

Doctoral Thesis

The investigation of applicability of acoustic emission technology for the assessment of mechanical properties of wood

Kánnár Antal

University of West Hungary

Faculty of Wood Sciences

Sopron

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I. THE AIM OF THE RESEARCH

The use of wood is an organic part of everyday life from the beginning of history of mankind. However, the ways of application are diverse, more and more attention is paid to the load-bearing wood structures, including engineered ones, backing away from traditional forms and thus allowing constructions of new design, proper to the expectations of our age. The increasing requirements and the search for new architectural solution challenges Wood Science to produce more precise and reliable material models in order to increase safety and economy of the building structures. It was arising from this challenge that I investigated the applicability of the acoustic emission analysis in relation with the mechanical properties of wood in the last seven years. This method still new in the field of wood science is based on the detection of elastic waves, that accrue from the damage process of loaded wood, giving valuable information on the damage process itself. The acoustic emission technique has been object of research since the '50ies an object of industrial application from the '70ies. In Hungary, investigations on the possibility and applicability of method began in the Central Research Institute of Physics (KFKI) in the year 1976. The apropos of introducing the method was the controlling of reactor vessels of the nuclear plant in Paks in the course of construction work and pressure test. This institute devised a measuring apparatus called DEPHECTOPHONE still in use. My own experiments were carried out with the improved version of this apparatus too. The method had originally been worked out for investigation of metal, but afterwards was successfully applied for the investigation of minerals and fibre reinforced plastics as well. Lot of experimentation has been done all around the world using the method in some areas of wood sciences, but no comprehensive work has appeared to date that would reveal the acoustic emission properties of wood. Accordingly, I set the aim of my work to do the basic research for revealing the effect of the primary influential factors such as species of wood, moisture content etc. on the mechanical properties and damage process of wood. The dissertation is split into three main parts. The first part presents a review of research having already been done internationally, and of the criteria of setting up a measuring system. The second part describes the acoustic emission properties of wood as affected by the different influential factors, in the third part the findings of acoustic emission experiments are compared with the results of electron microscopic investigation, with the aim of arriving at a better understanding on the damage process of wood.

I hope that the results of my research can contribute to a better understanding of the behaviour of wood under load, allowing thereby the construction of a more precise failure model for wood applicable in practice.

II. Theoretical background and literature review

The phenomenon of acoustic emission (AE) means elastic waves, which accrue from release of stored energy in solid material. The AE is a voice of material, ergo a "talk". Each material has an own "language ". We have to understand this "language" in relation to the investigation of material. This method had not yet been applied in wood science in Hungary; therefore, our work is a basic research. The researchers abroad did make use of the method in many fields mainly as applied research. The main directions of this research can be summarised as follows:

- Ansell (1979) analyse the AE activity of Scots pine by different fibre angle.
- P. Niemz (1983) demonstrate two application possibilities in relation to wood:
 - I. Damage process in wood and wood products
 - II. Crack processes by seasoning
- Hansel (1989) Bending test of flake-boards with AE
- Poliszko (1994) Relationship between water binding energy in wood and its mechanical strength determined by AE
- Reiterer (2000) Mode I fracture and AE of softwood and hardwood
- Rice (2001) Estimating the moisture excluding effectiveness of surface coatings on southern yellow pine using AE technology.

Based on study of literature we can say that AE technology is applicable for examination of wood and wood products. The presented investigation shows that the number and properties of detected AE events depend on wood species, moisture content, applied stress and the loading history of the specimen. The research directions are very multifarious, every researcher used different AE apparatus and detectors, therefore the results can be generalised but by difficulties. Papers dealing with wood are very scarce. The reason for this can partly be the novelty of AE method for wood science; the anomalies experienced in relation with wood may also explain this fact. For example, it can be very high difference in acoustic activity between two specimens made from the same species of wood and tested under the same conditions. Because of such experiences, many of the investigators have focused on wood composites rather than solid wood. That is because dependably high number of AE events is originated from the numerous damages in decomposed wood and from the glue, which actively participates in the acoustical behaviour too. Summarising the cited investigations we can say that there exist applied research at first place, however, the underlying relations between the measured AE signals and mechanical properties of wood have not yet been established. Basic research is therefore needed to reveal the same.

Hence, the aim of my research work is to provide a scientific foundation of practical application through extensive basic research.

III. MEASUREMENTS APPARATUS AND METHODS OF THE RESEARCH

The AE experiments were carried out with an AE equipment of 4 channels and 2 parameter inputs, called DEPHECTOPHONE. The apparatus was designed in the Central Research Institute of Physics (KFKI Hungary). Two broadband piezoelectric transducers of type DECI 1000-H were used for the measurements; these were connected to the AE equipment through two logarithmic amplifiers. The measurement set-up is demonstrated in Fig. III.1. in case of one channel. Additional accessories were a logarithmic parameter amplifier and the software of analyses.

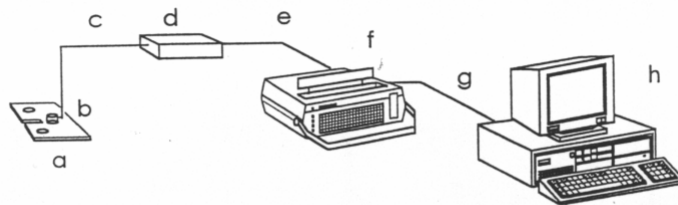


Fig. III.1. AE measurements apparatus (Czigány 1997)
a. specimen; b. piezoelectric transducer; d. preamplifier
f. DEPHECTOPHONE AE equipment; h. PC.

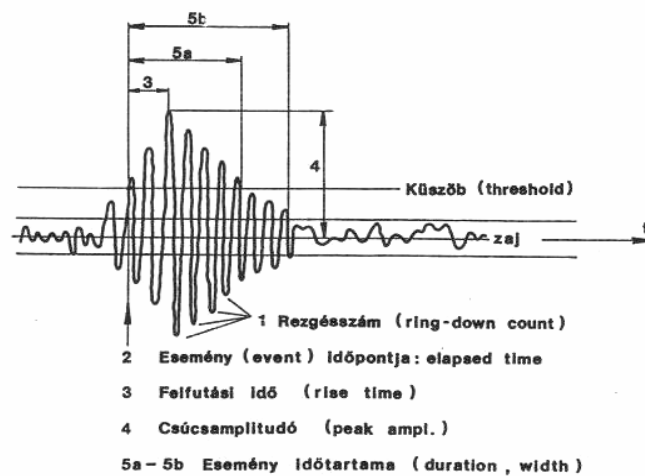
The measurements were carried out partly in the material testing laboratory of the Institute of Mechanics, partly in the Institute of Wood Science Zürich ETH Switzerland. An universal material testing equipment for tensile, compression and bending tests was available at both locations. Measurements were conducted as below:

The specimen designed corresponding to the stress to be applied was clamped in the testing machine and the two piezoelectric transducers were fastened to the specimen with rubber bands. The coupling material was silicon grease for good contact and to equalise the roughness. The transducers were connected to the AE equipment input channels through logarithmic amplifier. The AE equipment was in direct contact with the control PC and software. The parameter channel of the Defectophone records the parameter signal of loading force and strain from the material tester.

Before starting the measurement, one has to set many parameters, that provide the filtering of noise, but allow filtering some components of the useful signal domain too. After the setting, measurement begins with the simultaneous starting of the Dephectophone and the testing machine. The data are recorded on the Dephectophone and PC. too. The analysis of data is carried out with software, which allows additional filtering and graphical presentation of data.

The measured AE parameters are as follows (Fig. III.2.):

- events width (5a-5-b)
- rise time, the time elapsed until events reach their peak amplitude (3)
- peak amplitude (4)
- counts (1)
- elapsed time (2)



III.2. The measured physical parameters of an acoustic event (Pellionisz 1992)

Based on the measured parameters the software calculates further parameters:

- sum of events,
- energy, it is the integral of voltage square for the time interval during events,
- MARSE, it is the Measured Area under the Rectified Signal Envelope

The measured and calculated parameter can be presented as function of one another and their differential and integral distributions can also be produced.

We used specimen dimension for tensile, compression and bending test respectively as follows:

- For tensile test a special specimen was designed. The reason for this was that high number of events originated at grips because of the combined stress state. These had to be separated from the events accrued from clear tensile test. The weakening of the specimens' middle section caused fracture to occur or start from that location in 95% of cases. The measurement set-up allows events that originated from locations other than the tension mid-region to be filtered out, on the basis of time delay differences between the two transducers. This filtering possibility and specimen design allowed us to avoid the error included in the works of several investigators where the separation of events was not solved. In those cases, the events from tension and combined stress state are being detected together and give numerous events. In my investigation, it came out that the events number was significantly lower.

- For compression test, we used a specimen common for short time compression test with dimensions of 20 by 20 by 50 mm. The proportion of cross section dimensions to the length ensured that the specimen breaks as a squat stave that means without buckling.

-In case of bending stress the applied specimens dimensions were 20 by 20 by 300 mm. The method used was three points bending test.

During the research work were examined the following factors influencing AE properties of wood:

- **Influence of moisture content and wood species for acoustic attenuation of wood.**
- **Influence of wood species, moisture content, stress, and strain velocity for the AE frequency domain of wood.**
- **Influence of wood species, moisture content, stress, and strain velocity for the AE parameter properties of wood**
- **Effect of loading history for AE properties of wood:
Kaiser effect experiments in relation with AE events of Scots pine.**
- **Relation of the micro-damage processes of wood with moisture content and species.**
- **Relation of the micro-damage processes with origination places of AE events.**
- **Relation of the start of AE processes with strain and stress values.**
- **Relation the sum of AE events with strength.**

IV. THE THESES OF THE DISSERTATION

I. New results regarding the acoustic emission frequency domain of wood

I determined the AE frequency domain of wood not known before, by using a comprehensive frequency analysis to wood for the first time. I pointed out that the range of 20 to 250 kHz has to be assigned as the required measuring range of wood.

II. New results regarding the statistical method on the examination of AE properties of wood

Recognising, that the AE process of a wood specimens do not give an unequivocal picture about the damage processes in wood - the acoustic activity of specimens made of the same species being sometimes nearly zero while in another case very high -, I applied a statistical method in the analysis of AE behaviour of wood. The acoustic events detected at the same settings were pooled into and examined in clusters. I demonstrated that valuable conclusions can be drawn from the examination of the distribution of AE events concerning the fracture behaviour of wood.

III. New results regarding the effect of moisture content on the acoustic activity of wood

On the basis of the results it could be established that the increase of MC cause important decrease of the acoustic activity. I proved, that the phenomenon originates from the decreasing number in friction type events and increasing acoustic attenuation. I established, that the number and character of fracture type events do not change with changing MC, and these events are the elements of maximum frequency classes in the probability density functions.

IV. New results regarding the effect of species on acoustic activity and character of damage processes

On the basis of the analysis of AE process by different species, I showed that considerable differences can be measured on their acoustic activity. Most active was Scots pine followed in decreasing order by black locust, poplar, spruce, beech and oak. There was experienced six times difference of acoustic activity between the most and less active species. I proved that on micro-damage level the characteristic AE parameters are the same order of magnitude in case of different species. I established that species of wood when fail can be categorised regarding the feature of damage process rather than the common way – hardwood and softwood.

V. New result regarding the effect of strain velocity on AE processes of wood

I demonstrated that the strain velocity does not influence notably the AE properties of wood in the 2-20 mm/min domain. Subsequently, strain velocity does not influence the micro-damage processes of wood; on the contrary, strength increases with increasing strain velocity in the investigated relative low strain velocity domain.

VI. New results regarding the effect off stress on AE processes of wood

The influence of what type of load is applied was shown as small increase of events energy in case of compression stress as compared with tension. It has been proved through an analysis of the characteristic values of AE parameters' cumulative probability function that the sign of stress does not influence considerably the micro damage processes. It has also been verified that the difference in strength values is not related to the AE parameters of the micro damage processes.

VII. New results regarding the effect of loading history on AE processes of wood

In relation with the loading history it has been determined that damages having occurred in wood affect the AE processes in the next loading cycles. My investigation revealed the Kaiser effect in wood, i.e. preliminary loading decreases AE activity in the course of a next loading cycle leading to failure, when conducted within one month. It has also been revealed, that micro damages resulting from loading history hasten the damage process in a next loading cycle if after two months, thereby increasing the AE activity of wood. I proved evidences of the changes in climatic environment helping the Kaiser effect to disappear in wood.

VIII. New results regarding the effect of moisture content on the fracture pattern of wood

The analysis of fracture surfaces by electron microscope conducted on specimens of different species and moisture content allowed us to confirm statements in the literature about fracture of oven-dry wood being brittle. I could also generalise this statement for higher moisture contents.

IX. New result regarding the location of micro damage places

By locating micro damages, I proved that they occur in the course of the damage process at random places within the full volume of the stressed specimen, wherever the momentary state of stress is critical.

X. New results regarding the relationship between stress and strain and the start of acoustic emission

I demonstrated that the start of acoustic emission of wood does not depend on moisture content. All micro damage processes start in the same strain domain (0.22-1.2%). The stress belonging to the start of acoustic activity follows the dependence of the strength on moisture content. The start of emission is near the ultimate strength, which fact is a further evidence of brittle fracture of wood.

XI. New result regarding the relationship between the strength and the total number of acoustic events

It has been shown that the total number of events results from a random process of micro-damage events in wood, affected by the particular specimen's anatomical structure, and is not in functional relation with strength.

XII. New results regarding the applicability of acoustic emission technology in wood research

My work is the first large-scale, systematic basic research aiming to define the relationship between acoustic emission (AE) parameters (frequency, measured and calculated parameters) and the influencing wood properties, i.e. species, moisture content, stress, strain velocity. On the basis of my research, it can be stated that the acoustic emission technology is applicable for the investigation of wood, first of all for the analysis of damage process and mechanical behaviour of wood.

V. POSSIBLE APPLICATION OF THE SCIENTIFIC RESULTS

The work completed can be considered as basic research. I defined the relationship between the acoustic emission (AE) parameters - frequency, measured and calculated parameters - and the influencing wood properties, i.e. species, moisture content, stress, strain velocity. The results are fundamental in areas of applied research, which make the application of AE possible in the field of timber industry.

The following directions of application can be proposed:

- AE checking of wood structural elements during loading tests. AE control is capable to determine the extent of damages having occurred and whether it is critical or not for the whole structure.
- As evidenced from the Kaiser effect experiments, it is possible to assess the maximum load level that the structural parts underwent in the course of a considerable meteorological load (e.g. wind-storm). Namely, loading again the part it will not show acoustic activity, until the load attains its former maximum.
- The results offer the potential for the development of an AE - controlled drying oven system domestically. The method has already gained application in timber drying control in all over the world.

Additional practical use of experiments:

- It has been pointed out that the frequency range of 20 to 250 kHz is typical for acoustic events in wood. Accordingly, the sensitivity of detectors used for experiments on wood has to be in this domain.
- I demonstrated that wood is a brittle material in the 0-30% moisture content range. It means that unlike ductile materials, wood does not exhibit flow domain before it fails. The fracture noises, which are in the audible range, will start at load level higher than 90% of the ultimate load, and therefore denote a shortly occurrence of total break.
- I showed that damage process would only speed up considerably at load levels higher than 70% of the ultimate strength. It means that instantaneous increases of load below this level (e.g. due to wind gusts) do not entail considerable damage and decrease of load-bearing capacity of structures.
- I established, by locating micro damages that the damage processes take place randomly in the entire stressed volume and the whole specimen fails in a monolithic way. It follows that the usual relationship between loading force and cross-section ($\sigma=N/A$) is valid approximately only. Hence, the principle of dimensioning has to be reconsidered having regard to the whole stressed volume.

VI. PUBLICATION CONNECTED TO THE SUBJECT

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