, the Lagrange polynomial will take the form:

$$P(T) = -0.000083992644260501403349t^4 + 0.014084946303696303695t^3 - \\ - 0.7867660724691974691t^2 + 14.607068815113457969t + 30.0.$$

The graph of the Lagrange polynomial is presented in Figure 3.

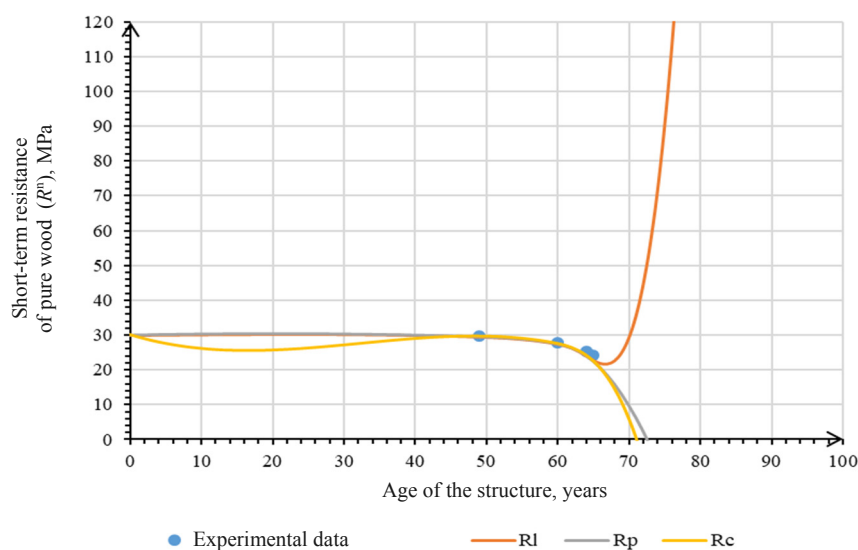
The interpolated data of short-term resistance values of pure wood obtained over a historical time interval when interpolated by the Lagrange polynomial cannot be used to predict their future behavior by extrapolation methods because the interpolated values over a time interval from 0 to 49 years reach more than 100 MPa, which they do not correspond to the physical conduct of the material.



**Figure 3.** Lagrange polynomial interpolation of short-term resistance of pure wood  
Source: made by S.I. Abrakhin

■ **Spline Interpolation.** Spline interpolation is a method of constructing a smooth function passing through specified nodal points of experimental data. The function is constructed from segments, each of which is a separate cubic function, selected so that at the nodal points not only the function itself, but also its first and second derivatives are continuous. At the boundaries of the experimental data, where it is impossible to achieve a complete convergence of the derivatives, additional conditions are applied: linear boundary conditions that define zero second derivatives at the boundaries; parabolic conditions ensure that the extreme segments of the spline are parabolas, the coefficient for the cubic term is zero; and cubic conditions ensure that the spline behaves like a cubic polynomial at the boundaries [18].

In the Figure 4 shows the results of spline interpolation of experimental data performed in MathCad, where  $Rl$ ,  $Rp$ , and  $Rc$  are spline interpolation under linear, parabolic, and cubic boundary conditions, respectively.



**Figure 4.** Spline interpolation of short-term resistance of pure wood  
Source: made by S.I. Abrakhin

The results of spline interpolation using cubic conditions at the boundaries of experimental data ( $R_c$ ) are not suitable for predicting their further behavior using the extrapolation method. The reason is that the interpolated values show a significant drop in strength to  $\sim 25$  MPa over a time interval from 0 to 49 years, and then an unexpected increase, which contradicts the nature of the degradation of wood properties.

On the contrary, the interpolated data obtained using linear ( $R_l$ ) and parabolic ( $R_p$ ) boundary conditions at the boundaries of the experimental data for coupling the first and second derivatives show a moderate increase in the values of short-term resistance of pure wood over a time interval from 0 to 49 years to  $\sim 30.5$  MPa. The data obtained can be used to predict future behavior by extrapolation, as they correspond to the physical behavior of wood.

## 2.2. Extrapolation of Experimental Data

Extrapolation is a method of estimating the values of short-term resistance of wood outside the range of available experimental data. It is used to predict the resistance values of pure wood in the future or under other unexplored conditions. Extrapolation is riskier than interpolation, as it assumes that the relationship identified within the experimental data will persist beyond its boundaries.

Experimental data extrapolation is the process of selecting a mathematical function or model that best describes a set of experimental nodal points. The goal is to find a relationship between variables that minimizes the error between the predicted model values and the actual experimental data.

Extrapolation by a power polynomial of power  $n$ :  $R_n(t) = a_0 + \sum_{i=1}^n a_i t^i$  and a linear function, which is its particular case when  $n = 1$ , is not considered, since these results will correspond to polynomial interpolation.

The following extrapolation options for the available experimental data are considered:

- exponential extrapolation:  $R_{\text{exp}}(t) = ae^{b \cdot t} + c$ ;
- logistic extrapolation:  $R_{\text{lg}}(t) = \frac{a}{1 + be^{-ct}}$ ;
- sinusoidal extrapolation:  $R_{\text{sin}}(t) = a \sin(t + b) + c$ ;
- power extrapolation:  $R_{\text{pwr}}(t) = at^b + c$ ;
- logarithmic extrapolation:  $R_{\text{log}}(t) = a \ln(b + t) + c$ .

Based on the results of minimizing the error between the model values and the real experimental data, coefficients  $a$ ,  $b$ , and  $c$  are calculated, which, when substituted, will allow to estimate the resistance value outside the range of the experimental data.

The results of extrapolation of the experimental data performed in the Mathcad software are shown in Figure 5.

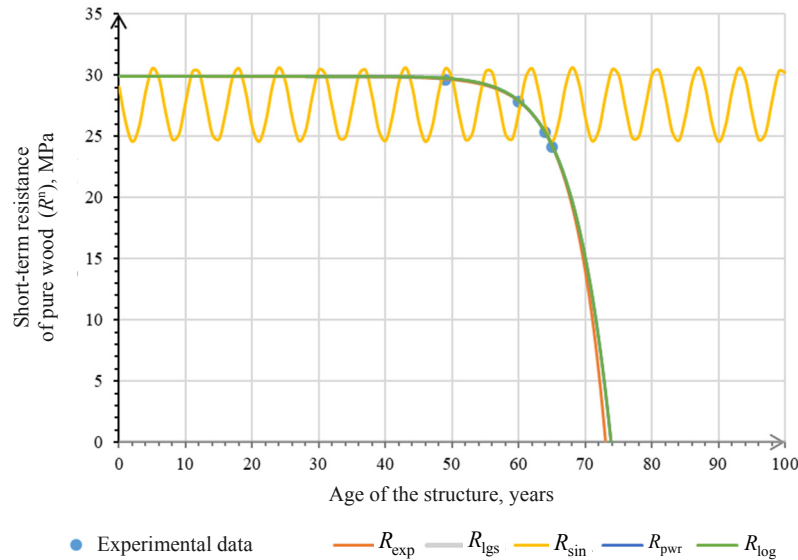
It can be concluded from the obtained results that sinusoidal  $R_{\text{sin}}$  extrapolation gives the resistance values varying from  $\approx 25$  to  $\approx 31$  MPa with a period of around 7 years. Sigmoidal  $R_{\text{sgn}}$  and logarithmic  $R_{\text{log}}$  extrapolation give a constant value (30 and 0 respectively). Exponential  $R_{\text{exp}}$  and power  $R_{\text{pwr}}$  extrapolation show good results in the historical range of experimental data with a coefficient of determination of 0.999 and 0.998, respectively, but outside the historical period, the resistance values become negative by the age of 75, which is not consistent with reality. Therefore, these extrapolation methods cannot be used to predict the residual strength of wooden structures.

There remains the option of extrapolating experimental data using the autoregression method. The autoregression (AR) method is a statistical time series analysis method that is used to predict future values of a series based on its previous observations.

The underlying concept of the autoregression method is that the current value of a time series can be represented as a linear combination of several previous values of the same series and a random error. The formula of the autoregression model is as follows:

$$R_t = a_{t-1}R_{t-1} + a_{t-2}R_{t-2} + \dots + a_{t-p}R_{t-p} + \varepsilon, \quad (4)$$

where  $R_t$  is the current value of the time series;  $a_{t-1}, a_{t-2}, \dots, a_{t-p}$  are the regression coefficients;  $R_{t-1}, R_{t-2}, \dots, R_{t-p}$  are the time series values from the previous periods;  $p$  is the order of the model (the amount of previous values of the time series considered);  $\varepsilon(p)$  is the prediction error.

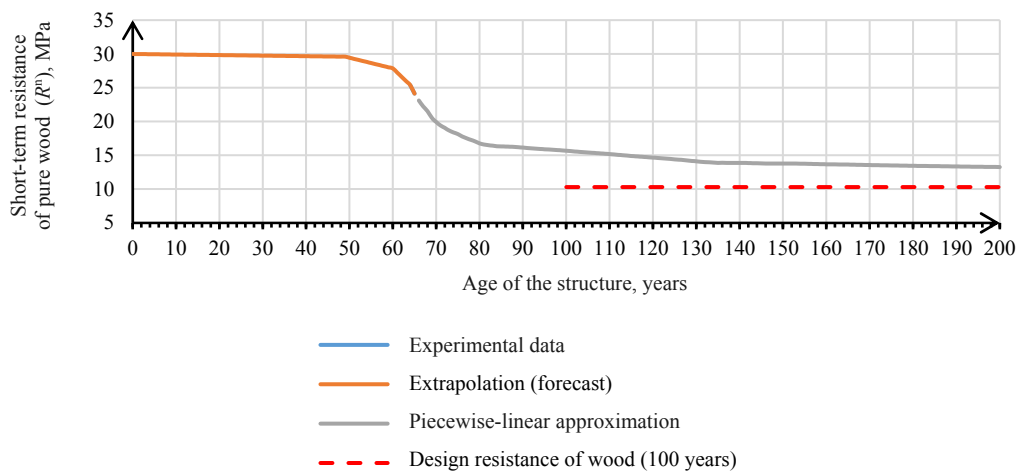


**Figure 5.** Approximation of short-term resistance values of pure wood

S o u r c e: made by S.I. Abrakhin

One of the autoregression methods of is the Burg method. Its main task is to find the coefficients  $a_{t-1}, a_{t-2}, \dots, a_{t-p}$  that minimize the prediction error  $\varepsilon(p)$ . The main difference between Burg method and other algorithms is that it minimizes the prediction error, both in the forward and backward directions. This leads to more stable and reliable estimates of the coefficients, especially when working with short time series.

The results of the extrapolation carried out in the MathCad software using the Burg method of interpolation of the experimental data obtained as a result of piecewise-linear interpolation are shown in Figure 6.



**Figure 6.** Results of extrapolation of piecewise linear interpolation of experimental data

S o u r c e: made by S.I. Abrakhin and A.V. Lukina

### 3. Results and Discussion

The developed model (Figure 6) should be verified by comparison with theoretical and experimental studies [19; 20]. As seen from the graph in Fig. 6, the system proposed as a predictive model for estimating the residual strength of wooden structures is consistent with the curve of long-term resistance of wood developed by F.P. Belyankin and U.V. Ivanov and the Weibull exponential law [21; 22]. The asymptotic nature of the curve of long-term resistance of wood shows that, although the ultimate strength decreases with increasing duration of the applied load, it is not unlimited — it tends to a certain constant value  $\sigma_{дл}$ , equal to the vertical coordinate of the asymptote of the curve [23; 24].

In the context of the reliability of wooden structures, the use of the Weibull exponential law allows to take into account the variability of the mechanical properties of wood and estimate the likelihood of failure under prolonged loading. In applied calculations, the reliability of a system is expressed by an exponential law [25]. A model based on the Weibull distribution is also often used. The probability of fail-safe operation is defined as:

$$P(t) = \exp \left[ - \left( \frac{t}{t_c} \right)^\beta \right], \quad (5)$$

where  $t_c$  and  $\beta$  are positive parameters.

For  $\beta > 1$ , formula (5) describes the behavior of “aging” objects, in which the failure rate increases over time. The failure rate is usually relatively high at the beginning. Then it decreases and remains approximately constant over a long period of operation, increasing towards the end due to aging or deterioration.

The developed predictive modeling graph for estimating the residual strength of wooden structures (rafter spars) based on experimental data (Figure 6) has a nonlinear relationship, where the initial strength of wood decreases with increasing time of being subjected to the load. An important aspect of this curve is that it allows to take into account the time factor when assessing the strength of wood, which is critical for long-term structural design.

In [26], the values of the ultimate strength of rafter spars in residential buildings built in the 1930s were determined: 15.25 and 15.36 MPa. At the time of the experimental studies, the age of the structures was just over 90 years. Analyzing the predictive modeling for estimating the residual strength of wooden structures based on the Burg method, it can be found that the experimental data of the author of [27] correlate very well with the graph in Figure 6.

The predictive modeling curve can be interpreted as a reflection of the change in the strength parameter over time. As the load exposure time increases, the strength parameter decreases, which leads to an increased probability of failure (destruction). Thus, the developed predictive modeling graph can be used to quantify the residual strength of wood over time.

### 4. Conclusion

Interpolation and extrapolation of experimental data on the short-term resistance of pure wood are important tools for estimating the residual life of wooden structures. They allow using limited data to predict changes in the strength characteristics of wood over time, which is essential for the safe and efficient operation of wooden structures.

Extrapolation, being a riskier process, requires the use of mathematical models of wood aging and confirmation of the results by additional experimental studies.

1. An interpretation of the processes of deformation and degradation of the strength of wooden structures is proposed based on modeling the values of the residual strength of wooden structures obtained experimentally.

2. A predictive modeling algorithm has been developed and implemented to estimate the residual strength of wooden structures based on experimental data.

3. The developed predictive modeling graph for estimating the residual strength of wooden structures has good convergence with the theoretical assumptions and experimental results of other studies.

4. The use of the described approaches will help engineers to manage the operational life of wooden structures more effectively, ensuring their reliability and durability.

The use of the results of the work in updating the regulatory framework and the practice of construction (repair) will ensure the adaptability of wooden load-bearing structures to prevent and eliminate failures through maintenance and timely repairs.

## References

1. Repin V.A., Lukina A.V., Strekalkin A.A. Parameterization of Maxwell — Cremona diagram for determining forces in elements of a scissors truss. *Structural Mechanics of Engineering Constructions and Buildings*. 2024;20(2):97–108. <http://doi.org/10.22363/1815-5235-2024-20-2-97-108> EDN: KZTKLX
2. Griбанov A.S., Roshchina S.I., Popova M.V., Sergeev M.S. Laminar polymer composites for wooden structures. *Magazine of Civil Engineering*. 2018;7(83):3–11. <http://doi.org/10.18720/MCE.83.1> EDN: ZDIKJN
3. Jašek M., Stejskalová K., Fojtík R., Ingeli R. Analysis of the service life of wooden bridge structures using structural protection. *Case Studies in Construction Materials*. 2025;22:e04453. <http://doi.org/10.1016/J.CSCM.2025.E04453>
4. Yadav S., Purchase D. Biodeterioration of cultural heritage monuments: A review of their deterioration mechanisms and conservation. *International Biodeterioration & Biodegradation*. 2025;201:106066. <http://doi.org/10.1016/J.IBIOD.2025.106066>
5. Qiao Ze.H., Jiang Sh.F., Tang W.J., Li Ni.L. Dual-indicator prediction model for the safety of Chinese ancient wooden structures subjected to bioerosion. *Journal of Building Engineering*. 2021;43:102868. <http://doi.org/10.1016/J.JOBE.2021.102868> EDN: XLWCSO
6. Mackiewicz M., Zimiński K., Pawłowicz J.A., Knyziak P. Evaluation of the historic wooden structure condition based on the results of non-destructive tests. *Engineering Failure Analysis*. 2024;159:108116. <http://doi.org/10.1016/J.ENGFAILANAL.2024.108116> EDN: GQTVZV
7. Andersen C.E., Hoxha E., Rasmussen F.N., Sorensen C.G., Birgisdottir H. Temporal considerations in life cycle assessments of wooden buildings: Implications for design incentives. *Journal of Cleaner Production*. 2024;445:141260. <http://doi.org/10.1016/J.JCLEPRO.2024.141260> EDN: DPSBPV
8. Califano A., Leijonhufvud G., Bichlmair S., Kilian R., Wessberg M., Sepe R., Lamanna G., Bertolin C. Cumulative climate-induced fatigue damage in wooden painted surfaces: The case of wooden churches in Sweden. *Journal of Cultural Heritage*. 2024;67:313–325. <http://doi.org/10.1016/J.CULHER.2024.03.017> EDN: QRXCCF
9. Silva A., de Brito J. Service life of building envelopes: A critical literature review. *Journal of Building Engineering*. 2021;44:102646. <http://doi.org/10.1016/J.JOBE.2021.102646> EDN: GPEQBG
10. Shirmohammadi M., Leggate W., Redman A. Effects of moisture ingress and egress on the performance and service life of mass timber products in buildings: a review. *Construction and Building Materials*. 2021;(290):123176. <http://doi.org/10.1016/J.CONBUILDMAT.2021.123176> EDN: JOSSIT
11. Wang Q., Wang Z., Feng X., Zhao Y., Li Z. Mechanical properties and probabilistic models of wood and engineered wood products: A review of green construction materials. *Case Studies in Construction Materials*. 2024;(21): e03796. <http://doi.org/10.1016/J.CSCM.2024.E03796> EDN: GGNEVS
12. Gomon S., Homon S., Pavluk A., Matviiuk O., Sasiuk Z., Puhach Y., Svyrydiuk O. Hypotheses and prerequisites for modelling the stress-strain state of wooden element normal cross-section using the deformation calculation method. *Procedia Structural Integrity*. 2024;(59):559–565. <http://doi.org/10.1016/J.PROSTR.2024.04.079> EDN: JCSOQ
13. Lisyatnikov M., Lukina A., Lukin M., Roschina S. Experimental study of a wooden girder truss with composite chords. *Architecture and Engineering*. 2024;9(2):47–56. <http://doi.org/10.23968/2500-0055-2024-9-2-47-56> EDN: IFJAHS
14. Roshchina S.I., Lukina A.V., Narmania B.E., Lisyatnikov M.S., Lukin M.V. Life cycle study of buildings wooden coverings in the textile industry. *Izvestiya Vysshikh Uchebnykh Zavedenii, Seriya Tekhnologiya Tekstil'noi Promyshlennosti*. 2024;(4):201–208. (In Russ.) [http://doi.org/10.47367/0021-3497\\_2024\\_4\\_201](http://doi.org/10.47367/0021-3497_2024_4_201) EDN: LZQWBR
15. Chernykh A.G., Korolkov D.I., Danilov E.V., Kazakevich T.N., Koval P.S. Estimation of the residual resource of wooden structures by the amount of physical wear. *Housing Construction*. 2022;(4):66–72. (In Russ.) <http://doi.org/10.31659/0044-4472-2022-4-66-71> EDN: OFDSHE
16. Roschina S.I., Lukina A.V., Sergeev M.S., Vlasov A.V., Griбанov A.S. Restoration of wooden constructions by impregnation of polymer composition on the example of industrial buildings of light and textile industry. *Izvestiya Vysshikh Uchebnykh Zavedenii, Seriya Tekhnologiya Tekstil'noi Promyshlennosti*. 2016;(5):76–80. (In Russ.) EDN: XHYJRT
17. Lam D.H., Cuong L.N., Van Manh P., Van Minh N. On the conditioning of the Newton formula for Lagrange interpolation. *Journal of Mathematical Analysis and Applications*. 2022;(1):125473. <http://doi.org/10.1016/J.JMAA.2021.125473>

18. Kalitkin N.N. *Numerical methods: textbook. stipend.* 2nd ed., revised. St. Petersburg: BHV Petersburg publ.; 2011. (In Russ.)
19. Zoteev V.E., Makarov R.Y. Numerical method of determining creep model parameters within the first two stages of creep. *Vestnik of Samara University. Aerospace and Mechanical Engineering.* 2017;16(2):145–156. (In Russ.) <http://doi.org/10.18287/2541-7533-2017-16-2-145-156> EDN: ZAETOH
20. Chernykh A., Korolkov D., Nizhegorodtsev D., Kazakevich T., Mamedov S. Estimating the residual operating life of wooden structures in high humidity conditions. *Architecture and Engineering.* 2020;5(1):10–19. <http://doi.org/10.23968/2500-0055-2020-5-1-10-19> EDN: LYBAZC
21. Ivanov Yu.M., Slavik Yu.Y. Assessment of long-term bending strength of wood based on the results of short-term tests. *Bulletin of Higher Educational Institutions.* 1981;(2):66–70. (In Russ.) <https://lesnoizhurnal.ru/apxiv/1981/%E2%84%962-1981.pdf>
22. Belyankin F.P. *Long-term resistance of a tree.* Moscow, Leningrad : ONTI Publ.; 1934. (In Russ.) Available from: <https://djvu.online/file/ElrD5VAqf2tv1> (accessed: 15.02.2025).
23. Sindhu T.N., Atangana A., Riaz M.B., Abushal T.A. Bivariate entropy-transformed Weibull distribution for modelling bivariate system-simulated data from a computer series: Mathematical features and applied results. *Alexandria Engineering Journal.* 2025;117:593–608. <http://doi.org/10.1016/j.aej.2024.12.107>
24. Roshchina S.I. Theoretical studies of reinforced wooden structures taking into account long-term force effects. *Industrial and Civil Engineering.* 2008;(1):48–49. (In Russ.) EDN: IJBHCR
25. Sheshukova N.V. Rheological behavior of wood under permanently acting load. *Bulletin of the St. Petersburg Forest Engineering Academy.* 2008;(184):180–185. (In Russ.) EDN: MVLVIL
26. Hung K.-C., Wu T.-L., Chen Y.-L., Wu J.-H. Assessing the effect of wood acetylation on mechanical properties and extended creep behavior of wood/recycled-polypropylene composites. *Construction and Building Materials.* 2016; 108:139–145. <http://doi.org/10.1016/j.conbuildmat.2016.01.039>
27. Nikitina T.A. *Technological lifespan of coniferous retrowood in the elements of wooden structures. dis. ... Candidate of Technical Sciences.* 2021. (In Russ.) EDN: RQLTBR