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Visualization of Deformation and Stress Waves in Wooden Solid and Glued Elements of Building Structures.

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Abstract

The basis of the research hypothesis is the assumption that in wooden structures, deformations and stresses propagate in waves. The numerical experiment demonstrated a correct qualitative visual picture of the wave propagation of deformations, with wave manifestations and characteristic effects on the surface of the sample, at axial and corner points. Visually, the numerical model showed Rayleigh waves on the surface layer of the sample, depending on the ratio of the external geometric dimensions of the sample model, with pronounced wave interference on the outer shell. The visual manifestation of deformation on the outer sides (faces) and the reflection of deformation waves from the outer boundaries of the elastic medium of the sample in the form of Rayleigh waves confirm the correctness of the general hypothesis and the implemented model. Visualization of the process of emergence, propagation and attenuation of deformation waves on the surface of the sample shows that in the quantitative description of the deformation gradient, areas dangerous for the material can be identified.

Keywords: wood and wooden structures, visualization of stress and deformations waves, Rayleigh waves, gradients of deformations and stress.

1. Introduction

The processes of occurrence and propagation of stresses and strains under loading of solid physical bodies take a certain time. When testing building materials and elements of building structures, due to the lack of technical ability to visually observe and describe a continuous process, test methods have been adopted based on a discrete, phased application of a test load with the necessary endurance after each stage of loading. Fixing and recording the indicators of measuring equipment and instruments, as a rule, are also carried out in stages.

If we proceed from the fact that the strain propagation rates in solids are quite high, comparable with such a physical property of solids as the speed of sound propagation in the material, then the application rates of external test loads are relatively low, comparable to or exceed thousandths of the strain propagation velocity. The time duration of the application of the load is much greater than the time of occurrence, propagation and attenuation of the resulting deformations in the physical body. In turn, the deformations propagate at a very high, but with a finite speed, in the volume of the test sample, the emergence and stabilization of a new stress-strain state does not occur instantly.

The basis of the research hypothesis is the assumption that in wooden structures, deformations and stresses propagate in waves. The emergence, propagation and attenuation of strain waves, respectively, and stresses, occur as physical processes of propagation of longitudinal strain waves in the volume of an array of wooden structures, and propagation of transverse strain waves on the surface of structures.

2. Choice of approach and mathematical model

The authors, at the North-Eastern Federal University named after M.K. Ammosov (Yakutsk), theoretical models of the propagation of strain and stress waves in wood, solid wood and glued wood elements of building structures were developed and implemented in several numerical experiments.

As part of the specification of the main hypothesis of wave propagation of strains and stresses, models of the propagation of single transverse strain waves on the surface of bodies with boundary conditions in the form of loading areas and a section of a sample were analyzed when solving a plane problem [1–3]. Considered models of wave-like deformation are the basis for the visual representation of the analyzed physical processes.

The problem of numerical modeling of an all-wood sample with idealized anisotropy of elastic properties as a medium for the propagation of elastic waves of deformations and stresses is solved. Calculations were performed by the finite element method for spatial approximation and by the finite difference method for discrediting in time. The defining conditions of the problem were taken to be the physical properties of wood, such as elastic characteristics, the velocity of propagation of the strain wave, and geometric indicators, such as the length of the sample (finite or infinite), transverse dimensions specified relative to the median plane. The elastic parameters of wood were taken according to E.K. Ashkenazi [4], the orthotropic structure of the model sample was specified in a cylindrical coordinate system.

For calculations in the Cartesian coordinate system, the elastic parameters of wood were transformed based on the corresponding transition matrix. The numerical experiment demonstrated a correct qualitative visual picture of the wave propagation of deformations, with wave manifestations and characteristic effects on the surface of the sample, at axial and corner points. Visually, the numerical model showed Rayleigh waves on the surface layer of the sample, depending on the ratio of the external geometric dimensions of the sample model, with pronounced wave interference on the outer shell. The visual manifestation of deformation on the outer sides (faces) and the reflection of deformation waves from the outer boundaries of the elastic medium of the sample in the form of Rayleigh waves confirm the correctness of the general hypothesis and the implemented model. Visualization of the process of emergence, propagation and attenuation of deformation waves on the surface of the sample shows that in the quantitative description of the deformation gradient, areas dangerous for the material can be identified [5]. In subsequent tasks of the hypothesis, it is necessary to establish the correct relationship between the visual qualitative picture of deformation and the quantitative assessment of stresses in the considered wave processes, based on the use of real attenuation coefficients of wave processes obtained in full-scale vibration experiments.

In the development of this problem, a model of the process of resistance of a wooden cross-glued panel (the so-called CLT-panel, Cross-Laminated Timber) was calculated [6-8]. A breakdown into solid tetrahedra is adopted, with the corresponding number of common points of their vertices, according to the accepted breakdown.

The model provides for the application of a load distributed along the panel, which excites a single wave with one pulse. The load is distributed in the form of a triangle, the load value increases from left to right, the maximum value is at the right edge of the panel. The load simulates a transient load applied vertically from the bottom up. The panel support along the upper face is continuous. The described computational numerical model is implemented in a certain range of physical and mechanical characteristics and geometric dimensions of wooden CLT panels (Fig. 1).

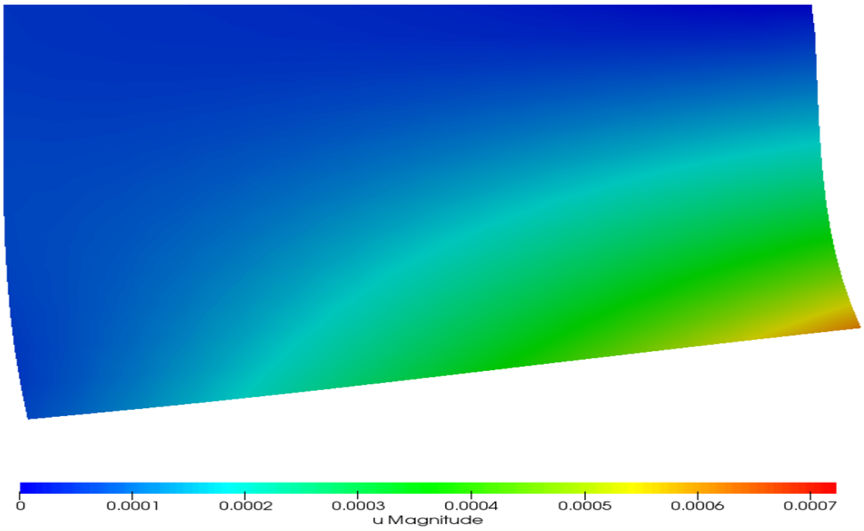

Fig. 1. Visualization of deformation of the sample model at t = 0,50 milliseconds (ms).

The following numerical experiment also describes the resistance process of the CLT-panel when a shear force is applied. Panel dimensions are accepted: length 2000 mm, width (height) 1000 mm, thickness 175 mm. The panel consists of 7 layers of pine wood boards, 25 mm thick, glued crosswise. The volume of the panel is divided into 293360 vertices and 1516873 elements - individual tetrahedra with common adjacent faces.

The short-term load (sudden) is applied to a platform 175 mm wide, in the corner of the panel, and is directed parallel to the long side of the panel. The load increases linearly for 1 ms, after which it is released. The support is organized in a similar way, that is, the panel rests diagonally to the site of application of the external load. The support also has a width of 175 mm. The design scheme is shown in Fig. 2.

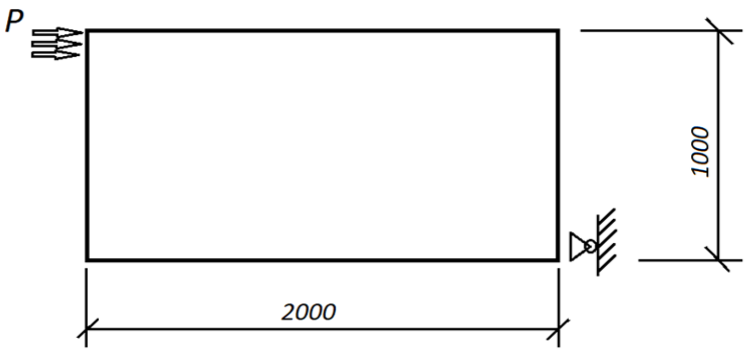

Fig. 2. Loading the CLT-panel with a shear force.

The shear force, within the considered time period from zero to 200 milliseconds, causes a process of continuous deformation, which is visualized with minimal time steps specified by the experimental conditions. The time steps are set, as a rule, tolerably small to optimize the total time for solving the problem. For visual comparison and analysis of an array of images, the researcher has the ability to select visual images based on the need to obtain a sufficient visual difference between images of the position in space of the locus of tangential strain tensors.

The calculations were carried out using finite element methods for spatial approximation and finite difference methods for time discretization. The numerical implementation was performed on a freely distributed open source computing platform FeniCS [9-11].

FEniCS is a free and open-source computing platform in the C++ and Python programming languages for the numerical solution of partial differential equations using the finite element method. The problem statement for FEniCS is initialized personally by the user in the form of a variational formulation of partial differential equations describing the phenomenon, while the construction of a finite element basis and translation into systems of linear algebraic equations (SLAE) is carried out automatically. To solve the resulting SLAE, FEniCS has a fairly large selection of preconditioners and solvers.

When working in C++, a convenient FFC compiler (FEniCS form compiler), which creates header files for integration into the main program from a variational formulation from ufl code. The convenience lies in writing the equation in a form similar to the analytical one. When working in Python, equations are initialized in the main code. The main program for the numerical implementation of finite elements in FEniCS in the C++ programming language consists of the following parts: initialization of the finished mesh, setting function spaces, boundary conditions, linear and bilinear forms, solving the SLAE and saving the results.

The movement of an elastic wave along a wooden sample is described by a non-stationary elasticity equation, which consists in the condition of conservation of linear momentum:

$$\nabla \cdot \boldsymbol{\sigma} + \rho \boldsymbol{b} = \rho \ddot{\boldsymbol{u}}, \tag{1}$$

where $\boldsymbol{u}$ is the displacement field vector, $\ddot{\boldsymbol{u}} = \partial^2 \boldsymbol{u}/\partial t^2$ is the acceleration, ρ is the density of the material, $\boldsymbol{b}$ is the given body force, and $\boldsymbol{\sigma}$ is the stress tensor, which is related to the displacement by means of the generalized Hooke's law for an anisotropic body:

$$\boldsymbol{\sigma} = \boldsymbol{C} : \boldsymbol{\varepsilon},$$

where $\boldsymbol{\varepsilon} = (\nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^T)/2$ is the linearized strain tensor, $\boldsymbol{C}$ is the fourth-rank elasticity tensor, which in our timber approximation can be described in terms of the Voigt notation for an orthotropic body in the form:

$$C = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{21} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{31} & C_{32} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix},$$

where the coefficients are given as

$$C_{11} = \frac{1 - \mu_{at}\mu_{ta}}{\Delta E_t E_a}, C_{22} = \frac{1 - \mu_{ar}\mu_{ra}}{\Delta E_r E_a}, C_{33} = \frac{1 - \mu_{rt}\mu_{tr}}{\Delta E_r E_t},$$

$$C_{12} = C_{21} = \frac{\mu_{tr} + \mu_{ar}\mu_{ta}}{\Delta E_t E_a}, C_{13} = C_{31} = \frac{\mu_{ar} + \mu_{tr}\mu_{at}}{\Delta E_t E_a}, C_{23} = C_{32} = \frac{\mu_{at} + \mu_{rt}\mu_{ar}}{\Delta E_r E_a},$$

$$C_{44} = G_{rt}, C_{55} = G_{ra}, C_{66} = G_{ta},$$

$$\Delta = \frac{1 - \mu_{rt}\mu_{tr} - \mu_{ra}\mu_{ar} - \mu_{ta}\mu_{at} - 2\mu_{tr}\mu_{at}\mu_{ra}}{E_r E_t E_a},$$

Due to the symmetry of the problem (the wooden sample is symmetrical, with idealized anisotropy), the solution was carried out on a quarter of the sample. Equation (1) is supplemented with boundary conditions responsible for the absence of transverse deformations on the symmetry planes. The initial deformed state is to assume the initial conditional deformation in Δx at time t = 0.

To obtain a variational formulation, we use integration by parts using the test function $v \in \boldsymbol{V}$, where $\boldsymbol{V}$ is the space of test functions that satisfies the boundary conditions for displacements:

$$\int_\Omega \rho \boldsymbol{u} \cdot \boldsymbol{v}\, dx + \int_\Omega \boldsymbol{\sigma}(\boldsymbol{u}) : \boldsymbol{\varepsilon}(\boldsymbol{v})\, dx = \int_\Omega \rho \boldsymbol{b} \cdot \boldsymbol{v}\, dx + \int_{\partial\Omega} (\boldsymbol{\sigma} \cdot \boldsymbol{n}) \cdot \boldsymbol{v}\, ds \text{ for all } \boldsymbol{v} \in \boldsymbol{V}.$$

The previous equation can be rewritten as:

$$\text{Find } \boldsymbol{u} \in \boldsymbol{V} \text{ such that } m(\ddot{\boldsymbol{u}}, \boldsymbol{v}) + k(\boldsymbol{u}, \boldsymbol{v}) = L(\boldsymbol{v}) \text{ for all } \boldsymbol{v} \in \boldsymbol{V}.$$

where m is the symmetric bilinear form associated with the mass matrix, and k is the form associated with the stiffness matrix.

We also add dissipation to the variational form, as a term proportional to $\dot{\boldsymbol{u}}$:

$$\text{Find } \boldsymbol{u} \in \boldsymbol{V} \text{ such that } m(\ddot{\boldsymbol{u}}, \boldsymbol{v}) + d(\dot{\boldsymbol{u}}, \boldsymbol{v}) + k(\boldsymbol{u}, \boldsymbol{v}) = L(\boldsymbol{v}) \text{ for all } \boldsymbol{v} \in \boldsymbol{V}.$$

The dissipative term can be considered bilinear and symmetric.

Post-processing was done with ParaView [12, 13]. Based on the vtk library [14, 15], ParaView is a software with a clear graphical interface and a powerful toolkit for building the necessary graphs, animated video files and presenting the distribution of the solution on the computational domain.

Paraview is an open source multi-platform data analysis and visualization application. Paraview uses the VTK (Visualization Toolkit) as a tool for rendering images and for data processing. Paraview's user interface is written using the Qt environment [16].

Qt is a framework for creating programs based on the C++ programming language, Python. Among the advantages of Qt are convenient libraries and an application programming interface.

Visualization Toolkit (VTK) is a free and open source software system for creating 3D computer graphics, modeling, image processing, volumetric rendering, 2D plotting and most importantly, scientific visualization. Based on VTK, you can create your own visualizer of calculation results with the ability to process images using various useful filters. In our case, filters were used to visualize isosurfaces.

When developing a problem hypothesis, the conditions are:

- the magnitude and nature of the applied external load;
- the duration of the application of the load (impulse), from the minimum possible to the maximum allowable, determined by the speed of wave propagation and the size of the sample under consideration (time, and period - wavelength);
- for a numerical experiment, if it is necessary to compare with a full-scale experiment, restrictions may be dictated by the technical capabilities of the test bench, power or measuring equipment, climatic or other conditions;
- certain restrictions can be introduced by software, characteristics of computers or computer programs, computer time resource (for example, breaking down the simulated structures into too small finite elements dramatically increases their number and, in turn, increases the time for solving problems).

The color scale for visual assessment of stress strains is adopted in the range from blue to red, which corresponds to values from 0.3 to 3 MPa for stresses, and 0 to 5 mm for strains (Fig. 3).

Next, the task was formulated to represent a solid continuous body simulating the structure of a wooden glued CLT-panel, which is also loaded according to the design scheme in Fig. 2.

Visualization of the results of a numerical experiment made it possible to see a detailed picture of the stress distribution according to a given scale (Fig. 4-6). As can be seen from the figures below, part of the physical volume of the model is not identified (there are "voids" and other discontinuities of the body). This circumstance is explained by the fact that in places of "emptiness" stresses have an intermediate value between the levels of a given breakdown of the numerical value of the scale. In turn, high stresses exceeding the maximum numerical value of the scale specified by the boundary condition (red color) turned out to be less than the actual maximum stresses according to the numerical experiment, and “emptiness” is also represented at these points of the model volume. In a numerical experiment, researchers have the opportunity to observe the emergence and propagation of stress waves, reflection from the edge of a given space, complex processes of interaction of reflected stress waves as a single continuous physical process. A qualitative and quantitative continuous wave pattern of stresses shows areas of the model volume where stress and strain waves arise and move. Stress gradients are visualized; visualization of strain gradients is possible.

In general, such an approach to a numerical experiment makes it possible, by varying the ratio of the initial and final values of the specified stress scale in a wide range, to obtain various visual and quantitative representations of wave processes in structural models. It is possible to visualize and quantify stress waves in almost any narrow or wide range of values.

It is possible to divide the stress values expected in a numerical experiment into arbitrarily narrow intervals and separately track these processes in numerical models.

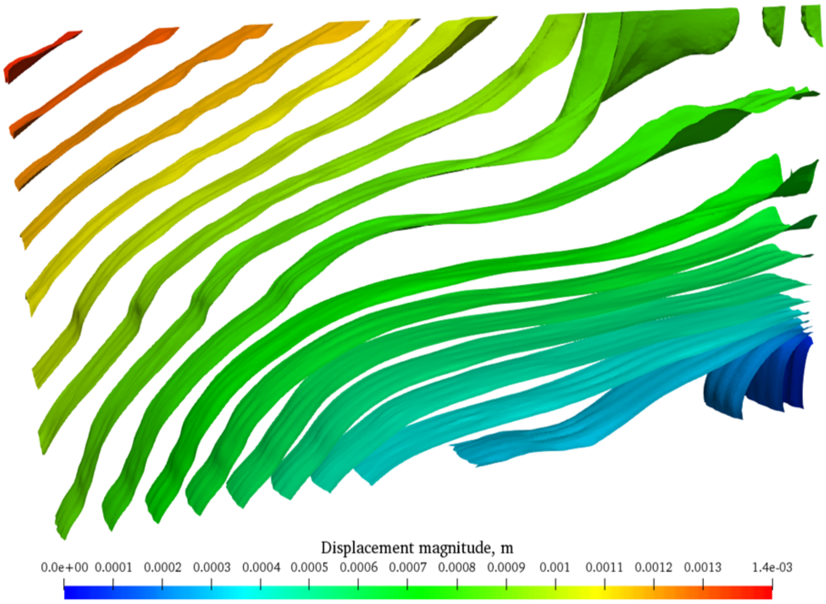

Fig. 3. CLT - panel. Axonometric image of surfaces with the same values of the strain vector, at t=2 milliseconds. The color scale of deformations visualizes gradual distribution of deformations in the volume of the sample.

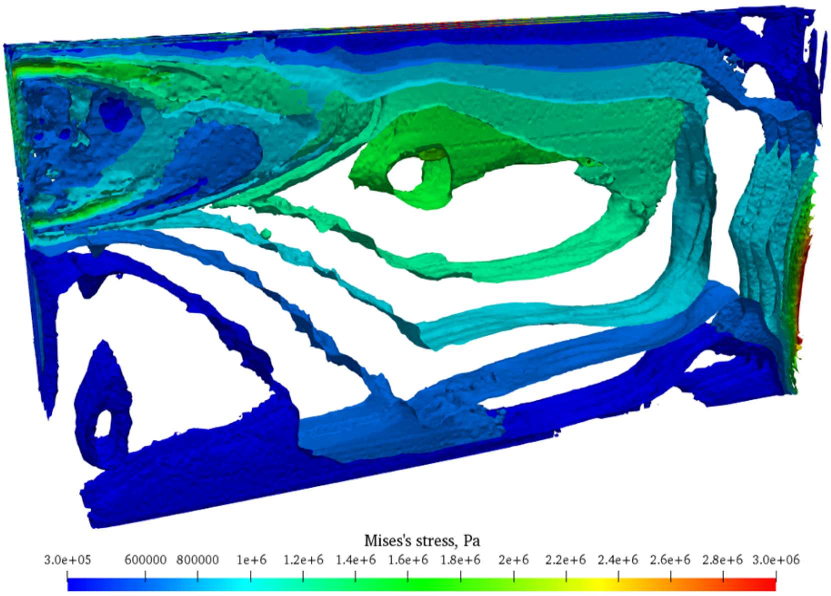

Fig. 4. CLT panel. Visualization of stresses at the beginning of shear, t=1,2 ms .

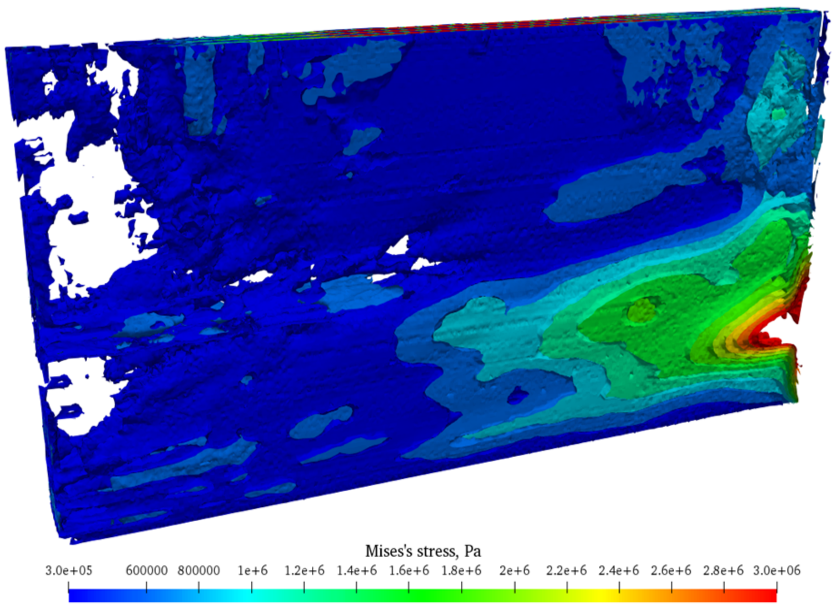

Fig. 5. CLT panel. Visualization of shear stresses. The formation of the reflected wave, the beginning of the backward movement of the reflected wave. t=2 ms.

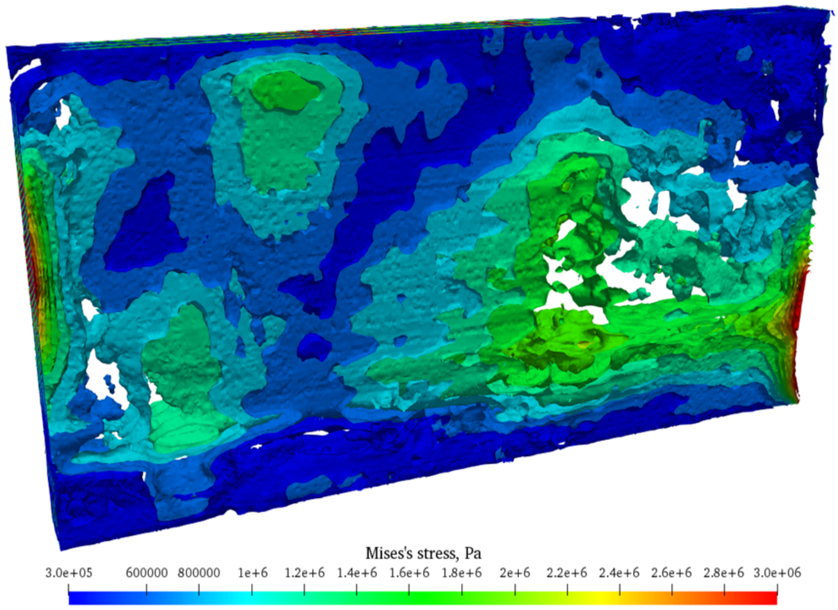

Fig. 6. CLT panel. Visualization of shear stresses. t=5 ms .

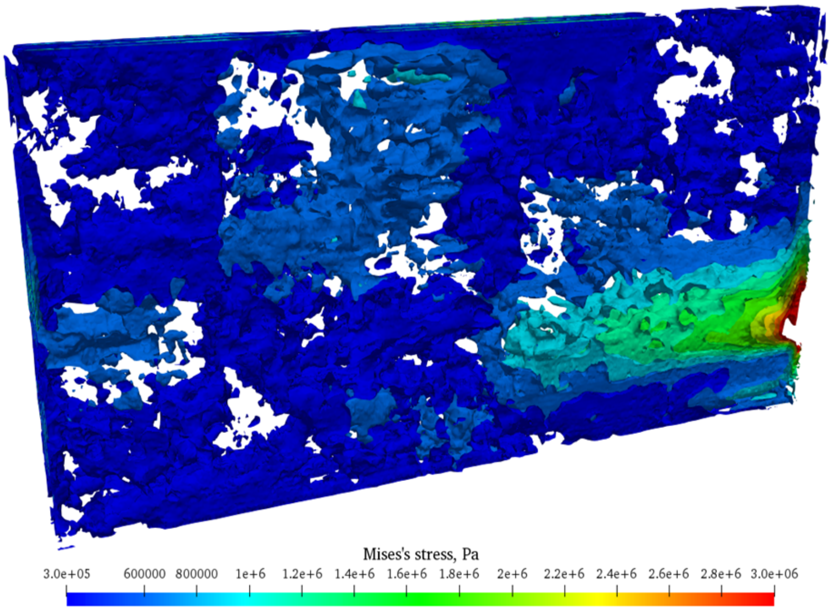

Fig. 7. CLT panel. Visualization of shear stresses. Attenuation of stress waves, t = 20 ms.

Conclusions

The article gives a consistent description of the modeling of the elastic properties of the material - solid and glued wood. As a result of numerical experiments, the main research hypothesis was confirmed - that in wooden structures, deformations and stresses propagate in waves. The emergence, propagation and attenuation of strain waves, respectively, and stresses, occur as physical processes of propagation of longitudinal strain waves in the volume of an array of wooden structures, and propagation of transverse strain waves on the surface of structures. For the first time, wave processes of propagation of strains and stresses have been identified and visualized, and qualitative patterns of changes in the volume of the studied wooden surface samples with the same values of strain vectors and stresses are especially indicative.

We noted that wave manifestations of deformations, as a result of the resistance of the sample material, after the application of an external test load, in the future, it is possible to fix using appropriate equipment [5-8]. High-speed special video recording, combined with the visualization of the numerical description of wave deformations on the surface of the samples, will allow a deeper understanding of the physical picture of the deformation of a complex system, such as glued wood. Naturally, the most characteristic picture of the visualization of these wave manifestations throughout the entirety and spectrum of wave characteristics will be presented on the surfaces of large-sized planar structures, such as CLT panels.

The obtained visualization results are the correct physical basis for further improvement of the research hypothesis in order to obtain correct quantitative results, with the refinement of the initial data and boundary conditions by natural experiments.

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