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POSSIBLE SOURCES OF ACOUSTIC EMISSION DURING STATIC BENDING TEST OF WOOD SPECIMENS

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Abstract

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The paper is dedicated to identification of sources of acoustic emission generated during static bending test of wood specimen. Information on wood structure, wood failure behavior and computer-generated finite element method (FEM) simulation of static bending test were used to localize and estimate power of individual acoustic emission sources. Significant acoustic emission sources are expected in the specimen in two areas: under the upper central support (during the entire bending test run) and in the tension portion of the specimen at the centre of lower baseline (at the fracture/destruction time). Strong acoustic emission sources were registered in tension portion of the specimen in direct connection with final fracture of specimen.

acoustic emission, wood, static bending test, finite element method

Strength properties are critical for safe utilization of wood as a construction/building material. Basic mechanical properties of wood are derived from static bending test. Results of the static bending test procedures according industrials standards include parameters of MOE (Modulus of Elasticity) and MOR (Modulus of Rupture). Further correlation relationships make it possible to estimate elastic constants and yield strength values. Currently, there is an ongoing research project in the Department of Wood Science laboratory of Mendel University in Brno that includes an innovative approach to static bending test applied to wood specimens. Acoustic emission method is being used in conjunction with the standard 3-point static bending procedure to gain additional information about the test progression for selected wood types (3 hardwoods, 2 softwoods).

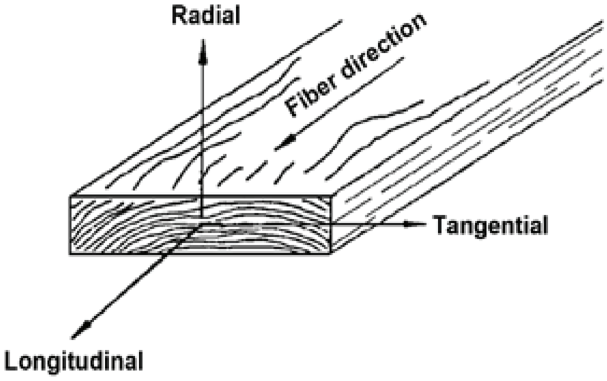
In this project, we tried to estimate acoustic emission development and source localization in standard wooden specimens. As far as the acoustic emissions point of view is concerned, the static bending test represents rather complicated area of interest. As a result, multiple sources of acoustic emission are expected to be identified. Information on wood structure, wood failure behavior, computer-generated Finite Element Method (FEM) simulation, and acoustic emission of static bending test will be used to localize and estimate power of individual acoustic emission sources.

MATERIAL AND METHODS

Structure and failure mechanisms of wood

Wood may be described as an orthotropic material; that is, it has unique and independent mechanical properties in the directions of three mutually perpendicular axes: longitudinal, radial, and tangential (Winandy, 1994), (Green, 2001), and (Winandy, Rowelll, 2005). The longitudinal axis is parallel to the fiber (or grain); the radial axis is normal to the growth rings (perpendicular to the grain in the radial direction); and the tangential axis is perpendicular to the grain but tangent to the growth rings. Fig. 1 shows the axes.

The exact microstructure of wood depends on whether the material is taken from coniferous trees (so called softwood) or broad-leaved trees (hardwood). In both types of wood, 90–95% of the cells are aligned along the longitudinal axis, while



1: *Three principal axes of wood (Augustin, 2008)*

the remainder is in the radial directions. There are no cells in a tangential orientation. The distribution of cells is different in all three principal sections (in cross section, tangential section and radial section and wood is therefore very anisotropic.

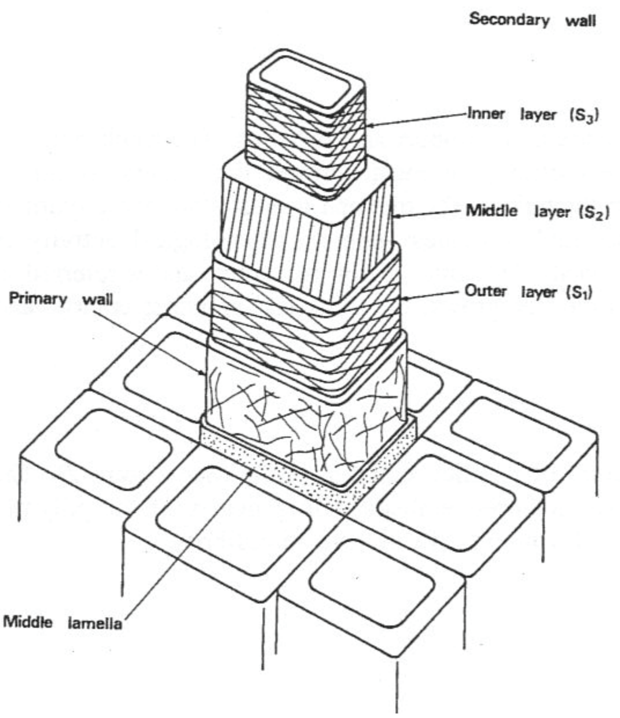
There are four different types of cells in hardwood (Winandy, Rowelll, 2005).

- Parenchyma cells are responsible for carbohydrate storage. Their diameter is about 250 µm. Parenchyma cells may be aligned horizontally or vertically.
- Tracheids perform function of both storage and support.
- Vessels (or pores) are responsible for conduction. Their end walls have been dissolved away and they are 0.2–1.2 mm short with width of approx. 0.5 mm.
- Fibers provide the principal source of support. They are long (1–2 mm) with an aspect ratio of 100:1.

On the other hand, softwood consists mostly from a single kind of wood cells – the tracheids. There are no vessels in coniferous wood. As a result, such wood material is much more uniform in structure than that of most hardwoods (Hoadley, 2000).

When viewed in microscopic scale, wood has predominantly a structure including parallel columnar cells (Winandy, Rowelll, 2005). The elongated cells can be considered as fibers, embedded in a matrix of the polymer lignin. The cell walls contain helical windings of cellulose micro fibrils, see Fig. 2.

The source of strength in solid wood is the wood fiber (Winandy, Rowelll, 2005). Wood is basically



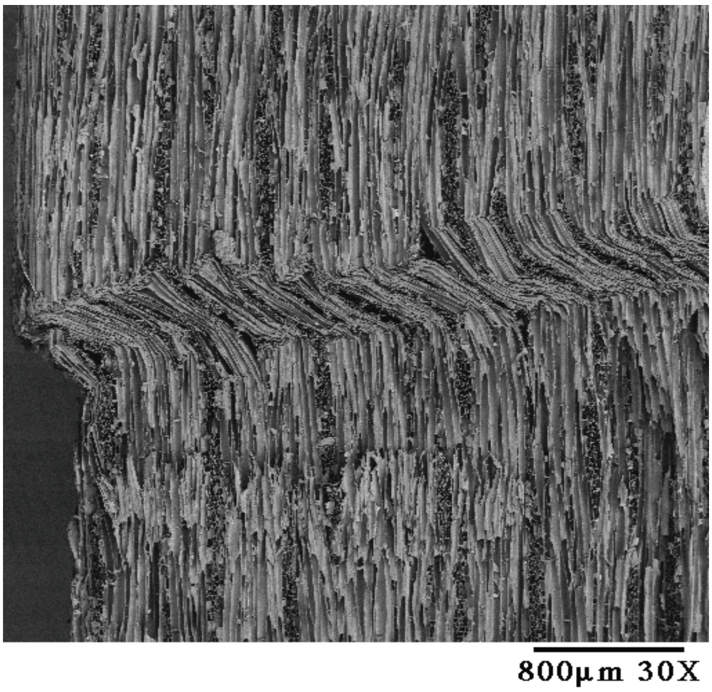
2: *Simplified structure of the cell wall showing orientation of the micro fibrils in major wall layers (Winandy, Rowell, 2005)* a series of tubular fibers or cells cemented together. Each fiber wall is composed of various quantities of three polymers: cellulose, hemicelluloses, and lignin. Cellulose is the strongest polymer in wood and, thus, is highly responsible for strength in the wood fiber because of its high degree of polymerization and linear orientation. The hemicelluloses act as a contact matrix for the cellulose and increase the packing density of the cell wall. Lignin not only holds wood fibers themselves together but also helps bind carbohydrate molecules together within the cell wall of the wood fiber.

Major wood damage mechanisms in compression include buckling, crushing, and kinking (Benabou, 2008). Buckling may be described as sudden failure of a structural member subjected to high compressive stress, where the actual compressive stress at the point of failure is less than the ultimate compressive stresses that the material is capable of withstanding. Crushing, on the other hand, represents breaking of material matrix into small fragments or powder. Kinking is a specific failure mode when initial misalignment of fiber causes damage of the fibers with subsequent shear deformation in the kink band region. However, outside this region, compression prevails. In tension, the behavior is much simpler: semi brittle rupture stands for major failure mode. Obviously, all these phenomena are oriented directionally.

When a compression load is applied parallel to grain, it produces stress that deforms (shortens) wood cells along their longitudinal axis. In this scenario, failure initially begins as the micro fibrils begin to fold within the cell wall, thereby creating planes of weakness or instability within the cell wall. As stress in compression parallel to grain continues to increase, the wood cells themselves fold into S shapes forming visible wrinkles on the surface. Large deformations occur from the internal crushing of the complex cellular structure. Several wood species, hardwoods and softwoods, are damaged by formation of kink bands, see Fig. 5. Compressive kinking strength of wood is governed mainly by its yield strength in shear and by certain features of its anatomy related to the so-called ray cells. Fiber misalignment precipitates fiber micro buckling with the subsequent shear deformation occurring in the buckling region. Then, as a result of this local state of shear stress, it is probable that the kink bands are also governed by the shear strength of wood.

When a compression load is applied perpendicular to grain, it produces stress that deforms the wood cells perpendicular to their length. Once the hollow cell cavities are collapsed, wood is quite rigid as no void space exists.

Parallel to its grain, wood is very strong in tension. Failure occurs by a complex combination of two modes: cell-to-cell slippage and cell wall failure. Slippage occurs where two adjacent cells slide past one another. Cell wall failure involves rupture within the cell wall with little or no visible deformation prior to complete failure. In contrast to tension parallel to grain, wood is relatively weak when loaded in tension perpendicular to grain. Stresses in this direction act perpendicular to the cell lengths and produce splitting or cleavage along the grain, which can have a significant effect on structural integrity. Deformations are usually



3: *Kink bands in wood (Benabou, 2008)*

low prior to failure because of the geometry and structure of the cell wall cross-section.

When used as a beam, wood is exposed to compression stress on one surface of the beam and tensile stress on the other. This opposition of stress results in a shearing action through the section of the beam. This parallel-to-grain shearing action is termed horizontal shear. Conversely, when stress is applied perpendicular to the cell length in a plane parallel to grain, this action is termed rolling shear. Rolling shear stresses produce a tendency for the wood cells to roll over one another. In general, rolling shear strength values for clear specimens average 18 to 28% of the parallel-to-grain shear values.

Static Bending Test

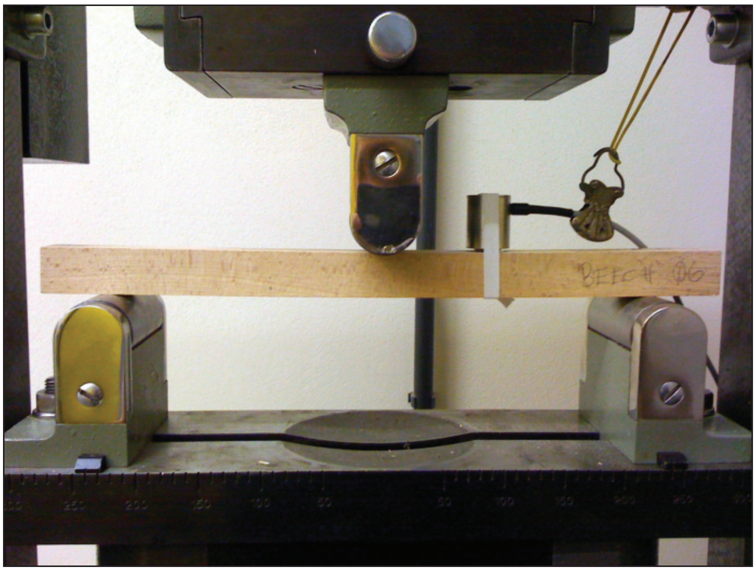
According to the ČSN 490115 standard, static bending test procedure is performed to find ultimate static end load causing permanent damage of the tested specimen. Testing specimens must be in form of regular-shaped boxes with cross dimensions of 20 × 20 mm and length of 300 mm. The fiber direction has to correspond with specimen length dimension. The width b is measured in direction parallel to the annual rings, while the height h is measured in direction perpendicular to the rings. In static bending test procedure, the specimen is placed on two supports at the ends while the third point provides downward pressure at the centre. The forces from above acts in radial direction, i.e. the annual rings are close to horizontal. The distance between the supports is defined as 12× height. With the standard specimen size (see above), the support span is equal to 240 mm. For the static bending test, the ZDM 5/51 machine was used in the Department of Wood Science laboratory, see Figure 4. Acoustic emission signal was measured and evaluated by Dakel XEDO system.

Acoustic Emission

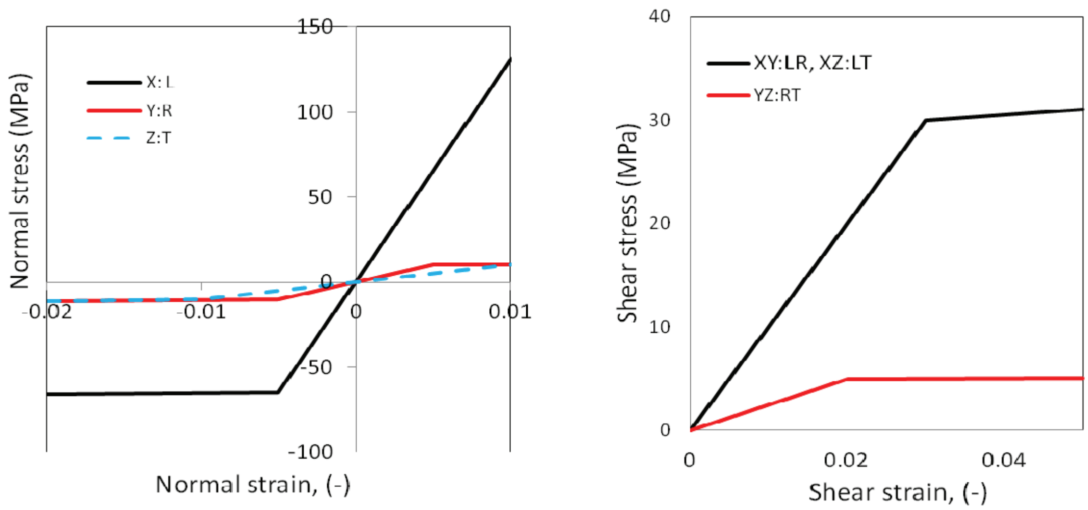
Acoustic emission ranks among NDT (non-destructive testing) methods. Acoustic emissions are stress waves produced by the sudden internal stress redistribution of the materials caused by the changes in the internal structure. Possible causes of the internal-structure changes are crack initiation and growth, crack opening and closure, dislocation movement, twinning, phase transformation in monolithic materials and fiber breakage in composites (Varner, 2007). Most of the acoustic emission sources are damage-related; thus, the detection and monitoring of such emissions are commonly used to predict material failure. In technical diagnostics, acoustic emission method has been used to monitor rotational part status (friction/cavitations of bearings and gears), detection of micro-cracks, pressure vessel defects, tubing system defects, aircraft structure testing, and bridge status diagnostics. Acoustic emission technique has proven useful in fatigue testing and destruction experiments (Kreidl, 2006). Many interesting applications for acoustic emission testing have been developed in recent years in wood science. The objective of the technique is to measure parameters for specific properties of the material under test. As far as wood science applications are concerned, the method was used to monitor sap flow in grown-up trees (Černý, Mazal, Čermák, 2011). In order to determine acoustic emission parameters, influence of wood species, moisture content a type of sensor should be taken into account (Bucur, 1995).

FEM Simulation

Wood has significantly different elastic behavior in longitudinal, tangential and radial directions (Green, Winandy, 1999). Graphical representation of this simplified behavior of selected oak wood, i.e. stress-strain curve is in Fig. 5.



4: *Static bending test specimen with acoustic emission sensor attached*



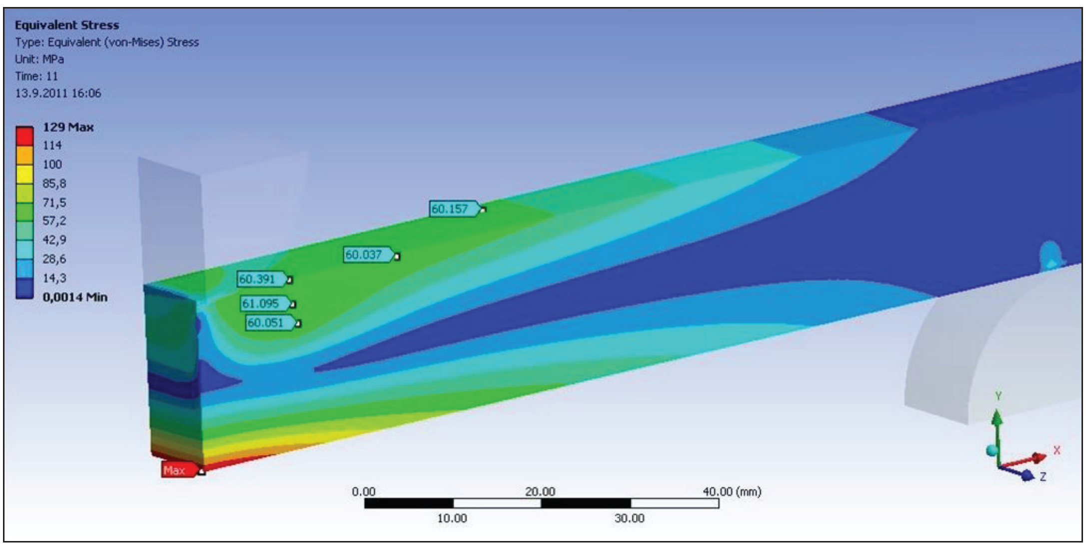
5: *Stress-strain curves for selected oak wood*

The geometry of the normalized wood specimen in the test machine was modeled with two vertical planes of symmetry. The first plane of symmetry was going through longitudinal axis of specimen; second plane of symmetry was going through centre of specimen and was perpendicular to its longitudinal axis. Lower supports were fixed in horizontal plane and free in longitudinal direction of the specimen. Upper support mounted on cross member of test machine was fixed in longitudinal and transversal directions. Friction contacts between steel supports and the wood specimen were modeled with friction coefficient of 0.6 (Klepš, Nožička, 1986). Mesh element size was 0.5 mm with total number of 324,086 nodes created on the model.

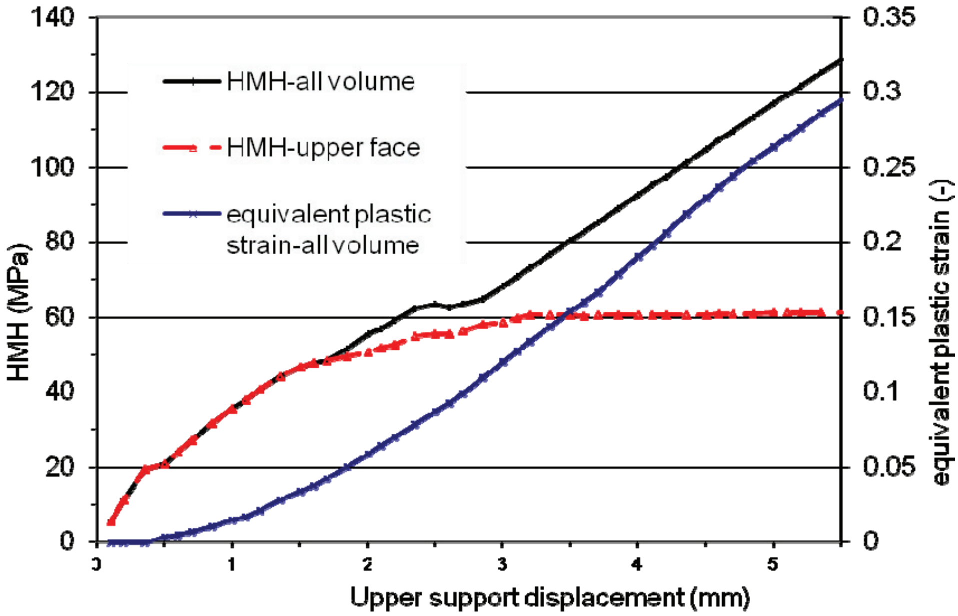
The anisotropic plasticity option was used to simulate three-point bending test of oak specimen. Steel supports are considered in the model. Nonlinear task both in materials, contact and deformation was solved by the finite element method. Evaluation of simulated results carefully respects compound failure surface of wood materials: Hill-type criterion for pure compression quadrant of stress space coupled with a Rankine-type criterion for the other quadrants (Lourenco, de Borst, 1997).

RESULTS AND DISCUSSION

In this experiment, acoustic emission captured during destruction on compression side of the specimen originated probably from buckling of reinforced cell wall, development of kinking bands, and friction of cell wall debris. Results of static bending simulation performed on oak clear wood specimen indicate time/location variable distribution of acoustic emission sources. Fig. 6 shows Von Misses stress distribution just prior to final fracture of the specimen. Due to symmetry reasons, only a half of the specimen was modeled.



6: *Stress distributions in wood specimen subject to static bending*



7: *Stress/strain values vs. upper support displacement*

The stress value of 60 MPa is in compression in longitudinal direction of the upper compression area of the specimen. The maximum stress value amounts 129 MPa in lower tension area.

Fig. 7 shows displacement courses of maximum Von Misses stresses on whole body and upper face of specimens and equivalent plastic strain on whole specimen body.

Shortly after the static bending test start, when the deflection is 0.4 mm, the yield strength of cell walls in perpendicular direction is reached in location right under the central support (see curve "equivalent plastic strain-all volume" in Fig. 7). The collapse region grew larger during the entire test run until the final fracture of the specimen. In this moment, plastic strain reached maximum value of 0.29 and Von Misses stress is 129 MPa, see curves "equivalent plastic strain-all volume" and "HMH-all volume". Over lower supports, similar conditions are reached when the deflection is approximately 1.3 mm. However, this zone is much smaller and maximum plastic strain was 0.024. The formation of two kinking bands is expected under boundaries of contact zone in the vicinity of top support contact. By deflection of about 3.2 mm, the yield stress in compression in longitudinal direction is reached, followed by hardening of cells in compressed part of the specimen (i.e. on upper surface), see plateau on curve "HMH-upper face".

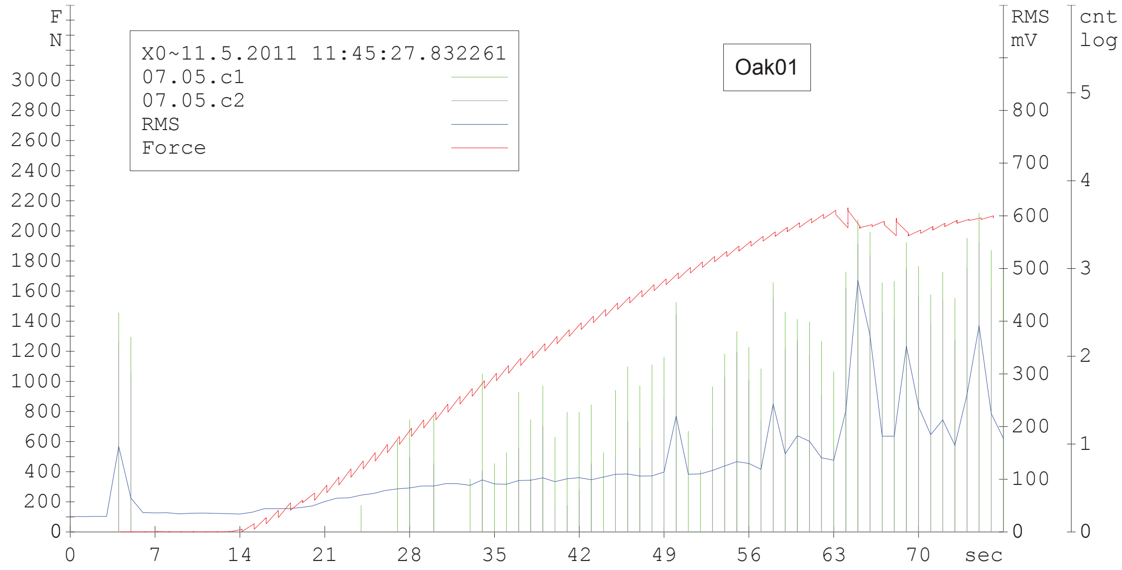
Due to anisotropic properties, acoustic emission generated during clear wood damage process shows parameters dependent on loading type and its orientation with respect to grain direction. When tensile load is being applied in the grain direction, the acoustic emission is expected to come from several sources including separation of cellulose micro fibrils and lignin matrix, actual micro fibril breakage, and final fracture of the entire cell wall. Final stage fracture obviously generates strong acoustic emission bursts. In perpendicular direction, the cell walls are less reinforced with micro fibrils and overall cell wall strength is reduced. When a tensile loading is applied in this direction, it is likely that acoustic emission signals originate in degradation-related changes of cell wall lignin mass. Also, the presumption of about kink band development was confirmed by visual observation; two kinking bands were clearly visible the specimen after the static bending experiment.

In general, low activity of acoustic emission sources may be expected in area of prevailing compressive stress. Ultimate strength in tension in longitudinal direction is reached on the lower surface of the specimen when the deflection is approximately 5.5 mm (see Fig. 7). Brittle fracture of fibrils releases big quantity of elastic energy and thus should produce massive acoustic emission burst signal.

In general terms, acoustic emission in wood during static bending test may come from several source groups:

- Compression-invoked damage with kinking, buckling, and friction of cell wall fragments during plastic deformation on upper face of the specimen.
- Tension-invoked progressive fractures of fibrils on lower face previous of total specimen fracture.
- Instrumentation of the experiment (loading machine, supports, wood-steel contact friction).

Parasite signals from the instrumentation chain might be eliminated using a low friction-high attenuation separation inserts. In this experiment, a thin Teflon tape was inserted between the specimen and supports. This insertion of the tape did not affect acoustic emission signal parameters



8: *Loading force and acoustic emission signal during static bending test of oak wood specimen*

during the static bending test. Thus, it can be expected, that presence of acoustic emission events corresponds solely to actual damage of wood specimen. Acoustic emission signal parameters (RMS and C1/C2 counts) during static bending test are shown in Fig. 8. It can be seen that the very first set of acoustic emission signals occurs some 20 seconds after the beginning of the test. After several local bursts, the final fracture of the specimen is witnessed by robust activity of acoustic emission sources. Note the initial pulse caused by the loading machine start.

SUMMARY

The paper deals with a unique NDT method – acoustic emission. Acoustic emission can be used for real-time monitoring of defect/micro crack development process. In general, wood ranks among orthotropic material both with respect to structure and mechanical properties. The experiment was focused on utilization of this method during static bending tests of standard wooden specimens. The aim was to acquire specific acoustic emission signal patterns for individual wood types. For this purpose, a single acoustic emission sensor was rubber-fixed to the wood specimen subject to the static bending test. Unwanted parasite signal were examined using Teflon-tape low-friction insert between the specimen and supports. Evaluation of wood structure and damaging behavior formed ground for identification of acoustic emission signal sources and estimation of their robustness within various loading scenarios. The evaluated acoustic emission plots included RMS and C1/C2 count values.
Parameters of stress/strain during static bending test of oak wood specimen were further described using a finite element method of the static bending test simulation. In this case, a meshed model was numerically subject to bending load just as the real-life wood specimen. The simulation reveled that maximum of 129 MPa was reached in lower tension portion of the specimen, while compression region close to upper specimen face showed 60 MPa. Acquired results of simulation were used to estimate space and time location of acoustic emission sources during a real-life bending experiment. Strong acoustic emission sources are expected in the specimen in two key areas: under the upper central support (during the entire bending test run) and in the tension portion of the specimen at the centre of lower baseline (at the final fracture time).

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