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NUMERICAL SIMULATION OF ELASTIC WAVE PROPAGATION IN WOOD WITH DEFINED TREE RINGS

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ABSTRACT

The objective of the study was to perform a finite element (FE) simulation of elastic wave (EW) propagation in wood (*Picea abies spp.*). Based on measuring of tree rings width a FE model of wood with defined tree rings, substituted as an ideal annulus, was created. FE model was loaded to force impulse at different positions via the specimen length. Subsequently a propagation and travel time of the EW through a material was observed. FE simulations were compared to the experimental ones acquired by different non-destructive acoustical tools (ADD, Geotron, FAKOPP and TICO). Results say that the FE model preserves trend of velocities of EW obtained from experiments, although comparing to them it embodies lower EW velocities in general. Relative difference of FE model towards experimental average is 20 %. Presented simulation of EW propagation can be supposed as a relatively accurate, but to achieve higher agreement with experiments, it needs to be optimized in terms of its material properties.

KEY WORDS: elastic wave propagation, numerical simulation, tree ring, experimental measurement

INTRODUCTION

Wood is anisotropic material with high level of variability of properties, not only between different species but also within one species whose members grow in differing conditions (altitude, position in the stand, etc.). Consequently, this variability increases the demands placed upon the testing of wood material properties, both in destructive and non-destructive ways. Currently, the attention focuses on the perfection of the non-destructive testing of wood and wooden constructions as it provides very good results in a relatively short time, which is more suitable for the practice. The non-destructive methods used most frequently are those which are based on the measuring and analysing of ultrasonic – elastic – wave propagation through the material.

The aim of this study was to create a numerical (finite-element) model of an ultrasonic – elastic – wave propagation in wood in its cross-section. The numerical model is based on a real structure – a board on which the width of individual tree rings was measured. These data were then used for the creation of the real numerical model of the board; the model retains the cylindrical arrangement (tree rings) and material properties. The numerical model was subjected to a very short force impulse and then the passage of the stress wave through the board in time was measured. To verify the numerical model, a number of experimental measuring procedures using various instruments (FAKOPP, ADD, Geotron, Geotron – PC, TICO) were conducted. For this reason, the paper contains a large amount of verification of the numerical model and it provides an idea of its accuracy. If we acquire a trustworthy verified numerical model of the phenomenon in question in such material as wood – with references to its anisotropy, heterogeneity and variability – we will obtain a number of ways of pushing our basic questions beyond the limits of experimental feasibility.

Wood science and research has been looking into the propagation of elastic wave in wood for quite a long time. The importance of elastic wave propagation through wood which was considered to be orthotropic continuum for the purpose of the research was dealt with by Buchar et al. (2000). They conducted their analysis in LS DYNA explicit solver. They monitored the wave course and reflection coefficients at the wood-steel edge. Veres and Sayir (2004) carried out an experimental measuring of ultrasonic wave propagation through a specimen with rectangular cross- section and orthotropic material model together with the subsequent calculation of material properties in individual directions. Their study uses a semi-analytical method of finite elements to establish dispersion curves of a prismatic specimen and a considerable agreement with their experimental measuring is achieved. One of the first attempts to deal with this task in wood implicitly in the ANSYS system is obvious in the work of Scheffler et al. (2002). These authors conducted a harmonic analysis of a prismatic specimen from wood without defect and with defect at various frequencies. The output of the analyses was the stress state and the displacement. The results show very explicitly how a defect (a hole) affects the field at various frequencies. However, the harmonic analysis is insufficient for a more detailed result quantification and interpretation. In this respect, a fully transient dynamic analysis, which includes time and so allows for the visualisation and tabulation of the results at any time of the analysis, as well as for the visualisation of the entire course of the elastic wave propagation through the material in time, seems to be more suitable. The solution for this task lies in the solution of this general equation of motion:

$$M\,\ddot{u}(t) + C\,\dot{u}(t) + K\,u(t) = f,$$

where M is the mass matrix, C is the damping matrix, K is the stiffness matrix, is the nodal acceleration vector, is the nodal velocity vector, u is the nodal displacement vector and f is the load vector. The solution of the system of equations is done implicitly using Newmark method. The

searched for displacement u is found at the end of each time step, referred to as sub-step. Recently, to simulate an elastic wave propagation through the wooden trunk, Schubert et al. (2006) developed a finite-difference-time domain method (FDTD) code in order to investigate an influence of fungal decay on travel times of the wave. Although it was stated that wave propagation in the ideal trunk, i.e. without knots and other inhomogeneities, is complex phenomenon, the developed DFTM code showed clearly that elastic wave velocity decreases with increasing fungal decay in the trunk, in radial-tangential plane respectively. Hence this work together with Schubert et al. (2009) showed, that the numerical simulations of elastic wave propagation are necessary and suitable for construction or tree condition assessments.

To deal with the motion of the elastic wave, very small integration time step was chosen in correspondence with the following equation:

$$c = \sqrt{\frac{E}{\rho}} ,$$

where c is the wave (sound) propagation velocity (m.s^{-1}), E is the modulus of elasticity (Pa), ρ is the wood density (kg.m^{-3}).

For the purpose of the task convergence, the size of the time integration step has to meet the Courant–Friedrichs–Lewy condition (Strikwerda 2004). Based on the practice of numerical modelling of dynamic analyses, this condition is expressed as (Kohnke 1998):

$$\partial t \leq \frac{l}{3\mathrm{c}} ,$$

where ∂ is the integration time step (s), l is the size of the element in the specific direction (m), the 3 constant represents a safety factor ensuring both the task convergence for the calculation and the capturing of the elastic wave in the finite element.

MATERIAL AND METHODS

To verify the numerical model, a number of measuring procedures were taken using several measuring instruments, which differ both in their construction and the used frequencies. However, the principle of measuring and result interpretation is the same for all of them. The time of the passage of the pulse through the material is measured and then its velocity is calculated. In our research, we used the following equipment: Arborsonic Decay Detector (ADD), Geotron (with user's evaluation), Geotron – PC (computer-driven evaluation), TICO, and FAKOPP. Using the measured values, we calculated the average velocity of the pulse passage in specified locations on the board. This provided us with average values – the curve of average values, which served as referential for the comparison with our numerical model. One of the experimental samples was chosen and its width of early and late wood was measured using the PAST32 application, see Fig. 1 a. The width of the tree rings was exported to a txt file (ASCII). The file was then loaded as a vector into the ANSYS computational system. Using the APDL language (ANSYS Parametric Design Language), a general and parametric script was created; on the basis of the loaded tree ring widths it created a corresponding 2D geometric model of the log. The real tree rings of a general shape are thus represented and idealized by concentric annular rings. As the pith is obvious in our sample, it proved sufficient to measure the X and the Y coordinates of the sample (board) centre in relation to the position of the pith. These coordinates together with the sample dimensions are sufficient to cut the desired section out of the log geometry and in this way to obtain the resulting sample, see Fig. 1 b.

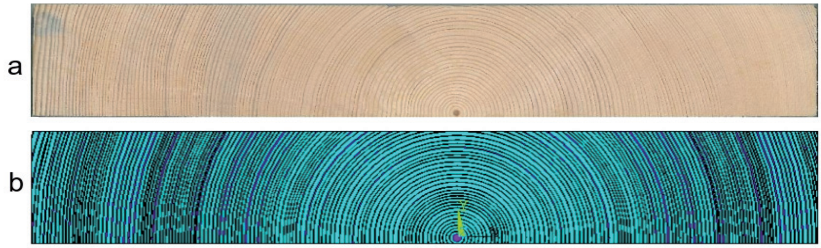

Fig.1: a) The specimen for the numerical model; b) geometrical model of the wood specimen

Subsequently, the geometrical model was meshed into a finite-element model. The used element was PLANE182 with linear shape function. The initial size of the element was set to 0.5 mm but as the tree ring widths of late-wood of the sample often reach even below this value, the option to adjust the element size to the geometry was remained open. The finite-element (FE) mesh of a part of the model is shown in Fig. 2. The FE mesh of the entire model consists of about 100,00 elements and 101,00 nodes. The size of the FE model database file is about 100 MB.

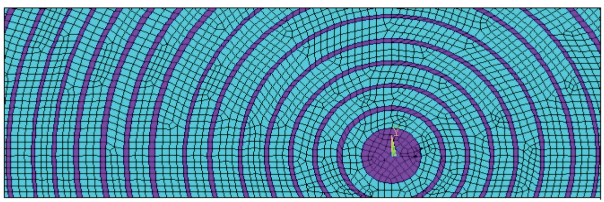

Fig. 2: A detail of the finite-element mesh (colours are used to distinguish the material models of late and early wood)

This model (Fig. 1b and Fig. 2) was subjected to 12 transient dynamic analyses of elastic wave propagation in wood. The individual computations only differ with regard to boundary conditions – in the location of the force impulse, see Fig. 4 b). The force impulse was applied directly onto the bottom edge nodes in the distance of 2.5 cm. The other boundary conditions consisted in the binding of displacement degrees of freedom of the board bottom edge in the direction of the X axis and of the board right and left edges in the direction of the Y axis in the 7th up to 12th computations. The cylindrical coordinate system in relation to the pith centre was defined in all the elements.

If follows from equation (3) that with the size of element being 0.5 mm, the limiting integration time step is around 2.18×10^{-7} s. Therefore, the time step of the analysis, or the substep, must be smaller than 2.18×10^{-7} s. We have chosen a triangle waveform with the length of 2×10^{-7} s, see Fig. 3 a. A half of this time represents the increase of the force to the final value – 1st load step, the second half of the interval expresses the following decrease of the force back to zero – 2nd load step; the interval of the 3rd load step in which the force is zero is intentionally longer than the previous steps so that we could monitor the response of the structure to the impulse – the elastic wave propagation.

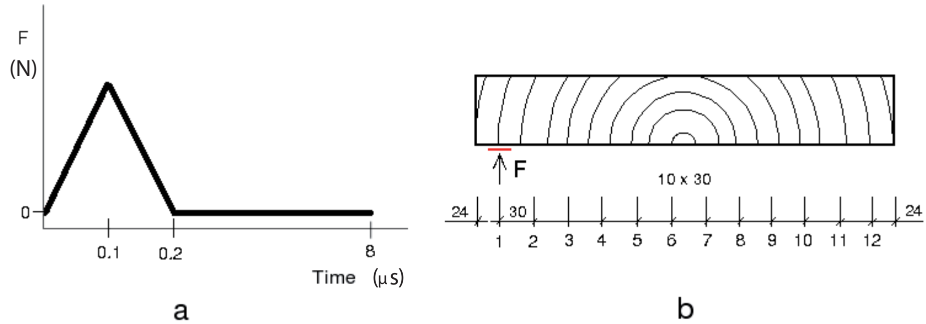

Fig. 3: a) progress of the force in time; b) location of the force on the numerical model (experimental measuring)

After velocities and times of propagation of elastic wave in particular position withing a board, a relative error of FE simulations in compared to the average of all experimental measurement. Calculation of it is as follows:

$$R = \frac{|v_{fem} - v_{\exp}|}{v_{\exp}} \cdot 100$$

where R is the relative difference of FE simulations compared to the experimental measurements, v_{fem} is the wave propagation velocity computed by FEM ($m.s^{-1}$), v_{exp} is the wave propagation velocity measured by particular tool ($m.s^{-1}$), ρ is the wood density ($kg.m^{-3}$).

Wood material properties – orthotropic model

The orthotropic material model assumes different material properties in two mutually perpendicular directions (in 2D). Because the board consists of tree rings, it was necessary to consider the material properties of wood in cylindrical coordinate system. In this coordinate system, the X coordinate is replaced with R radius and thus it represents the radial anatomic direction; the Y coordinate is replaced with the angle of deflection θ and thus it represents the tangential anatomic direction to the tree ring. The transformation of material properties was conducted by the transformation of the coordinate system in each element of FE model. The used material properties are presented in Tab. 1.

Tab. 1: Material properties of the numerical model

Material properties (*Picea abies* spp.)		
	Early wood	Late wood
Density ($kg.m^{-3}$)	350	890
MOE E_R (E_R)(MPa)	730	7100
MOE E_θ (E_T)(MPa)	170	1800
Shear MOE $G_{r\theta}$ (E_{RT})(MPa)	55	570
Poisson's ratio $\mu_{R\theta}$ (-)	0.31	0.405

RESULTS AND DISCUSSION

Within the framework of the project, 12 computations were carried out and the times of elastic wave passage through wood were evaluated in post-processor. The times of wave passage obtained through numerical simulation and those obtained through individual experimental measuring were compared. The times of the elastic wave passage through the board were measured using the individual courses of stress in the direction of Y axis in time, i.e. in the direction of the applied force. The times of passage were then used to calculate the velocity of the elastic wave – ultrasound – propagation through wood in the location of a probe. These values of velocity together with the results of experimental measuring were then used to create a graph and compared, see Fig. 4.

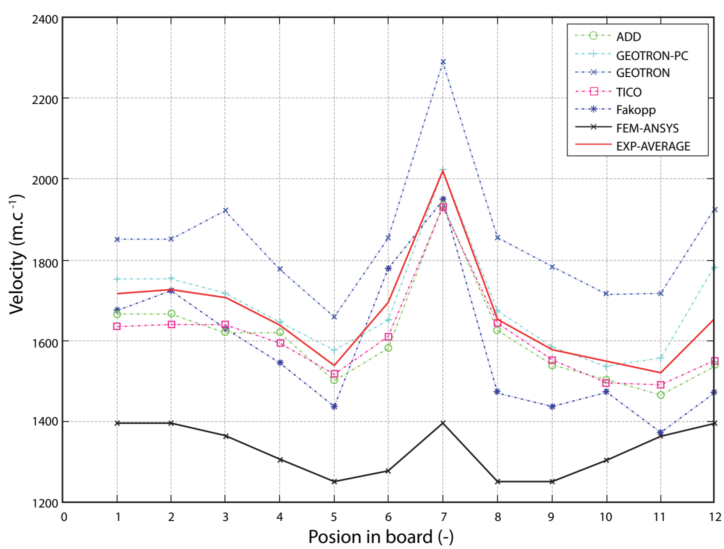

Fig. 4: Dependence of velocity on position in board Questionnaire

The graph in Fig. 4 shows that the values of experimental measuring (ADD, FAKOPP, GEOTRON- PC, GEOTRON, TICO) do not differ considerably. However, the results of the numerical simulation (FEM_ANSYS) are largely different – all the 12 computations provided much lower values of the elastic wave velocity than experimental ones, see the black solid curve at the bottom of the graph. A curve of the mean values of experimental measuring sessions was added to the graph (the solid red line) and this curve was then used as the referential one for the results of the numerical simulation and individual measuring instruments. From the Fig. 4 is also obvious that curves of elastic wave velocities are influenced by position in the board, tree-ring angle eventually. In all cases the elastic wave velocity is the highest in the middle of the boards, where a radial wave direction prevails. This corresponds with most of literature, for instance Bucur (2006). Going from the center of the board (position no. 7) to its both sides, the velocity decreases rapidly and then starts slowly increasing. This is caused by changing of tree-ring angle. First, the angle is very high so the direction of the wave is radial-tangential (positions no. 5,6, 8, 9 and 10). Moreover the path of the elastic wave goes through the many abrupt changes in elastic moduli, which can cause resonance and slow down the wave velocity. At the ends of the specimen (positions no. 1, 2 and 12) the tree ring angle is the lowest, so the elastic wave can propagate without just described difficulties, but also can preferably propagate in the late wood, which has higher elastic modulus causing to wave to propagate faster. Although the FE simulation shows lower velocity values, a trend of the elastic wave propagation compared to average from experimental measurements is obviously preserved. The relative differences of the velocities given by FE simulation from the average experimental data are presented in Table 2.

Tab. 2: Relative difference of numerical simulation to average experimental measurements

Relative differences of numerical simulation (ANSYS – FEM)												
Position in board	1	2	3	4	5	6	7	8	9	10	11	12
Tree ring angle (˚deg)	7	7	15	24	26	41	90	45	31	26	27	14
Relative difference from average values (%)	18.7	19.2	20.1	20.3	18.7	24.7	31.1	24.4	20.8	15.5	10.3	15.6

Average relative difference of particular measuring tool (%)					
ANSYS – FEM	ADD	Geotron	Geotron – PC	TICO	Fakopp
20.0	3.6	11.0	1.9	3.6	6.1

Tab. 2 also shows the average relative difference of particular measuring instruments from the average curve of all measurements. The results show that the lowest difference is achieved by Geotron with PC data processing (1.9 %), followed by TICO (3.6) and ADD (3.6 %), Fakopp (6.1 %) and Geotron without PC correlation (11.0 %). Therefore, the experimental measuring shows that all the measuring instruments are accurate to a similar degree, the only exception being Geotron without PC data processing. Its relative inaccuracy is brought about by the fact that the passage and the results are processed by a human being. The lower ability to distinguish can lead to the overlooking of the 1st peak of elastic wave, which is, on the other hand, bound to be registered by a computer. Therefore, Geotron with PC data processing prevents the error and thus enhances the accuracy of the equipment, in our case by about 9 % (in comparison to human processing). The character of the elastic wave propagation is best represented in the images reflecting von Mises stress in individual time steps, see Fig. 5. These images were created using the general postprocessor ANSYS (POST1) and they serve illustrative purposes. To provide precise quantification of results in time, the Time history postprocessor (POST26) was used.

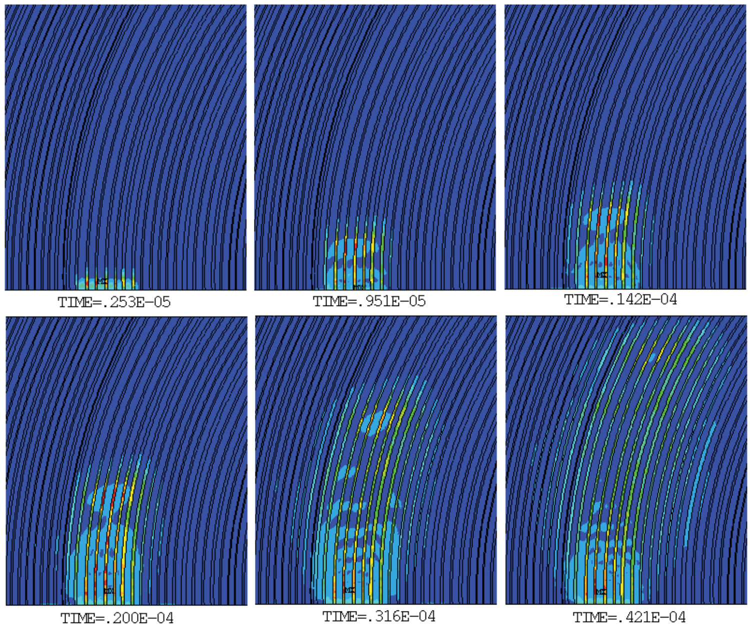

Fig. 5: Graphical illustration of elastic wave propagation using von Mises stress in time

Fig. 5 presents the overall situation of the propagation in time and in the part of the numerical model where the stress pulse is defined. It clearly shows that the angle of tree rings affects the direction of elastic wave propagation. We can see that the elastic wave significantly follows the course of the rings; moreover, we can see that it spreads faster in late wood than in early wood. This also confirms the assumptions created on the basis of the theory of elasticity. The difference is illustrated by the advance of coloured lines of von Mises stress in late wood ahead of the colour in the wider strips of early wood.

The results prove that quite an accurate and reliable numerical model of elastic wave propagation in the cross section of a wooden board was built. The average relative difference vis-àvis the mean of experimental measurements is 20 %. The accuracy of the model is mainly affected by the density of the mesh and also by damping. Using the theory we can conclude that the density of the mesh was sufficient for elastic wave capturing and task convergence, therefore, we can only limit our discussion to the damping. The damping coefficients, which enter the analysis as Rayleigh's constants, are divided into two basic ones - α and β damping. α expresses mass damping and it is the multiplier of mass matrix; β represents hysteresis damping and it is the multiplier of stiffness matrix. Damping matrix is expressed as:

$$[C]=\alpha[M]+\beta[K] \ .$$

Equation (4) shows how the damping coefficients enter the computation of the numerical model – through the damping matrix (C). In our projects we used damping coefficients α =0.05 and β=0.0000034. However, these are coefficients for isotropic damping, or in other words, coefficients for isotropic materials. Our model uses a 2D orthotropic material model in a cylindrical coordinate system. It means that ideally we would need orthotropic damping coefficients, separately for late and for early wood, in a cylindrical coordinate system, see Dániel and Trojáková (2008). Unfortunately, to obtain orthotropic damping characteristics would be beyond the scope of this paper; moreover, ANSYS version 11.0 does not provide the option to define orthotropic damping. Therefore, we have to put up with the homogenized coefficients, i.e. coefficients loaded with an error, for isotropic damping α and β . The created numerical model (ideally, after it is tuned up with respect to damping coefficients) can also serve as an input model for sensitivity analysis of ring deflection influence on propagation of ultrasound – elastic wave.

CONCLUSIONS

In order to be able to monitor the propagation of an elastic wave in wood with defined early and late wood – tree rings – a numerical simulation was created using the finite-element computational system ANSYS. As the simulation was conducted as a fully transient dynamic analysis, it allowed us to quantify nodal displacements and the velocity of wave propagation through wood. The results of the simulation were compared with experimental measuring carried out using ADD, TICO, Geotron, Geotron-PC and FAKOPP. Regarding the FE model it can be stated that the model follows the board morphology, tree ring angle eventually, which causes different velocities of elastic wave on different position in the board and subsequently agree with theory and literature.

The comparison with experiments showed that the created numerical model of elastic wave propagation is relatively accurate with the mean relative difference of 20%. Taking into account that some of the input simulation parameters were obtained from literature and not experimentally, e.g. Poisson's ratio and the damping coefficients, the difference can be considered acceptable. However, for further research it is necessary to "tune up" the numerical model in this respect. As far as the graphical representation of results is concerned, we can state that for visualisation of the wave propagation through material the component stress in the direction of the applied force (Y axis in our case) and von Mises stress seem to be the most suitable. visualisation makes it obvious that the elastic wave spreads faster in late wood than in early wood, which corresponds to the theory of elasticity.

Another interesting task for the future is the comparison of our results obtained by implicit solution with an explicit solution (e.g. using AUTODYN or LS DYNA systems). A big advantage of our numerical model is its parametrization. All simulations, including the analysis and the export of results, have been written parametrically in APDL and as such they allow for a user-friendly recalculation of results for new model specifications. This opens up the possibilities for changing the physical model itself as well as for creating a complex study with the sensitivity analysis of the influence of tree ring or late wood proportion on the overall character of elastic wave propagation or its passage.

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