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Modeling the Influence of Bio-Deterioration on the Load-Bearing Capacity of Historical Buildings Wooden Structures

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Abstract: Historic buildings wooden structures are subject to bio-deterioration during operation. The main cause of bio-deterioration is the activity of wood-destroying fungi and insects. In the process of bio-deterioration, voids and inhomogeneities are formed in wood, which reduce the load-bearing capacity of historical buildings wooden structures, which is an urgent problem. The aim of the study is to analyze the changes in the load-bearing capacity of the elements of historical buildings wooden structures depending on bio-deterioration. To achieve the goal, the author used methods of physical and numerical modeling of material behavior in wooden structures with artificial bio-deterioration in the form of holes. The paper contains the results of testing of specimens and their finite element analysis. It is revealed that bio-deterioration of wooden structures elements in the form of voids and inhomogeneities reduces their load-bearing capacity. Thus, the load-bearing capacity of specimens with 8 holes decreased relative to specimens without holes by 38.69 %. The degree of degradation of load-bearing capacity depends on the size and localization of bio-deterioration. With the increase of bio-deterioration of elements of wooden structures, their load-bearing capacity decreases nonlinearly, which is reflected in the proposed model.

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1 INTRODUCTION

Historically, wood has been the main building material in many countries of the world, and construction from wood has become the most widespread in Russia. The reason for this is the abundance and availability of construction timber, its renewability, and the relative ease of wood processing. Wooden construction for many centuries had a mass character, wood was used to build dwellings, temples, fortress walls, towers, bridges and embankments [Bode, 2019; Švajlenka, 2022]. Many historical buildings and structures made of wood that have survived to the present day have an important cultural significance and are classified as architectural monuments.

Elements of historical buildings wooden structures are exposed to bio-deterioration during operation. The main cause of bio-deterioration is the activity of wood-destroying fungi and insects [Martín, 2023; van Niekerk, 2021; Zabel, 2020]. In the process of bio-deterioration, voids and inhomogeneities are formed in wood, which reduce the load-bearing capacity of elements of historical buildings wooden structures, which is an urgent problem that needs to be solved.

A number of authors [dos Reis, 2022; Su, 2024; Curling, 2002; Arantes, 2014; Kononov, 2020; Verbist, 2020; Degl'Innocenti, 2022; Brunetti, 2024] have devoted their works to the issues of changes in the load-bearing capacity of wooden structures elements. Thus, [dos Reis, 2022] considers the loss of strength of wood from trees due to rotting or cavities in their trunks using tomographic imaging data in combination with known equations; [Su, 2024] describes a laboratory study of changes in the strength characteristics of samples of straight tongue-and-groove joints of wooden buildings incubated with fungi that cause wood rot; papers [Curling, 2002; Arantes, 2014] study the effect of brown rot on the composition of hemicellulose and the relationship between brown rot and mechanical properties of wood; paper [Kononov, 2020] describes the results of the study of changes in the mechanical properties of wood affected by white rot; paper [Verbist, 2020] presents the results of laboratory compression tests of wood samples damaged by wood-destroying insects; papers [Degl'Innocenti, 2022; Brunetti, 2024] assess the impact of biodegradation of wood of historical buildings under the influence of insects on its load-bearing capacity.

In most of the existing studies on the influence of bio-deterioration on the strength characteristics of elements of wooden structures, the differentiation of types of bio-deterioration agents, tree species and natural and climatic conditions is strictly traced. This differentiation does not allow building a general model of the process of bio-deterioration of elements of historic buildings wooden structures and changes in their load-bearing capacity, which is a significant problem for the development of universal approaches to calculating, modeling and predicting the load-bearing capacity of wooden structures elements in the process of their bio-deterioration. The solution of this problem is possible through an integrated approach in the study of the influence of bio-deterioration on the load-bearing capacity of wooden structures elements, including the construction of a model with a shift of focus from the causes and conditions of bio-deterioration to the magnitude and geometric characteristics of bio-deterioration of wooden structures elements. Therefore, the purpose of this study is to analyze the change in the load-bearing capacity of the elements of historical buildings wooden structures depending on bio-deterioration.

2 MATERIALS AND METHODS

2.1 Experiment

To study the influence of bio-deterioration on the load-bearing capacity of elements of historical buildings wooden structures, specimens of *Pinus sylvestris* wood were made in the form of rectangular parallelepipeds with dimensions 40×40×40 mm with holes located across the wood fibers, 4.5 mm in diameter, simulating bio-deterioration. The number of holes varied from 0 to 8 pieces. The testing procedure followed the requirements specified in the international standard (ISO 13061-1:2014). The specimens were compressed along the fibers of the wood. The mechanical properties if the samples were tested using an electronic universal mechanical testing machine Shimadzu AGX300 controlled by a microcomputer (see Fig. 1).

Figure 1: Wood property test process.

2.2 Modelling

Modeling of the influence of bio-deterioration on the load-bearing capacity of the elements of historical buildings wooden structures was carried out by means of finite element analysis. The elements of historical buildings wooden structures were modeled using a threedimensional solid element. The wood was simplified as an orthotropic material, allowing for consideration of its perpendicular properties in the radial, rotational, and transverse directions. The models took the form of rectangular parallelepipeds with dimensions 40×40×40 mm with holes of 4.5 mm diameter located across the wood fibers. The number of holes varied from 0 to 8 (see Fig. 2).

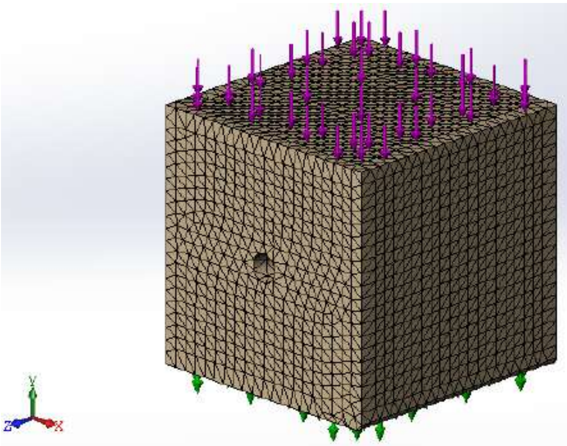
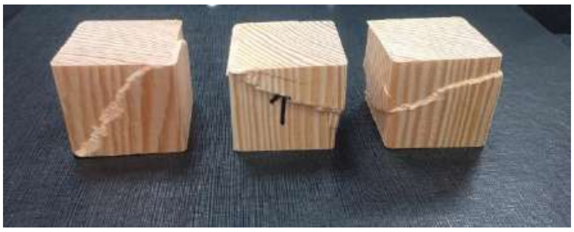


Figure 2: Finite element model.

The compressive load was directed along the wood fibers.

3 RESULTS AND DISCUSSION

During the tests, the specimens were loaded until they cracked at a controlled displacement rate of 10 mm/min (see Fig. 3).



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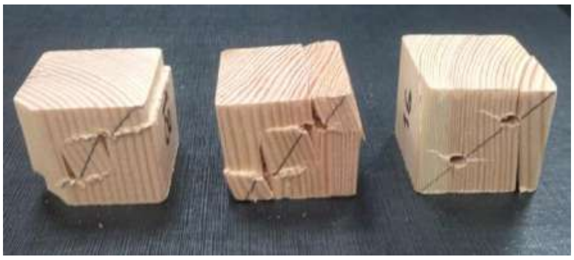
b



c

d

e

Figure 3: Specimens after testing:
a – without holes, b – with one hole, c – with two holes, d – with four holes, e – with eight holes.

Load (F)-displacement (u) curves were obtained for each sample (see Fig. 4).

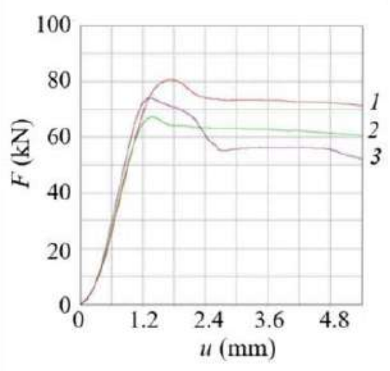


Figure 4: Experimental load-displacement curves for specimens.

The author processed the experimental load-displacement curves obtained for each specimen and determined the load-bearing capacity values of specimens with different number of holes (Table 1).

Table 1: Variation of load-bearing capacity of specimens depending on the number of holes.

Number of holes, pcs.	Load-bearing capacity, kN
0	84.171
1	75.917
2	64.975
4	61.502
8	51.605

Based on the obtained data, the regularity of change of load-bearing capacity F_{max} of specimens depending on the number of holes n can be described by the model (1):

$$F_{max} = 0.54 \cdot n^2 - 8.23 \cdot n + 83.08, \quad R^2 = 0.96. \tag{1}$$

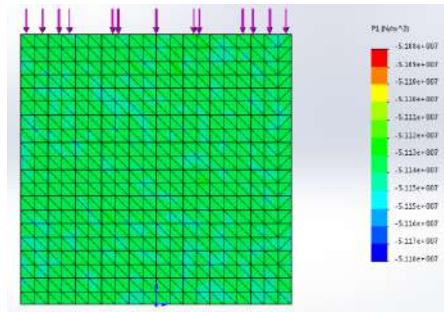
The data presented in Table 1 and the proposed model (1) show that with the increase in the number of holes the load-bearing capacity of the specimens decreases. Thus, the load-bearing capacity of specimens with 8 holes decreased relative to specimens without holes by 38.69 % from 84.171 to 51.605 kN.

As can be seen from Fig. 3, the failure of specimens without holes occurred due to the shear of wood fibers at an angle close to 45°. It is known that the greatest tangential stresses occur at an angle of 45°. Therefore, the cause of failure of the specimens is the excess of the highest tangential stresses over the allowable stresses, which corresponds to the theory of the highest tangential stresses.

The failure of specimens with holes occurred due to the occurrence of transverse cracks in the areas concentrated near the holes, i.e. at an angle of 0°. It is known that at an angle of 0° the highest normal stresses occur. This fracture pattern is characteristic when the highest normal stresses exceed the allowable stresses, which corresponds to the theory of the highest normal stresses.

In this regard, it can be assumed that the appearance of holes in the specimens changes the character of the distribution of normal and tangential stresses, and the holes in the specimens are stress concentrators.

The nature of stress distribution in specimens without and with holes was determined by finite element analysis of their models. Fig. 5 and Fig. 6 show the first principal normal and tangential stress distribution diagrams of the specimen models.



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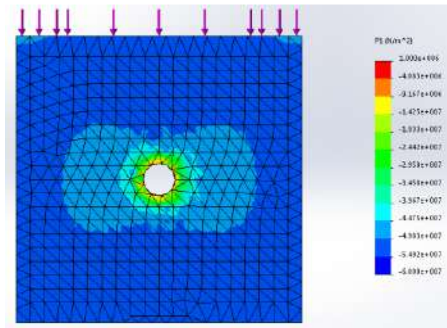

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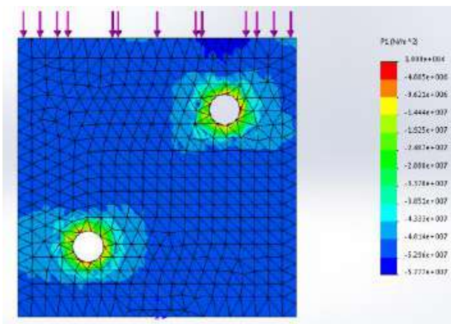

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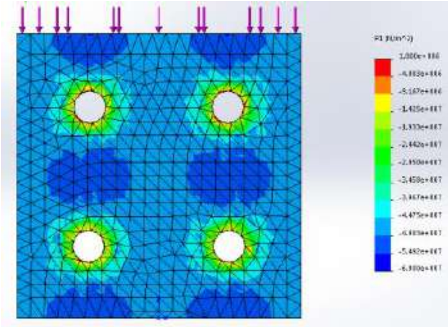

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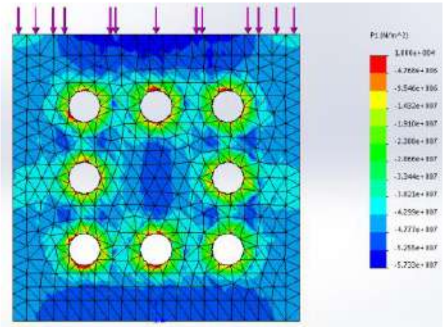

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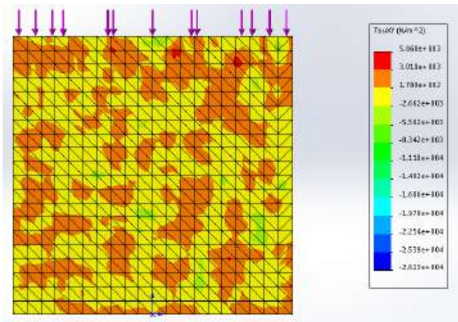
Figure 5: Stress nephogram of specimen (principal stresses): a – without holes, b – with one hole, c – with two holes, d – with four holes, e – with eight holes.



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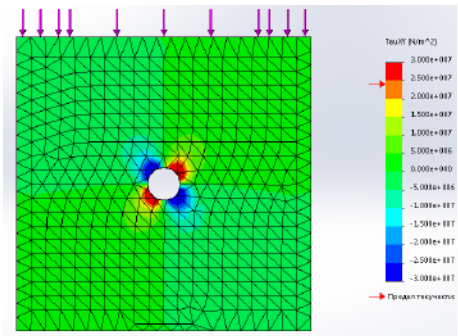

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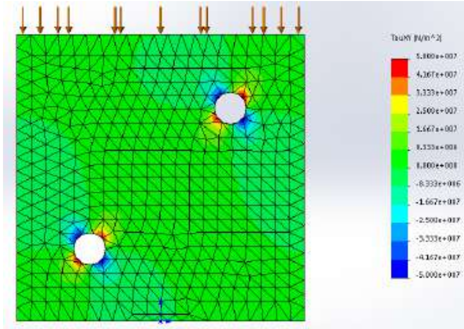

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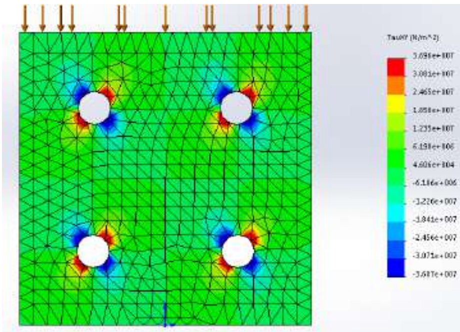

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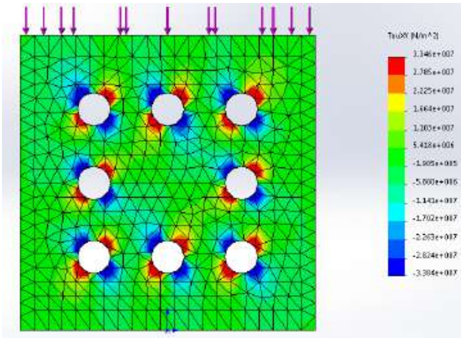

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Figure 6: Stress nephogram of specimen (tangential stresses): a – without holes, b – with one hole, c – with two holes, d – with four holes, e – with eight holes.

As can be seen from Fig. 5, in the model of specimens without holes, compressive stresses occur at any point of the material. In the specimen models with holes, compressive stresses occur at most points in the material, but the points localized in the areas above and below the holes have the highest tensile stresses. These tensile stresses lead to the detachment of material particles and the appearance of transverse cracks.

Fig. 6 shows that in the model of specimens without holes, the positive and negative tangential stresses are distributed uniformly throughout the material volume. In the models of specimens with holes, the highest positive and negative tangential stresses are observed in the points localized in the areas near the holes, directed perpendicularly to each other, which corresponds to the law of pairing of tangential stresses.

Regarding possible directions for future research, we note that the adaptation of the methodology [Shekov, 2024; Kolesnikov, 2022; Gavrilov, 2020] to the analysis of the above-mentioned cracks may be appropriate.

4 CONCLUSIONS

In the course of the study it was revealed that bio-deterioration of elements of historical buildings wooden structures in the form of voids and inhomogeneities reduces their load-bearing capacity. Moreover, the degree of degradation of load-bearing capacity depends on the size and localization of bio-deterioration. With the increase of bio-deterioration of wooden structures elements their load-bearing capacity decreases nonlinearly in accordance with the model (1).

When the load-bearing capacity of the wooden structures elements with bio-deterioration is exhausted, transverse cracks appear in them.

Cracks are formed in the vicinity of the bio-deterioration, this means that bio-deterioration play the role of stress concentrators, which is consistent with existing studies [Barashkov, 2017; Ratkova, 2023].

In the areas above and below the holes, the highest tensile stresses occur, exceeding the permissible stresses and leading to the tearing off of particles of wooden structural elements.

The presented model of changes in the load-bearing capacity of elements of historical buildings wooden structures depending on changes in the magnitude and localization of bio-deterioration can be used as an additional tool in determining the load-bearing capacity of historical buildings wooden structures within the framework of justification of decisions on their restoration and conservation.

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