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ISSUES OF DETERMINING THE RESOURCE OF BEARING CAPACITY OF ANCIENT TIMBER STRUCTURES ELEMENTS

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Abstract

Introduction: The resource of bearing capacity (RBC) of timber structures in historical buildings and structures with an operational life of 100 years or more cannot be determined without considering their specific characteristics. At the same time, this problem has important theoretical and practical significance for assessing the technical condition, preservation, and restoration of cultural heritage sites. **Objective**: to systematize scientific data on the influence of various factors on the RBC of ancient timber structure elements. **Methods**: The operational bearing capacity of timber structure elements is mainly determined by the thermofluctuation mechanism of cellulose macromolecule ("skeleton" of wood) failure, which leads to strength degradation, creep, as well as physical wear. Assessing the combined effect of these factors allows determining the RBC of the structure. Furthermore, with long service lives, it is necessary to additionally consider possible changes: climate, landscape, properties of protective-decorative coatings, structural and spatial-planning solutions, spatial position, functional purpose, status of the object as a monument, as well as the legislative framework for design and restoration. A refined assessment should include an analysis of the influence of construction technological features. **Results**: A comprehensive analysis has demonstrated the need for joint consideration and interrelations of force and environmental impacts, deformation and strength properties of wood, physical wear and defects, and the complex nature of the stress-strain state of timber structure elements in historical buildings and structures to assess their RBC, as well as to develop a strategy for ensuring a balance between mechanical safety and the preservation of the cultural and historical value of the objects.

Keywords: resource of bearing capacity; ancient timber structures; long-term strength; physical wear; geometric nonlinearity; physical nonlinearity.

Introduction

Ancient timber structures, as an important part of cultural heritage, not only carry rich historical information but also serve as material evidence of traditional construction technologies. Many valuable historical timber buildings have undergone multiple repairs, and when assessing and surveying these structures, accurately determining the resource of bearing capacity (RBC) of their elements faces a number of challenges (Wang, 2008). Firstly, due to the long service life of historical buildings, original construction data and long-term strength data are absent, making it difficult to predict the degradation patterns of timber element characteristics under permanent loads. Secondly, the diversity of wood species used in construction and the heterogeneity of their properties complicate the assessment of the structure's mechanical characteristics. The mechanical properties of different tree species vary, and natural defects such as wormholes and knots increase the complexity of material inspection. Differences in strength across different areas of wood affect the reliability of the entire structure (Bode et al., 2019). Furthermore, the combined impact of environmental factors (e.g., temperature and humidity fluctuations, biological degradation) and loads further complicates the analysis of the resource of bearing capacity of elements. Existing methods for predicting long-term strength have limitations and cannot accurately model the complex influence of real operating conditions.

At the same time, during the long-term operation of historical buildings, mechanical damage and biological degradation of timber structures gradually accumulate. In addition to creep and cracking of elements caused by the thermofluctuation mechanism, damage in timber structures often includes irregular components such as local rot, insect infestation, and traces of historical repairs. These factors are difficult to quantify using standard methods. Moreover, in the practice of preserving valuable historical buildings, there is a contradiction between the principles of historical restoration and modern structural safety requirements. In the process of identifying irregular damage, intervention into the original structure must be minimized. For this purpose, non-destructive methods such as stress wave testing (SWT), infrared thermography (IRT), and others are used to determine the extent and location of damage. In some cases, changes in the spatial position of the building are even analyzed to ensure its preservation (Korolkov, 2020). The aim

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of this work is to systematize scientific data on the influence of various factors on the resource of bearing capacity of ancient timber structure elements.

Heterogeneity of Wood Properties

The RBC of ancient timber structures significantly depends on the heterogeneity of wood properties, which manifests in aspects such as material aging, environmental impacts, and structural damage. Wood is a unique natural building material with structural heterogeneity. The annual rings, formed by layers of cells during tree growth, lead to differences in material strength depending on the wood species and fiber direction (Glebov, 2018). Furthermore, natural defects in wood, such as knots and wormholes, as well as accumulated decay processes over time, further enhance the influence of heterogeneity on the long-term strength of the material (Riggio et al., 2018).

Wood defects can be divided into the following three types: 1) natural defects occurring in the living tree; 2) defects arising during drying and processing of wood; 3) defects caused by fungi, insects, and wood borers (Vakin et al., 1980). Natural wood defects include knots, cracks, etc. Knots disrupt the continuity of wood fibers (Gubenko and Khandrov, 2015), leading to stress concentration and a 10–50 % reduction in material strength (GOST 2140–81). During long-term cycles of temperature and humidity changes in building structures, the difference in shrinkage rates between knots and surrounding fibers increases, causing radial cracks, further reducing the longitudinal tensile strength and shear resistance of the element (SP 64.13330.2017). Apart from natural defects, processing inaccuracies of timber structure elements can lead to excessive tightness or loosening of connections. Under long-term loads, excessive tightness causes initial stress concentration, and subsequent wood creep leads to the formation of hidden cracks. Loose connections under dynamic loads accelerate wood wear, reducing joint stiffness. In traditional Chinese timber structures, tougong joints were widely used, where the processing accuracy of elements was a critical factor for structural safety (Kirichkov, 2020).

Wood density is one of the key factors determining its mechanical properties and RBC. It usually depends on the tree species, growth conditions, trunk height, and harvesting location. Higher density wood generally possesses increased resistance to compression, bending, and shear, whereas lower density wood exhibits greater plasticity but lower stiffness. Wood density increases with slower diameter growth, a greater number of annual rings per centimeter, and a higher proportion of latewood. This leads to improved mechanical characteristics (Brunetti et al., 2013). Within a single trunk, these properties vary with height and radius. Along the trunk height, the best indicators are observed at the base, gradually decreasing towards the crown. In the radial direction, mechanical properties strengthen from the pith to the bark, reach a maximum, and then begin to decrease again (Papulova, 2014). During long-term operation, wood density affects its durability and resistance to environmental impacts. Denser wood, due to its compact structure, usually has lower hygroscopicity and better resistance to biological degradation (fungi, pests), allowing it to maintain its bearing capacity longer under cyclic temperature and humidity changes. Conversely, low-density wood without antiseptic treatment, when exposed to prolonged moisture or pests, can degrade rapidly, leading to loss of bearing capacity (Borovikov and Ugolev, 1989; EN 408).

The heterogeneity of wood significantly affects the RBC of ancient timber structures, manifesting in differences in wood species and the uneven distribution of natural and accumulated damage. To ensure the long-term safe operation of historical buildings, it is necessary to apply non-destructive testing methods for scientifically based prediction of the RBC of different wood types.

Complexity of Interrelated Environmental and Load Impacts

During the long-term operation of historical buildings, the combined impact of environmental factors (temperature, humidity) and mechanical loads significantly accelerates the degradation of material properties, which in turn affects the RBC. Wood as a natural polymer material is a network structure formed by cellulose, hemicellulose, and lignin through hydrogen and covalent bonds. The long-term degradation of its properties is mainly due to the thermofluctuation mechanism. Temperature and humidity fluctuations lead to repeated cycles of moisture absorption and loss by wood fibers, causing volume changes and internal stresses, making the viscoelastic properties of the material more pronounced.

The Soviet scientist S.N. Zhurkov established that the thermofluctuation mechanism reveals the process of gradual damage accumulation in solid materials (including wood) under the action of stresses and environmental factors, driven by thermally activated processes at the atomic or molecular level (Yartsev and Kiseleva, 2009). According to this theory, material failure is essentially a statistical process of chemical bond breakage induced by the combined action of thermodynamic fluctuations and mechanical stresses. This process is described by the Zhurkov equation:

$$\tau = \tau_0 \exp\left(\frac{U_0 - \gamma\sigma}{kT}\right),$$

where:

τ is time of the material failure under load σ,

τ_0 is atomic vibration period (~10^{-13} c),

U_0 is initial activation energy of the chemical bond (in the absence of stress),

γ is stress sensitivity coefficient, reflecting the structural properties of the material*,*

k is Boltzmann constant,

T is absolute temperature.

It has been established that even in the absence of external loads, damage in wood accumulates nonlinearly over time (Kovshov, 2020). The main load-bearing elements of wood are microfibrils composed of cellulose molecules linked by hydrogen bonds and van der Waals forces. The Zhurkov equation demonstrates that the synergistic influence of the environment enhances the effect of the thermofluctuation mechanism on the strength characteristics of wood (Yartsev, 2003) (Table).

It follows that the thermofluctuation mechanism is the direct cause of the reduction in bearing capacity of timber structure elements during long-term operation. V.P. Yartsev conducted strength tests of pine under longitudinal and transverse bending in various temperature and humidity conditions. The experiment involved gradual heating in a thermostat, and material samples were soaked in various solutions to obtain test samples with different moisture contents, allowing the determination of the material's strength characteristics under different temperature and humidity conditions.

Experimental studies have shown that increasing temperature and humidity accelerates the failure process of timber structures, reducing the long-term strength of the material, especially the bending resistance. An increase in temperature changes the glass transition temperature of lignin: at high temperatures, lignin softening leads to intense interfiber sliding, reducing the fatigue life of timber elements and accelerating wood creep. Under high humidity conditions, water penetration destroys hydrogen bonds between cellulose molecules, reducing the stiffness of the material. Simultaneously, the load promotes the propagation of microcracks along weakened zones. The dependence of wood strength on temperature and humidity is shown in Fig. 1 (Koval and Trunina, 2024). A more complex aspect is that the dynamic combination of temperature, humidity, and load can activate microbial activity: at humidity >20 % and temperature 15-30 °C, brown rot fungi metabolize intensively, secreting cellulases that primarily destroy cell walls in loaded areas. Such biomechanical coupled degradation in hidden parts of historical buildings (e.g., column bases inside walls) often goes unnoticed until sudden loss of bearing capacity occurs (Varfolomeev, 2010; Samoilov, 1996).

Ancient timber structures, which operated for decades or even centuries, undergo degradation of their characteristics under the combined influence of temporal, environmental, and load factors. Traditional research has two main problems: firstly, the natural aging of materials occurs over extremely long periods, requiring prolonged monitoring and making it difficult to quickly assess

Thermal fluctuation regime depending on environmental factors

Influencing Factors	***Effect on Thermal Fluctuations***	***Manifestations of Wood Degradation***
Temperature increase	When kT rises, the probability of chemical bond breakage significantly increases	Accelerated creep, loss of strength
Humidity change	Water molecules penetrate hydrogen bonds, reducing the effective activation energy U_0	Stress change and chemical bond breakage, leading to cracking and rot of wood
Loading	Dynamic loads lead to local temperature increases, promoting chemical bond breakage	Development of fatigue cracks

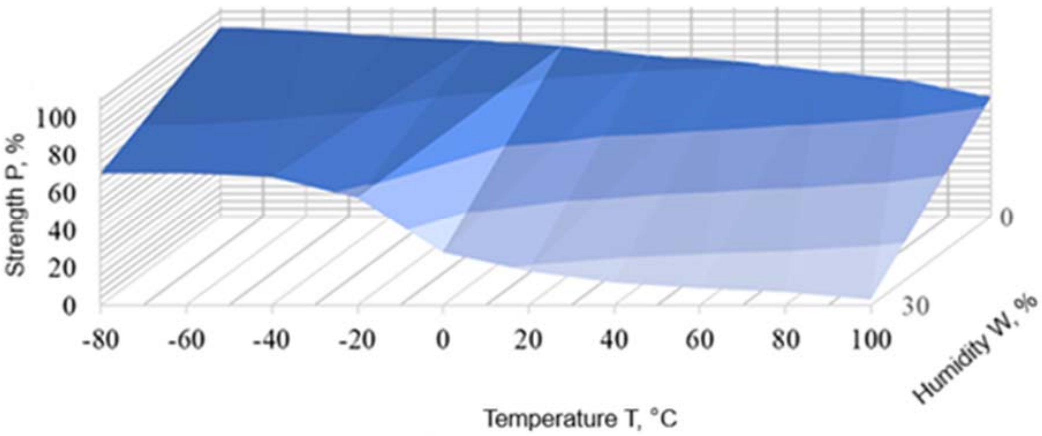

Fig. 1. Graph of the dependence of wood strength on temperature and humidity (Koval et al., 2024)

RBC; secondly, it is difficult to accurately assess the combined influence of temperature-humidity fluctuations (thermofluctuation mechanism) and biological damage during the long-term operation of historical elements, which directly affects their long-term strength indicators. Although linear loading allows rapid testing, the resulting “reduced time” is too short and does not reflect real long-term characteristics. Based on Zhurkov’s kinetic theory and the Yu.M. Ivanov model, P.S. Koval proposed an accelerated testing method under nonlinear loading (quadratic-parabolic loading) to determine the long-term strength of wood. The key idea is to apply slowly increasing stress, which increases the time to failure, effectively modeling the behavior of structural elements under long-term loading (Koval and Kushnir, 2024; Koval, 2024; Ivanov, 1972). This method combines Zhurkov’s fracture kinetics with nonlinear loading, expanding the experimental methodology for assessing long-term strength and significantly reducing testing time while increasing the practical value of the data. The thermofluctuation mechanism indicates that the reduction in material bearing capacity is the result of the combined impact of multiple factors. However, most modern loading tests control only one variable, making it difficult to model the combined influence of various factors during long-term operation. To investigate material strength under complex environmental impacts, it is necessary to combine new testing methods with theoretical advances in materials science (Chernykh et al., 2023).

Stress Redistribution under Combined Damage Modes

During the long-term service of ancient timber structures, damage to elements (such as mechanical defects, surface corrosion, internal rot, weakening of joint connections) leads to significant stress redistribution within the structural system, altering the original design stress state. The change in the stress state of elements not only accelerates the development of damaged zones (e.g., loss of stability of fibers in the compressed zone or crack growth in the tension zone) (GOST R 58033–2017) but can also cause a chain reaction in adjacent structural elements (Lourenço et al., 2013).

In the case of historical buildings, due to fiber delamination in timber structures, human activity during operation is more likely to cause section damage (Fig. 2) or fiber cracking due to temperature-humidity fluctuations (Fig. 3), directly reducing the strength, stiffness, and bending capacity of the structure. To assess the bearing capacity of such structures, the concept of effective cross-section is applied, representing the part of the original section capable of withstanding loads. The effective section accounts for degradation zones and excludes damaged areas. For square sections, the maximum permissible value for edge or end delamination is one-third, and for buildings with increased safety requirements, this value is reduced with the introduction of an additional deformation coefficient (Nocetti et al., 2021).

When mechanical damage (cracks, holes) or biological attack (fungi, insects) occurs in timber elements, leading to material heterogeneity, significant changes in their mechanical characteristics are observed. The natural anisotropy of wood is exacerbated by damage, creating high-stress zones where actual stresses significantly exceed nominal values. Simultaneously, the modulus of elasticity of the element decreases due to material failure, leading to increased deformations under the same loads. Uneven stiffness distribution causes force flow redistribution, increasing the load on undamaged areas. When cross-section

Fig. 2. Mechanical damage (Cabaleiro and Riveiro, 2016)

Fig. 3. Fiber cracks

asymmetry is caused by corrosion or damage, under bending conditions the neutral axis shifts towards the stronger part of the section (Fig. 4). This leads to increased deformations on the damaged side and premature attainment of ultimate strains. Axial loads in asymmetric sections create an additional bending moment, forming a combined stress state (tension-bending or compression-bending). Transverse loads on asymmetric sections can cause torsion, exacerbating the uneven distribution of shear stresses.

During the long-term operation of historical timber frame buildings, mechanical damage and biological erosion caused by changes in the cross-section of timber elements reduce the moment of inertia of the section and cause a sharp decrease in bending stiffness (EI). Long-term operation leads to the formation of irregular cross-sections, requiring modern non-destructive testing methods for accurate area measurement. During the initial survey of historical buildings, visual strength grading (VSG) is used to identify weakened sections. In cases where visual strength grading does not provide sufficient accuracy, standard design cross-sections are adopted. For timber beams, the nominal cross-sectional area is usually determined as the average value of areas at fixed intervals or the average value in the middle part of the span (Fig. 5) according to studies (Osuna-Sequera et al., 2020; Piazza and Riggio, 2008; UNE 56544). Modern assessment methods include laser scanning, allowing the acquisition of two-dimensional sections in computer representation (Cabaleiro and Riveiro, 2016), and for hidden structural elements, core drilling is used to assess the cross-sectional area (Cabaleiro and Branco, 2018).

For timber structures with irregular cross-sections, the moments of inertia about the x and y axes are determined by the following integral expressions:

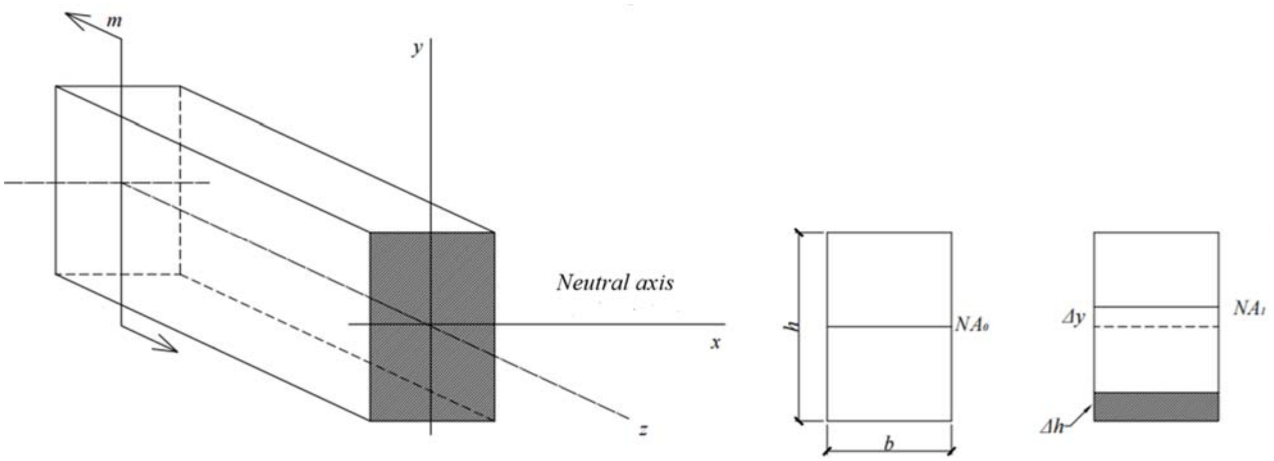

Fig. 4. Element damage leading to neutral axis shift (hatching indicates simplified damage)

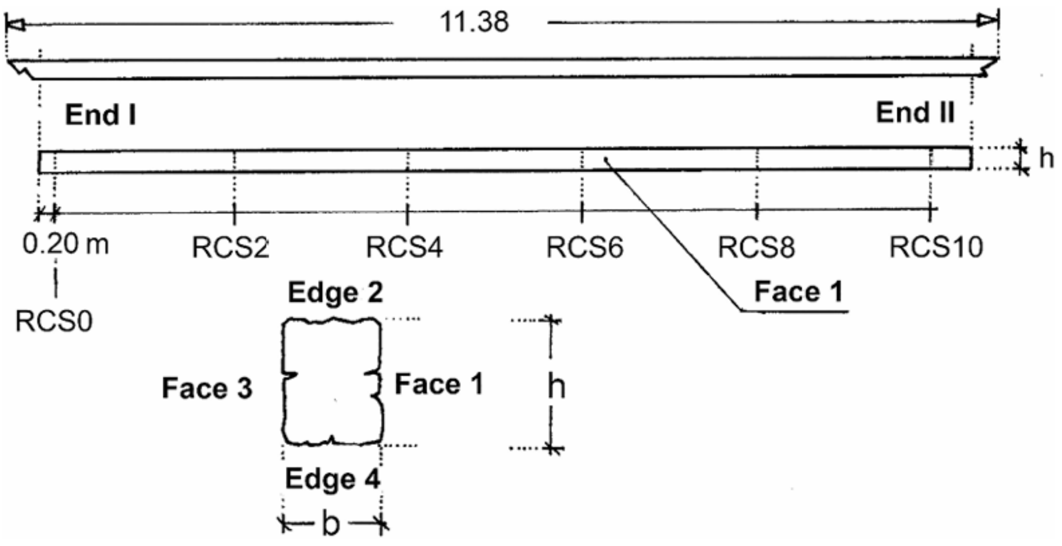

Fig. 5. Scheme for selecting the standard cross-section of a beam (Cabaleiro and Branco, 2018)

$$I_y = \int_A x^2 dA; \; I_x = \int_A y^2 dA;$$

$$I_x = \sum_{i=1}^{n} I_{xi} \quad I_y = \sum_{i=1}^{n} I_{yi} \quad I_{xy} = \sum_{i=1}^{n} I_{xyi}.$$

Laser scanning allows obtaining an accurate digital model of the beam cross-section as a point cloud that fully corresponds to the actual contours (Fig. 6). For calculation purposes, the obtained section is divided into many triangular elements. The cross-sectional area is determined as the sum of the areas of all formed triangles. The moment of inertia of the section is calculated sequentially: first, the moments of inertia of individual triangular elements are determined, then the total moment of inertia of the section is calculated using the Steiner parallel axis theorem. This technique ensures an accurate assessment of the RBC of aging elements of ancient timber structures.

Balancing Safety Requirements and Historical Heritage Preservation

The study of the RBC of ancient timber structures faces two fundamental difficulties. On the one hand, it is necessary to ensure compliance with modern reliability standards for building structures. On the other hand, it is extremely important to preserve authentic materials, historical manufacturing technologies, and the original spatial configuration of the architectural heritage. International principles for the protection of architectural monuments place special emphasis on the principle of minimal intervention. However, in real engineering practice, a contradiction inevitably arises between the requirements of ensuring structural safety and the need to preserve the historical and cultural value of the object (EN 17121, 2019).

When conducting research on the resource of bearing capacity of historical structures, specialists often face a lack of long-term strength data for structures that have been in operation for many centuries. Of particular interest in this regard is the timber structural system of the Church of the Nativity in Bethlehem (Fig. 7). The preserved timber elements of this unique structure include roof trusses reconstructed by Venetian masters at the end of the 15th century, as well as a system of cedar beams dating back to the era of Emperor Justinian (6th century). Throughout its history — in the 11th, 15th, and 19th centuries — the structure underwent multiple repairs and modernizations.

During the survey of the Church of the Nativity in Bethlehem in 2012, it was found that centuries of exposure to atmospheric precipitation and fungal attack led to a loss of up to 75 % of the cross-sectional area in certain timber structure areas. Long-term operation with stress concentration around natural wood defects reduced bending strength by 30–50 %. A comprehensive analysis, including on-site rapid assessment and laboratory studies, revealed that 14 % of the original oak and pine elements do not meet modern bearing capacity requirements and require priority strengthening or replacement (Macchioni et al., 2012). The preservation of architectural monuments requires a comprehensive approach combining structural safety with maximum preservation of the authenticity of building materials.

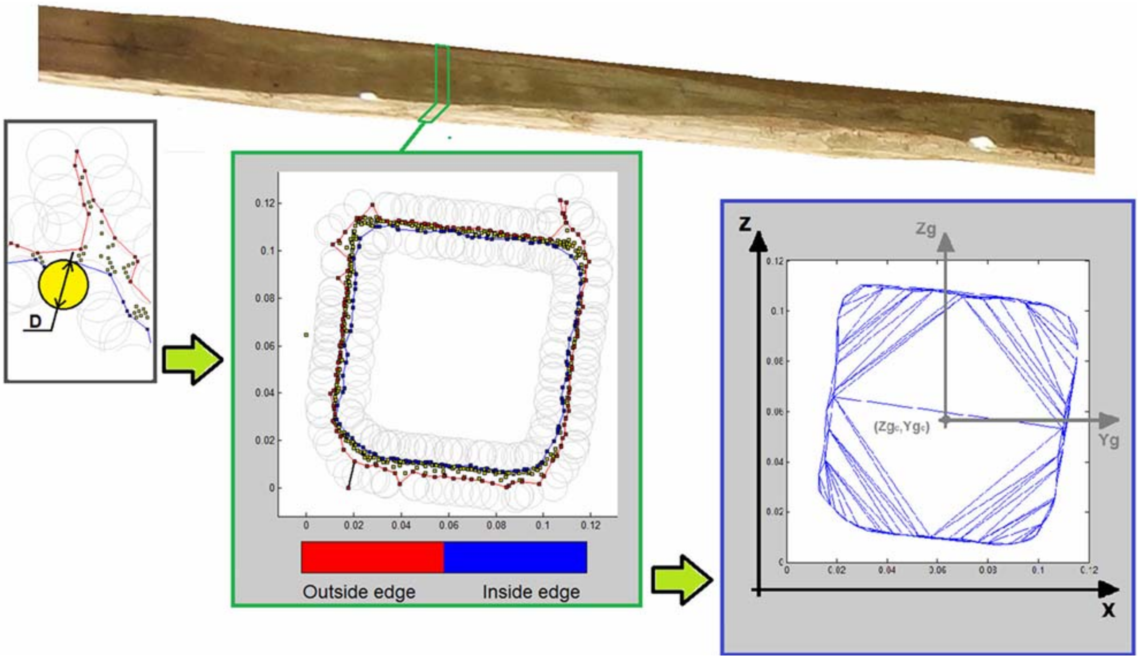

Fig. 6. Calculation of cross-sectional area and moment of inertia using the triangular segmentation method (Cabaleiro and Riveiro, 2016)

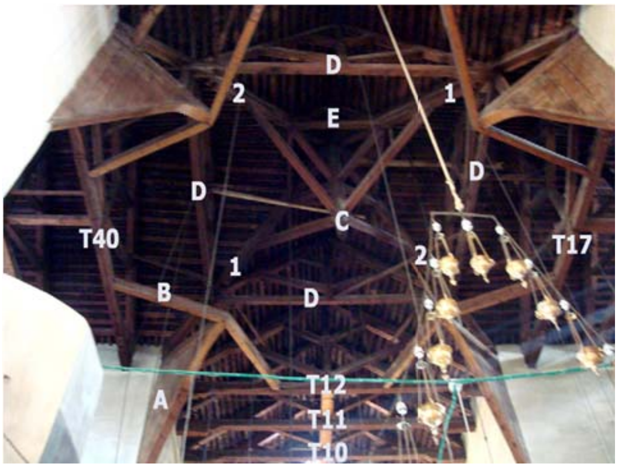

Fig 7. Star support system (Macchioni et al., 2012)

According to international restoration standards, special intervention criteria are established for historical timber structures. The replacement threshold for structural elements is set at 40 % of the original bearing capacity. For particularly valuable objects, this indicator may be adjusted to 40 %. In cases where the condition of elements exceeds this threshold, gentle conservation methods are applied, including treatment with epoxy compounds and antiseptic protection (ICOMOS; GOST R 55567-2013; GB 50165-2020; EN 16873:2016).

To protect historical buildings from natural disasters and municipal works, such as floods, landslides, or infrastructure projects, as well as to meet the needs of tourism and scientific research, it becomes necessary to relocate individual historical timber structures to special protection zones. This process requires a comprehensive interdisciplinary approach combining the principles of structural mechanics, materials science, and climatology. There are many well-known cases of historical building relocation, such as the complex of timber buildings on Kizhi Island, the Skansen Open-Air Museum in Sweden, and the complete relocation of the Yongle Palace in Shanxi, China (Gushchina et al., 2014; Rentzhog, 2007; Wang, 2005). The process of relocating timber structures includes several critically important aspects: careful dismantling and subsequent reassembly of structural elements, thorough analysis of the climatic conditions of the new location (temperature-humidity regime, snow loads), as well as prediction of possible foundation settlement. Special attention is paid to working with historical materials. Since original timber structures were often created without antiseptic treatment, accurate diagnostics of the internal condition of the material are necessary before dismantling. During transportation, it is essential to minimize possible damage. When replacing lost elements, material compatibility must be considered: matching wood species, coordinating shrinkage coefficients, and ensuring long-term stability of connections (Kisternaya, 2000; Tiunov and Shashkin, 2020).

Conclusions

Ancient timber structures, as an important part of cultural heritage, present a complex and difficult task in assessing and preserving their RBC. The heterogeneity of wood, the combined influence of environment and loads, biological degradation, and other factors make traditional assessment methods insufficiently accurate for predicting the long-term performance of structural elements. Research on this problem is significant not only for ensuring the structural stability of preserved historical buildings but also for providing a scientific basis for the sustainable preservation of cultural heritage. Traditional assessment methods are unable to fully reflect the degradation patterns of material properties during long-term operation, necessitating the use of modern non-destructive testing methods and interdisciplinary research to address this complex challenge.

The heterogeneity of wood is due to natural differences in species, defects, and fiber direction, leading to a scatter in strength characteristics. Research on the RBC of historical buildings requires an accurate assessment of the uneven accumulation of damage in old wood during long-term operation. When repairing and surveying historical buildings, it is necessary to fully consider the property differences between new and old wood, as well as their compatibility.

The loss of wood strength is mainly due to the thermofluctuation mechanism, temperature and humidity fluctuations, and biological degradation. Experimental studies show that increasing temperature and humidity significantly accelerates wood creep and fatigue crack growth, especially reducing its bending strength. Under high humidity conditions, the activity of fungi and insect pests increases, further exacerbating material degradation. Most existing experimental and prediction methods control only individual influencing factors, whereas testing methods under long-term loads considering the combined impact of multiple factors require further development.

When studying the RBC of ancient timber structures, the long-term accumulation of irregular damage leads to changes in the shape and cross-sectional area of elements. This directly affects the strength, stiffness, and bending characteristics of the structure, and also significantly alters the initial stress state of elements, causing additional bending moments and torsion not foreseen in the design, accelerating structural failure. Accurate identification and measurement of weakened cross-sections of elements is an important part of RBC research.

In conclusion, it should be emphasized that the study of the RBC of ancient timber structures is an important scientific direction with both fundamental and applied significance. This research not only allows understanding of the aging mechanisms of wood under the influence of long-term operational and environmental impacts but also creates a scientific basis for the preservation of architectural heritage monuments. Particular attention in future research should be paid to the comprehensive analysis of interrelated factors, including changes in the physical and mechanical characteristics of wood, geometric transformations of element cross-sections, and the associated redistribution of internal forces. Promising directions include the development of improved non-destructive testing methods and the advancement of computer modeling. Solving these problems requires the combined efforts of specialists from various fields of knowledge, which will allow finding an optimal balance between the requirements of structural reliability and the need to preserve the historical authenticity of architectural objects.

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ПРОБЛЕМЫ ОПРЕДЕЛЕНИЯ РЕСУРСА НЕСУЩЕЙ СПОСОБНОСТИ ЭЛЕМЕНТОВ ИСТОРИЧЕСКИХ ДЕРЕВЯННЫХ КОНСТРУКЦИЙ

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Аннотация
Введение: Ресурс несущей способности (РНС) деревянных конструкций исторических зданий и сооружений, срок эксплуатации которых составляет 100 и более лет, не может быть определен без учета их особенностей. В то же время эта проблема имеет важное теоретическое и практическое значение для оценки технического состояния, сохранения и реставрации объектов культурного наследия. **Цель работы:** систематизация научных данных о влиянии различных факторов на РНС элементов исторических деревянных конструкций. **Методы:** эксплуатационная несущая способность элементов деревянных конструкций главным образом определяется термофлуктуационным механизмом разрушения макромолекул целлюлозы («скелета» древесины), что приводит к деградации прочности, ползучестью, а также физическим износом. Оценка совокупного эффекта от воздействия данных факторов позволяет определять РНС конструкции. Кроме того, при длительных сроках эксплуатации сооружения необходимо дополнительно учитывать возможные изменения: климата, ландшафта местности, свойств защитно-декоративных покрытий, конструктивных и объемно-планировочных решений, пространственного положения, функционального назначения, статуса объекта как памятника, а также законодательной базы проектирования и реставрации. Уточненная оценка должна включать анализ влияния технологических особенностей возведения. **Результаты:** комплексный анализ показал необходимость совместного учета и взаимосвязей силовых и средовых воздействий, деформативных и прочностных свойств древесины, физического износа и дефектов, сложного характера напряженно-деформированного состояния элементов деревянных конструкций исторических зданий и сооружений для оценки их РНС, а также разработки стратегии обеспечения баланса между механической безопасностью и сохранением культурно-исторической ценности объектов.

Ключевые слова: ресурс несущей способности; исторические деревянные конструкции; длительная прочность; физический износ; геометрическая нелинейность; физическая нелинейность.