CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

Faculty of Forestry and Wood Sciences

Department of Wood Processing

Possibilities of Acoustic Emission Method for Evaluation of Characteristics Processes in Wood

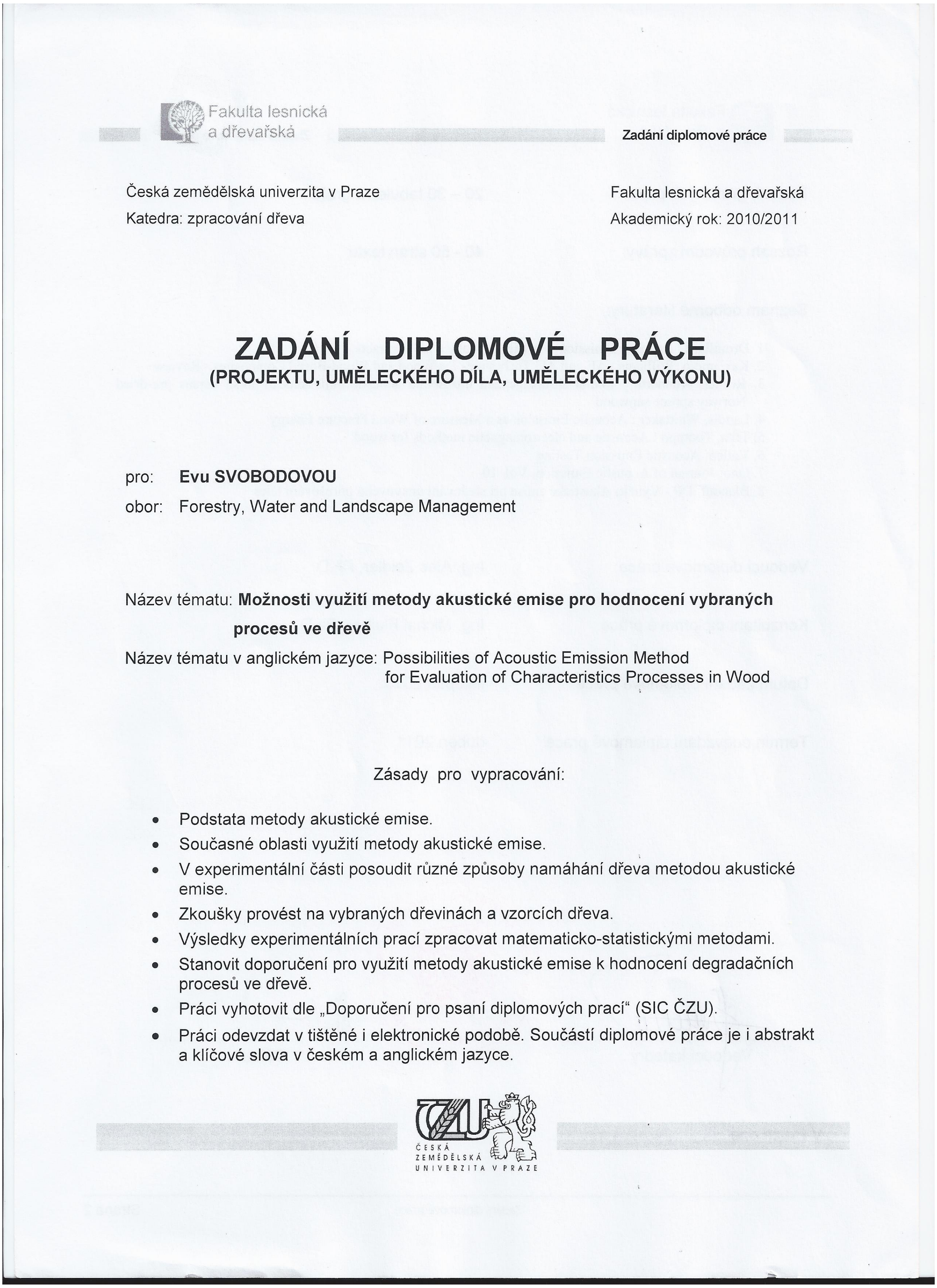
Author: Bc. Eva Svobodová

Study Program: Forestry, Water and Landscape Management

Supervisor: Ing. Aleġ Zeidler , Ph.D.

Consultant: Ing. Michal Kloiber, Ph.D.

Year: 2011



Fakulta lesnická a dřevařská

Zadání diplomové práce

Česká zemědělská univerzita v Praze
Katedra: zpracování dřeva

Fakulta lesnická a dřevařská
Akademický rok: 2010/2011

ZADÁNÍ DIPLOMOVÉ PRÁCE
(PROJEKTU, UMĚLECKÉHO DÍLA, UMĚLECKÉHO VÝKONU)

pro: **Evu SVOBODOVOU**
obor: Forestry, Water and Landscape Management

Název tématu: **Možnosti využití metody akustické emise pro hodnocení vybraných procesů ve dřevě**

Název tématu v anglickém jazyce: Possibilities of Acoustic Emission Method for Evaluation of Characteristics Processes in Wood

Zásady pro vypracování:

- Podstata metody akustické emise.
- Současné oblasti využití metody akustické emise.
- V experimentální části posoudit různé způsoby namáhání dřeva metodou akustické emise.
- Zkoušky provést na vybraných dřevinách a vzorcích dřeva.
- Výsledky experimentálních prací zpracovat matematicko-statistickými metodami.
- Stanovit doporučení pro využití metody akustické emise k hodnocení degradačních procesů ve dřevě.
- Práci vyhotovit dle „Doporučení pro psaní diplomových prací“ (SIC ČZU).
- Práci odevzdat v tištěné i elektronické podobě. Součástí diplomové práce je i abstrakt a klíčové slova v českém a anglickém jazyce.

ČESKÁ ZEMĚDĚLSKÁ UNIVERZITA V PRAZE

Rozsah grafických prací: 20 – 30 tabulek a grafů

Rozsah průvodní zprávy: 40 - 50 stran textu

Seznam odborné literatury:

1. Drouillard : Acoustic Emission - A Bibliography with Abstracts
2. Kawamoto, Williams : AE and AU Techniques for Wood and Wood-Based Composites - Review
3. Rosner, Konnerth : Radial shrinkage and ultrasound acoustic emissions of fresh versus pre-dried Norway spruce sapwood
4. Landis, Whittaker : Acoustic Emission as a Measure of Wood Fracture Energy
5. Tiita, Tomppo : Acoustic and electromagnetic methods for wood
6. Vallen: Acoustic Emission Testing
7. Ono: Journal of Acoustic Emission, Vol. 10
8. Blahout: DP - Využití Akustické emise při sledování únavového porušování těles

Vedoucí diplomové práce: Ing. Aleš Zeidler, Ph.D.

Konzultant diplomové práce: Ing. Michal Kloiber, Ph.D.

Datum zadání diplomové práce: listopad 2010

Termín odevzdání diplomové práce: duben 2011

L.S.

.... Vedoucí katedry

.... Děkan

V Praze dne ....…....

I declare that this thesis was composed by myself with the help of mentioned literature.

Acknowledgement:

I would like to thank...

... to Ing. Aleġ Zeidler, PhD. for the supervising of my thesis

... to company Preditest, s.r.o. for lending me whole equipment

... to Doc. Ing. JiŚí CEJP, CSc. from CVUT Prague for providing the tests

... to Ing. Michal Kloiber, PhD. for many usefull advice

... to my family, for supporting me

Abstract

The main containt of this work is the theoretical and experimental work on Acoustic Emission method as a means for evaluation of damaged processes in wood material.

At first part of study the main emphasis was given to general application of acoustic emissin response during loading different type of material.

Some theoretical knowledge was shown describing the type of burst AE signal generating in damaged areas of loading materials. In the experimental program three various damaged mechanism were proposed for three type of coniferous wood specimens ï Norway spruce *(Picea abies* L. *)*, Scots pine *(Pinus sylvestris* L*)*. and Silver fir *(Abies Alba* Mill.*)*.

During various loading processes acoustic emission signals were registered and evaluated in relation on acting force, distance of pin penetration into wood and during three point bending test. Also special Compact Tension (CT) specimens were used.

Activity of acoustic emission signals were compared with observation of damaged areas of wood samples.

Different types of load of wooden specimens can be described by acoustic emission activity. As it was supposed, AE activity was in good relation with damaging processes.

Table of content

1. Introduction

Non-Destructive testing (NDT) is defined as the technical method to examine materials or components. NDT can be used to detect, locate, measure and evaluate cracks, to asses integrity, properties and composition. Various NDT technologies, such as ultrasonic-based methods, radiographic methods, dynamic methods, acoustic emission (AE) techniques, and acousto-utrasonic (AU) technique have been studied. Each NDT technique has both advantages and disadvantages ï limitations of range use with regard to cost, speed, accuracy and safety.

NDT research on wood and wood materials started in the USA in 1980. NDT research includes measurement of physical and mechanical properties, grading of materials, and monitoring of defects in trees, logs, solid wood, sawn timber and lumber, engineered wood and composite products. (Kawamoto, 2002)

Acoustic emission applications for wood processing are relatively new, is developing in time and from obtained knowledge is being improving. On the beginning main emphasis was given to the questions of propagation and attenuation of ultrasonic waves in wood and associated measurement problems.

The properties of wood, unlike those of other materials, vary with respect to species,cracks and inhomogenities. No other material shows such as much anisotrophy as wood does. As a consequence, individual specimens, even those cut from the same board, often have different properties. In addition, AE responses are more variable in wood than in other materials. Although some investigation describe NDT techniques as usefull in detecting cracks in metals, polymers and ceramics, these techniques have had only limited succes in the wood.

More fundamental research is required to identify wood properties that affect wave propagation and attenuation, such as density, defects, and moisture content. (Kawamoto, 2002)

1.1. Aims of the study

The main aim of the study was concentrated in two parts.

In the first part, main affort was to collect theoretical possibilites of using of acoustic emission on wood and summarized various experimental works done with researchers around the world.

Second part was practically oriented on fracture tests on various wood specimens with acoustic emission measurement. Damaging processes are acompanied with the acoustic emission signals, which can be registered and evaluated.

2. Acoustic Emission Technique

Term of Acoustic emission (AE) historically appeared in 50´s of last century and is connected to the J. Kaiser. The AE phenomenon describes processes which occure in the various materials, where elastic stress waves are generated on base of various stimuls (pressure, force, temperature, chemical processes). This waves are propagating in the material and by means of its detection and analysis is possible to obtain information how the process occurs. (Svoboda, 2011)

All solid materials have certain elasticity. They become strained or compresses under external forces. The bigger is the elastic deformation, the higher is the stored elastic energy. If the elastic limit is exceeded a fracture occurs immediately in case of a brittle material, or it can occure after certain plastic deformation.

Definition of Acoustic emission, as a elastic stress waves, is sudden release elastic energy in material.

This rapid release of elastic energy is what we call an AE event. It produces an elastic wave that propagates and can be detected by appropriate sensors, and analyzed. The impact at its origin is a wideband movement (up to some MHz). The frequency of AE testing of metallic objects is in the ultrasound range, usually between 100 and 300 kHz.

AE testing is passive, receptive technique analyzing the ultrasound pulses emitted by a defect at the moment of its occurence. In contrast to the ultrasound technique one does not measure the response to an artificial and repeatable acoustic excitation of the test object. Instead, the sound signals which are produced by defects are evaluated every growth of a defect is a unique event and can not be exactly reproduced again.

The AE analysis is a dynamic technique. AE occurs when a crack grows or when the crack borders rub against each other, e.g. when a crack closes after relaxation of the test object. Usually, the test object must be stressed exceeding the operating level in order to have local defects grow and emit acoustic emission. Therefore AE analysis is the appropriate technique especially in those cases, where test objects are anyway stressed more than under normal conditions.

Acoustic emission monitoring can overcome many of the difficulties with the crack detection in service and is potentially a most powerfull method of inspections. It is sensitive to the propagating cracks, that is, the structurally significant defects, and provides information on growth rate under service loading conditions, guiding inspection and repair work for maximum cost effective maintenance. (Rogers, 2001)

2.1. Comparison of Acoustic emission to various NDT methods:

Acoustic Emission	**Other NDT methods**
- detects defect movements	- determine the size of defects
- needs loading of the structure	- constructions without loading
- every loading is original	- inspection can be repeated
- sensitive according to the material	- less sensitive on material
- less sensitive on the geometry (structure)	- more sensitive on geometry
- less dependant on service of structure	- more dependant on serivce of structure
- access to the sturcture only where sensors are fixed	- whole structure must be inspected
- inspection whole structure in the same time	- inspection is provided step by step
main problem: is sensitive on level of background	**main problem**: is very sensitive on the geometry

- one of the very practical advantage of acoustic emission is inspection of whole volume of structure and from this point the big and complicated structures can be inspected in one time

- application range of acoustic emission is very wide: from the point of view of volume it is acoustic emission inspection in seismic effects (earthquake) to comparison with investigation of dislocation movement in small volume in materials
- in between of this two extremes there are many applications of acoustic emission in the laboratory conditions and also in the various industries (Hartman et al., 1979)

Main factors influencing acoustic emission of material (Mazal, 1999)

Material characteristics	Factors favourable for signals with big amplitude	Factors causing signals with small amplitude
Mechanical qualities	High Mechanical resistance	Low mechanical resistance
Structure	Anisotrophy	Isotrophy
	Heterogenity	Homogenity
	Presence of defect	Material without defects
	Tenedency to twinning	Difficult twinning
	Casting structure	Formed structure
	Welding structure	Structure without stress
	Big-grained structure	Fine-grained structure
Method of fracture	Spreading of cracks	Homogenous plastic deformation
	Splitting fracture	Deformation by slip
Method of loading	High deformation speed	Low deformation speed
Geometry	Considerable thickness	Low thickness
Environment	Low temperatures	High temperatures

The main purpose of Acoustic Emission Testing is the detection of growing defects (cracks) of stuctures (tanks, pressure vessels, reactors, piping systems).

The detection of deffects is performed by measuring and analyzing acoustic emission signals, typically within the frequency range of 20 kHz up to 2 MHz.

Because of its capability to detect defects right at the moment of their growth, the AE technique may also be used as a real-time monitoring and warning system to avoid a failure of the structure under test with possibly disastrous consequences.

AE testing is very well suitable for a large number of applications, particularly for those, which are not accessible by other testing methods.

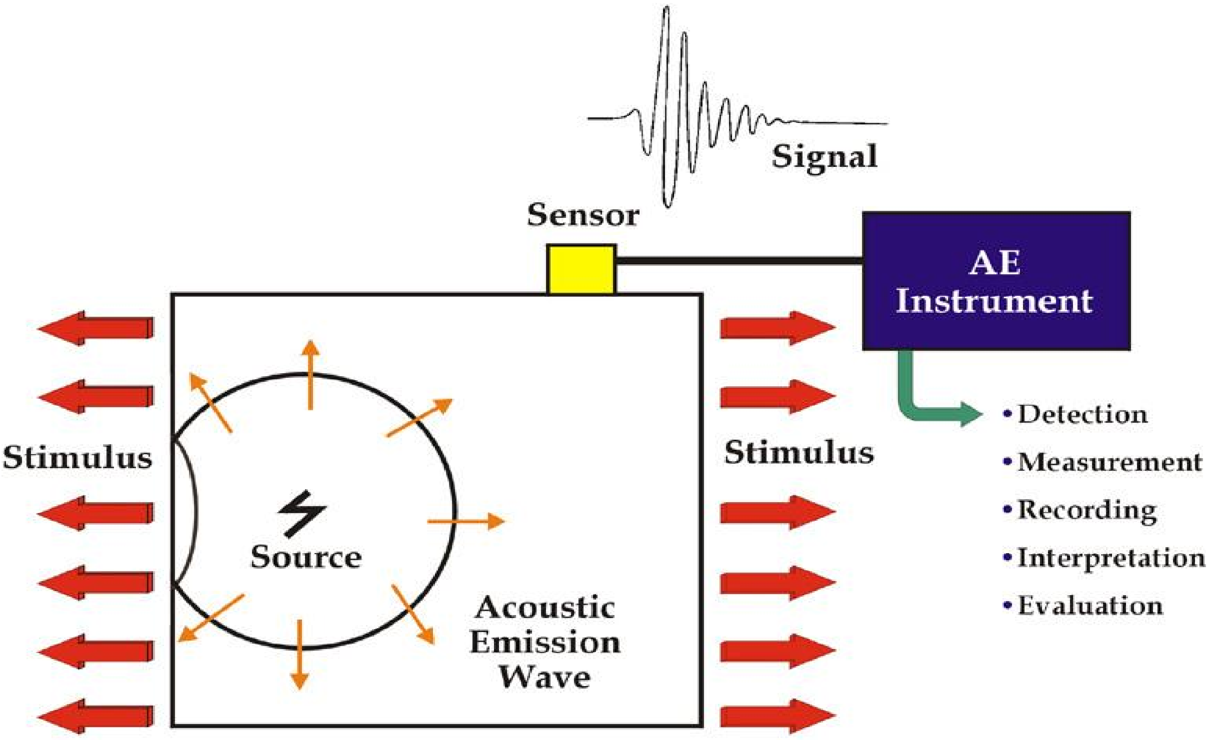


Figure 1: Schematic view of creating AE signals in materials

2.2. Terminology

AE	A transient elastic wave produced by rapid release of (elastic) energy or during certain processes
AE ï Event	A physical event causing AE, e.g. crack formation
AE ï Source	The physical origin of one or more AE events. This can be a crack, growing step by step. Each growing of the crack is an AE event.
AE ï Signal	The electrical signal of the sensor resulting from AE
	Transient signal,burst AE signal with clearly detectable start and end
Hit	A burst detected by the AE System

AE ï Activity	Occurence of AE signals as a result of AE
AE ï Channel	Single AE sensor including the associated instruments for the acquisition and measurement of the AE signals = measurement chain
Multi-channel system	System providing multiple AE channels, e.g. for source location, or for examining areas too large for one sensor
Hsu - Nielsen AE source	Artificial source used for calibration of AE sensors located on the structures

AE parameters

In very few cases, AE testing is based on only a few bursts. In general, some hundreds thousands of bursts are recorded for statistical evaluation. Statistical evaluation of the waverforms themselves is difficult. But there are certain features of waveforms which can be evaluated statistically. One has to determine the most important parameters of each waveform in order to compare the results of the structure under test with those of a defect-free test object and with those of a defective test object. which can be

The most commonly used features are (see figure 2):

- Arrival time (absolute time of first threshold crossing)
- Peak amplitude
- Rise-time (time interval between first thresthold crossing and peak amplitude)
- Signal duration (time interval between first and last threshold crossing)
- Number of treshold crossings (counts) of the threshold of none polarity
- Energy (integral of squared - or absolute - amplitude over time of signal duration)
- RMS (root mean square) of the continuous background noise (before the burst)

AE bursts are not only produced by the defects we are looking for but can also originate from drop-ins such as peak values of the background noise, which sometimes exceeds a low treshold. Therefore, it is very important to determine those characteristics that distinguish the wanted, from the unwanted bursts.

The peak amplitude is one of the most important burst features. Crack signals show medium to high amplitudes and have durations of some 10 εs, depending on the test objects´s properties.

In most cases, burst with less than 3 treshold crossings and durations of less than 3 εs can be regarded as unwanted signals. Most of the bursts with low amplitudes and long duration are friction noise. Very short signals may indicate electrical noise peaks, especially, if they arrive at all chanels at the same time. (Vallen, 2006)

In the following Figure 2 there is typical shape of acoustic emission signal ï so called acoustic emission event - with remarked features which are used for its evaluation.

Paralell to this event, acoustic emission equipment is registerating arrival time from place, where event has origin to the place, where sensor is located.

Using multi-channel AE systems than allowes to determine origin acoustic emission event at least from three different AE sensors placed on the structure. In complicated, large structures, the sensors are placed to cover whole volume of the structure. Distance between individual sensors is determined by attenuation of AE signals, usually measured before placing the sensors. This is usually done by using Hsu - Nielsen AE source.

Simplest case is linear location (for example on the pipe-lines or beams) where two sensors are used in certain distance on the surface of beam.

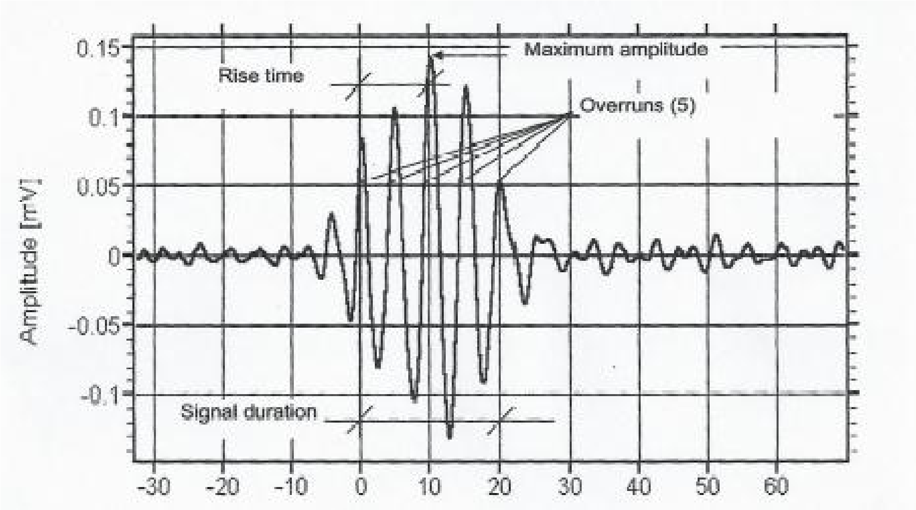


Figure 2: Features of transient signals

2.3. Two basic types of AE signals

a) Burst emission signal, which has timely-separated acoustic emission events, see Figure 3

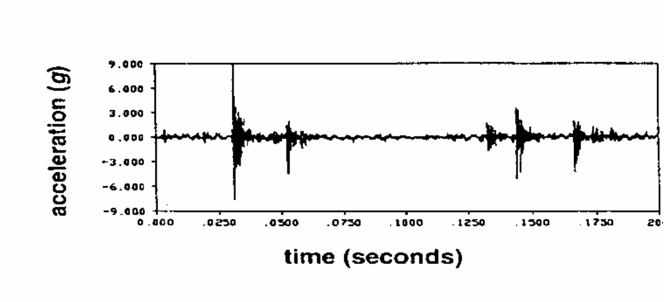


Figure 3: Burst emission signal

b) Continuous emission signal, which can not be timely-separated

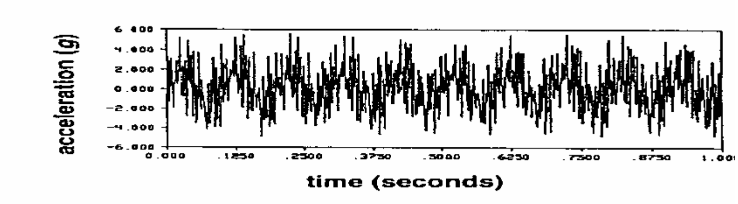


Figure 4: Continuous emission signal

2.3.1. AE response during loading

In the Figure 5 is described AE response during the loading process of steel construction up to the ultimate stress limit.

Loading curve shows yielding point which divides elastic and plastic deformations.

It can be seen very clearly that during the elastic loading the acoustic emission rate reached its maximum coming to the minimum during the plastic processing and again is increasing before reaching the failure point.

Kaiser effect has its role during the elastic loading whereas the Felicity effect plays its role in the plastic area. See Figure 7, where it is explained.

Main sources of AE signals during the elastic region are:

- dislocation movement

- fracture of slug inclusions
- creating the microcracks
- brittle fracture of particles

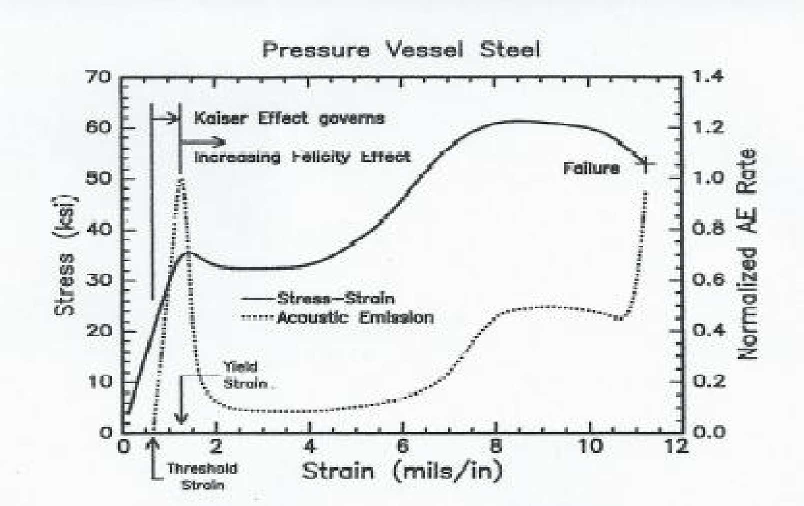


Figure 5: AE behavior of typical pressure vessel steel

Figure 6 gives relation between the load and acoustic emission response for reinforced laminate and materials with similar behavior.

Loading curve doesn´t show strong yielding point between elastic and plastic deformation. Acoustic emission has on the beginning linear behavior and when load is increased, AE activity is rapidly increasing.

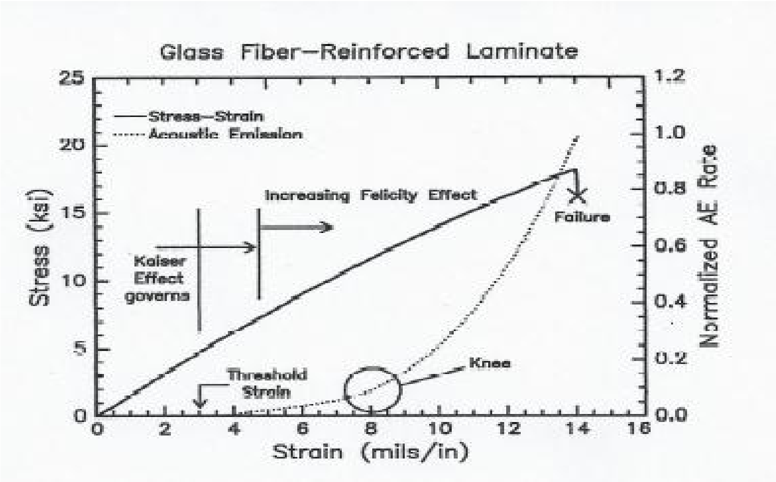


Figure 6: AE behavior of typical fiber-glass-reinforced laminate

2.4. Basic evaluation of AE signals

Some of the materials during the loading and unloading show the phenomenon, so called Kaiser effect. Kaiser discovered that the investigated material creates acoustic emission only when the maximum previous stress on the specimen is exceeded. In scope of this testing period it practically means, that specimens has no active defects, which will created acoustic emission signals. See figure 7 - bottom parts of graph, bounded by points A, B and C.

If a structure after release and during a second loading emits AE signals before the maximum of the first loading is reached, thereby violating the Kaiser-effect, this may indicate a defect. This procedure is very often used during testing of pressure vessels and other structures, mainly made from steels.

Second case can be by increasing the loading and again unloading, and repeating loading, the AE signals are registered before reaching the maximum load. This effect is called Felicity effect, which represents active defects in the structure and in many cases plastic deformation of the material in localized area. On the structure this can be located as a AE source. Felicity effect is bounded on Figure 7 by points D,E, F.

If during constant load rate of AE activity is rapidly increasing, very quickly becomes failure of structure, which has a very practical importance from safety point of view. See Figure 7, point G and H.

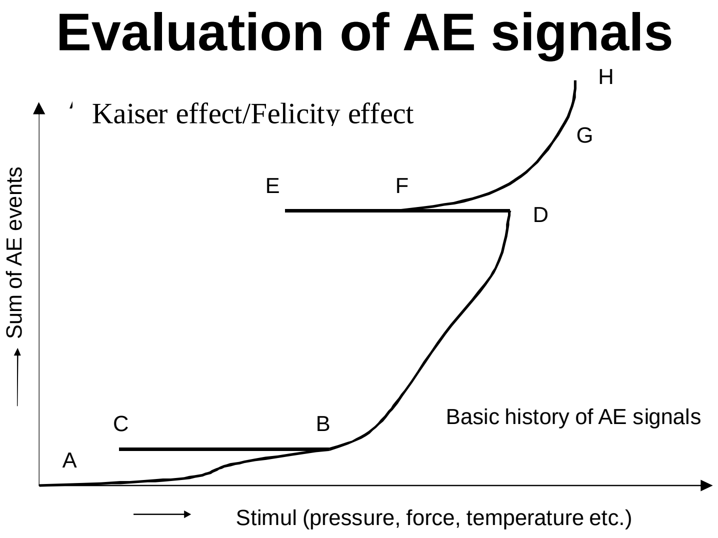


Figure 7: AE Signal Evaluation

2.5. Possibilities of application of Acoustic Emission Method

Acoustic emission is used to nondestructively monitor structural integrity and characterize the behavior of materials wen they undergo deformation, fracture, or both. Unlike ultrasonic or radiographic techniques, AE does not require external energy - acoustic emission is released from the test object itself. AE is the only NDT method that can be used to monitor defects during manufacturing. Other conventional NDT methods require that the line be interupted to test the materials. Acoustic emission techniques have been used for monitoring components and systems during manufacturing, detecting and locating leaks, mechanical property testing, and testing pressurized vessels. (Svoboda, 2011)

Advantages and Disadvantages

The advantages of AE techniques are the follows:

a) The position of developing cracks can be determined. The AE source can be determined from the time differential of AE signals among several AE transducers.

b) The classification and direction of cracks can be calculated by AE waveform analysis using moment tensor components.

c) The dynamics of the materials can be observed in real time.

The disadvantages of this method are as follows:

a) It is difficult to discriminate real AE signals from back-ground noise during measurement.

b) For some materials, the generation of AEs does not occur until the material is loaded close to the proportional limit of the deformation.

c) The output signal of the AE transducer is the combination of the AE source wave propagation, and transducer response. For wood or wood-based materials, unlike metal materials, small AEs generated from the wood cannot be detected as AE signals because of considerable attenuation of AE waves during propagation, unless appropriate transducers are used.

d) For wood, the wave velocities are 4 to 5 km/s for longitudinal (axial), 1,5 to 2 km/s for radial, and 1 to 1,5 km/s for tangential directions. Consequently, conventional AE source location techniques, which assume isotrophic velocity, cannot easily be used for wood.

3. Data Interpretation for Wood

The distance between the AE source and the transducers affects the results, particularly for materials like wood. Before AE parameters are interpreted, the effects of transducers, system sensitivity, background noise, and material properties should be taken into consideration.

In wood, attenuation and wave velocity are different for longitudinal (axial), radial, and tangential directions. Radial and tangential attenuation is larger than longitudinal attenuation. Individual specimens have distinct values. As for AE source location in wood and wood-based materials, the area where one transducer can distinguish the signals from the background noise should be taken into consideration.

Location software programmed for homogeneous materials should not be directly applied to solid wood, unless problems associated with snisotropic attenuation and heterogeneity can be solved. (Kawamoto, 2002)

Research on Wood

One of the first research with a new approach to the problem of failure prediction of wood components and structures was done by Adams (1969). He investigated that extension of cracks is acompanied by release of energy in the form of acoustic or stress wave emissions, which can be detected and have been found to be reliable indicators of crack growth. Using AE as a measure, crack growth was investigated in stress bending specimen of tree species. (Druillard, 1979)

The AE investigations for wood products can be classified into five fields:

1) Monitoring and control during drying

2) Prediction of deterioration (Wood decay)

3) Estimation of strength properties

4) Fracture analysis

5) Machine control

Most of the reserch works with acoustic emission is focused to the drying of wood - and its shrinkage.

3.1. Drying of wood

The use AE techniques to minimize defects during wood drying has been studied since 1980s. In early studies, methods were investigated for controlling kiln conditions by monitoring the AE count rate. The AE parameters used in the majority of studies were time-domain AE counts. The potential for using AE methods for contolling kilns was investigated by Honeycutt et al.(1985), Kagawa et al. (1980), Nochuchi et al. (1987), and Skaar et al. (1980). Noduchi et al. (1987) devised a feedback kiln controlling system for drying discs based on monitoring the AE count rate. Ogino and others (1986) used the cumulative AE energy determined by peak amplitude to predict checking in square cross-sections. Breeze and others (1986) used the cumulative AE energy determined by peak amplitude to predict checking during kiln drying without prolonged kiln residence time. Niemz and others (1994) compared signals detected by AE transducers to other priezoelectric transducers and indicated that AE transducers could be used to control wood drying.

Since 1985, the mechanism of AE associated with checking has been studied by various methods.

Acoustic emissions associated with early stress release during drying were investigated. Booker (1994) measured AE associated with surface checking of eucalyptus boards and hypothesized that AE was generated by intermittent slip in the crysalline regions of cellulose microfibrils in the cell walls. He reported that AE activity increased when surface elastic strain approached the proportional limit. Furthermore, the AE phenomenon was related to complex interactions between surface instantaneous strain and humidity/temperature change (Booker, 1994).

Acoustic emission associated with drying includes both emission generated by checking and emission generated by water movement. Early reports did not distinguish between these two possible causes of AE generation, although Rice and Skaar (1990) performed an experiment to detect AE associated with water movement in wood. Wood drying was monitored by measuring AE patterns generated from surfaces of wafers under transvers bending stress.

Okumura et al. (1987, 1989, 1992) and Kuroiwa et al. (1996) identified the mechanism of AE generation associated with water movement by observing AE waves generated during cyclic wetting and drying of the same specimen. Since thin small samples were used in this series of four studies, the efect of AE wave attenuation was negligible.

In the first study, Okumura et al. (1987) showed that AE activity was basically the same in each cycle. AE activty was not different between the specimens with and without slits at positions two-thirds the radial distance between the pith and the edge of the discs. In the second study, Okumura et al. (1989) showed that AE activity was similar in restrained specimens. As drying was completed, AE waves generated in a tangentially restrained specimen were associated with checking, but they did not affect the total AE event count, event rate, or amplitude distribution. The autors concluded that only a few AE waves are generated in conjunction with checking; most waves are generated from the whole volume of the specimen during drying.

In the third study, Okumura et al. (1992) showed that AE total events count corresponds proportionally to the rate of shrinkage at cross-sectional areas and is not affected by solvents used for chemical treatment. The autors also discussed the retardation of drying at the contact area with the transducer and dead time of the apparatus, both of which affect the AE count.

In the final study of this series, Kuroiwa et al. (1996) described differences between heartwood and sapwood in AE behavior associated with wetting and drying. Similar AE waves were observed for charcoal specimens during wetting and drying. Throughout this series of studies, AE was dependent on the length of the specimen tracheids.

In summary, several investigators have studied the characteristics of AE and the development of defects during wood drying. The majority of these studies used time-domain AE counts. The application of AE methods for controlling kiln conditions by monitoring the AE count rate has also been investigated. (Kawamoto, 2002)

Rosner (2009) was investigated during dehydration at ambient temperature Norway sapwood and sapwood exposed to the dehydration-reweting cycles in order to get information about the differences in dehydration stress. AE testing was performed. (Rosner, 2009)

3.2. Wood decay

Decayed wood generates AE at a lower stress level in bending than does sound wood (Beall and Wilcox, 1987; Noguchi et al. 1986). Noguchi et al. (1992) used partial compression to monitor early stages of decay in field tests. Raczkowski et al. (1999) also used AE measurement in a compression test in the radial direction to detect early stages of decay. Acoustic emission was used to detect termite damage using 150-kHz transducers in laboratory and field tests (Fuji et al. 1990, Noguchi and et al. 1991) Lemaster et al. (1997) investigated the effects of different AE transducers on detecting termite activity.

In 2001 Dunegan made a research works on detection of movement of termites in wood by acoustic emission technique. As a practical output of this research he developed instrument based on acoustic emission signals. (Dunegan, 2001)

3.3. Strenght properties

Porter (1964) used the AE approach to study wood fracture. Several early investigations were concerned with AE generated by bending tests of finger joint specimens (Porter et al. 1972, Dedhia 1980). Morgner et al. (1980) reported that AE was generated at a lower percentage of modulus of rupture for particleboard than for solid wood. Sato et al. (1990) hypothesized that AE is generated from the weak region at a lower stress. AE variables below the proportional limit of a static bending test were reported to correlate with proportional limit, strength, and ultimate deflection (Groom and Polensek 1987). After measuring AE during bending tests, Nakagawa et al. (1989) suggested that estimation of MOR could be improved by combining MOE and AE. Ayarkwa et al. (2001) reported that AE generated from bending tests of finger joints could be useful for predicting modulus of rupture.

Beall (1985) used AE to measure internal bond strength of wood-based materials. He also showed the effect of resin content and density on AE from particleboard during internal bond testing (Beall 1986). Ohtsuka et al. (1993) investigated AE behavior associated with the strength properties of adhesives in shear loading of plywood and analyzed the fracture mechanism by means of AE aplitude and source location. Sato et al. (1983,1984) investigated the mechanism of AE generation under tension. The researchers adhesive failure in plywood. Hwang et al. (1991,1993) used AE approach to study the durability of adhesives.

3.4. Fracture analysis

Ansell (1982) related the AE strain characteristics from softwood tested in tension to mechanisms of deformation observed by scanning electron microscopy (SEM). The correlation of AE total count with fracture toughness was reported. The realationship between fracture toughness and AE parameters was investigated though the observation of cleavage planes by SEM (Ando ond others 1991, 1992, 1995). Suzuki and Schniewind (1987) found a relationship between fracture toughness and AE during cleavage failure in adhesive joints.

Nakao applied the moment tensor method prosposed by Ohtsu to wood using large amplitude AE (Nakao 1990, Nakao et al. 1986, Ohtsu and Ono 1984).

Acoustic emission events were used to assess duration of load behavor in oriented strandboard during creep testing (Beall 1996). Fujimoto et al. (1999) performed a fracture toughness test during and after drying and found that characteristic of AE were related to the critical intensity factor and microfracture. Average AE amplitude during tensile pulsated load was found to increase in accordance with the stress term of internal friction (Kohara et al. 1999). Ogawa and Sobue (1999) measured AE generated by tensile force perpendicular to the fiber direction and discussed the effect of loading speed on crack propagation with respect to AE behavior. Berg and Gradin (2000) used AE monitoring during compression of spruce to investigate fracture history. The effect of temperature, strain, moisture content, and loading direction were investigated.

3.5. Machine control

Druillard (1993) included wood machining control in his bibliography of AE of bearings and rotating machinery. Lemaster et al. (1982) discussed the possibility of automating slow-speed cutting of wood using AE count rate. AE was found to be sensitive to both blade geometry and tool wear (Lemaster, 1990, Lemaster et al., 1985). Murase et al. (1995) reported the possibility of using AE to monitor wood sanding. Tanaka used AE for adaptive control optimization for feed speed of wood during cuttin (Tanaka et al. 1993, Cyra and Tanaka 1996). Lemaster et al. (1998) reported that AE corresponded to density frofiles of composite panels. AE was also used to measure surface roughness (Lemaster and Beall 1993).

3.6. Other research

Beall (1987) monitored AE generated during pyrolysis and combustion. Fuketa et al. (1993) performed AE source location in paper. Rasearch has also addressed the propagation properties of AE waves, propagation direction, and effect of moisture content (Bucur and Feeney 1992, Kawamoto 1994, Lemaster and Quarles 1990, Okumura et al. 1988). To estimate the moisture excluding effectiveness of surface coatings, Rice and Phillips (2001) used AE counts generated from weathered specimens immersed in water. (Kawamoto, 2002)

In 2008, Varner concentrated his effort on the detection of old-house borer (*Hylotrupes bajulus L.)* Wood pests impose a significant loses in the area of building and other industries. Thus, efective methods of non-destructive diagnostics are required to capture wood damaging activity. Their study inluded measuring of acoustic emission signals emitted by living old-house borer larvae feeding in wood samples. Using a small wood sample and single AE sensor, the experiment has proven that AE signals can be used to determine presence of feeding larvae. As the result, critical areas in the wooden constructions might be marked for repair/replace operation instead of complete disassembly.

Some experimental jobs were also done by Ģemliļka in 2007 to evaluate the possibilities of the old house borer (*Hylotrupes bajulus* L.*)* and its detection by acoustic emission method.

Generally can be stated, that the source of AE, in wood is created on base of micro and macro damage mechanisms during impact of various factors (loading, shrinkage, insect...).

4. Methods

Three types of measurement of wooden specimen were done. Concretly on Norway spruce *(Picea abies L.)*, Scots pine *(Pinus sylvestris L.)* and Silver fir *(Abies Alba Mill.).*The tree species were chosen from the reason of economical importance and simple structure of softwoods.

The following set of measuring equipment was used to make the measurements (except measuring of attenuation):

- 20-channel measuring system AE ACES IDT04
- piezoelectric AE sensors type PET04 , f_{rez} = 250 kHz with integrated pre-amplifier
- control computer with Pentium 4, 1.8 GHz processor
- PETK connecting signal cables

In general, this types of acoustic emission equipment can record and evaluate all features of emissions signals (hits, events, counts, amplitude, rise-time, duration, wave-forms). On the base of those characteristics of emission signal, the origin of various acoustic emission sources can be determined which correspond to damaging mechanism during the loading of specimen.

4.1. Measurement of attenuation of AE signal

To evaluate the way of propagation of acoustic emission signal in the wooden specimen was necessary to measure it´s attenuation with distance from the acoustic emission source. This was done by standard technique, where PEN TEST was used (Hsu - Nielsen-Source) according to Standard ASTM E976. It represents breaking lead 0,5 mm in the special pencil on surface of specimen. It generate acoustic emission signal of special amplitude which is propagating as a stress wave in the material.

For attenuation of the signal was used two-channel Pocket AE equipment produced by PAC (Physical Acoustics Corporation).

Pocket AE-1: Hand-Held Acoustic Emission System ï a computerized hand held instrument for AE testing and leak detection application. Due to its portable nature and full AE features and functions capabilities, this system can be used in any remote, short term AE application and evaluation, making it and ideal NDT test tool. (Physical Acoustic Corporation, 2007)

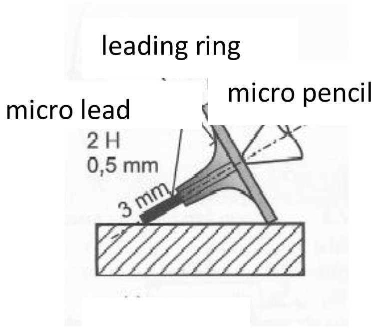


Figure 8: Pen Test (Hsu - Nielsen-Source)

This signal can be registered at various distances from the original source and attenuation of amplitude can be measured.

Attenuation was measured on specimen for three point bending test. Distance between individual measurement point 1 to 5 was 5 cm.

In the following figures, there is measured attenuation of AE signal from Pen Test (Hsu - Nielsen-Source) at the wooden specimen. It can be seen that for the length of specimen (300 mm), the attenuation is approximately (10 dB), so the distance between two sensors doesn´t influence the results due to the dispersion of initial signal.

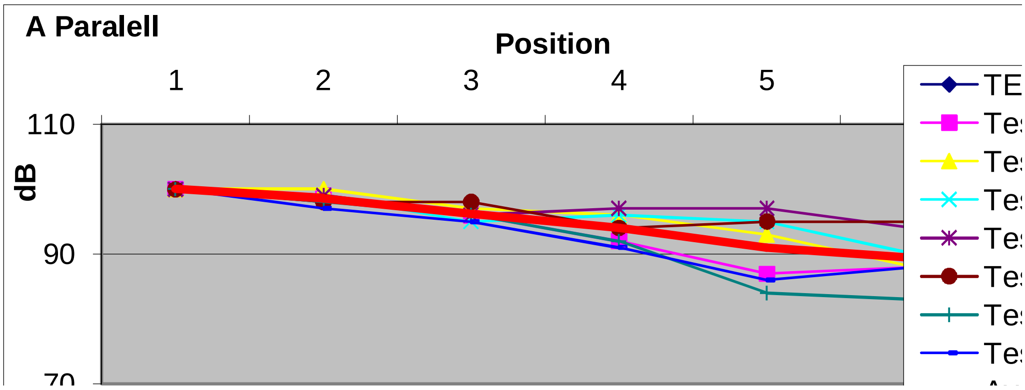


Figure 9: Attenuation of AE signal

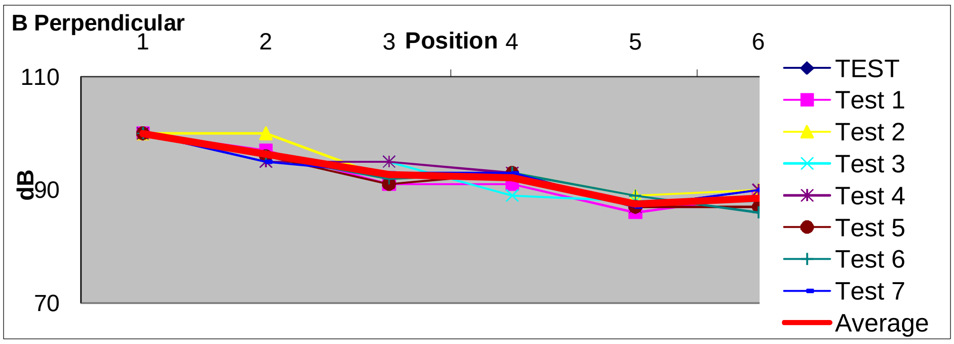


Figure 10:Attenuation of AE signal

4.2. Three-point bending test

First measurement was proposed to use standard testing technique according to Czech Standards for investigation of wooden properties ï ĻSN 49 0115. During testing of wooden specimen, acoustic emission was used to evaluate damaging processes. Increasing force, deflection and acoustic emission signals were recorded. It was proposed to use two acoustic emission sensors placed on the wooden specimen at the same distance from the middle where force was applied according to the standard ĻSN 49 0115.

ĻSN 49 0115

On the following figure, there is relationship of applied force and deflection of the specimen.

Wood has a strong visco-elastic behavior and by reaching the certain force the failure occurs.

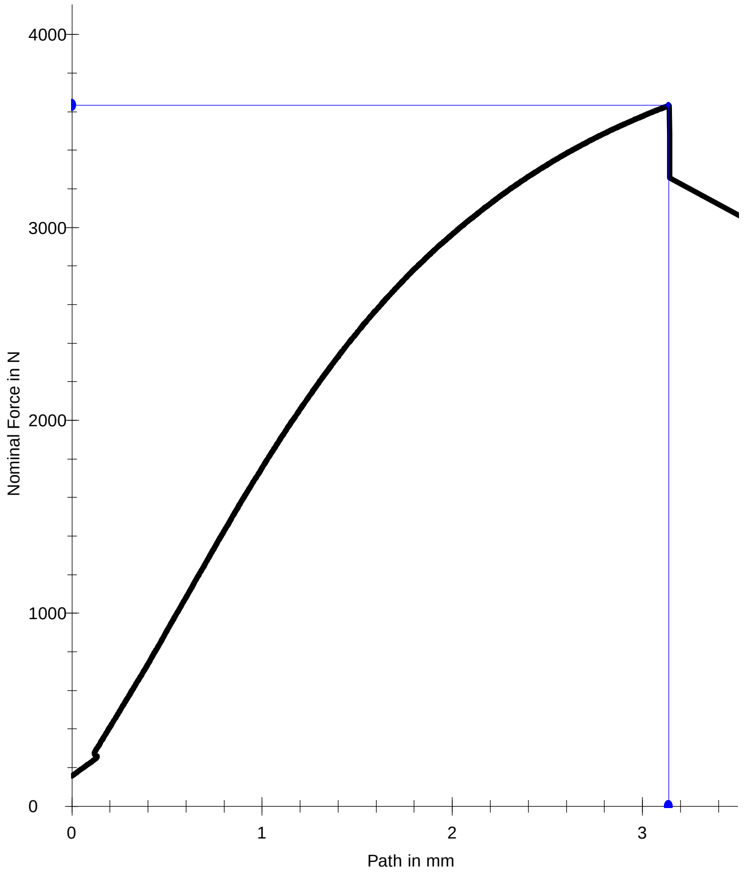


Figure 11: Relation between force and deflection during static loading

Figure 12 is schematic view of experimental setup for three point bending experiment. Force is applied uniformly in time by Instron loading machine.

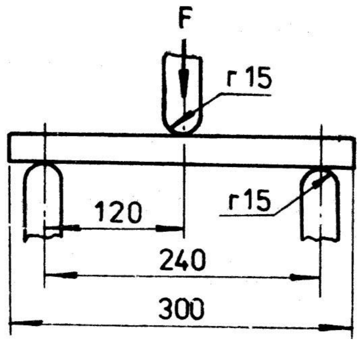


Figure 12: Schema of experimental setup

The **stress** in the specimen can be explained in the formula (1).

(1)

$$\sigma_w = \frac{3F_{\max} l}{2bh^2}$$

F_{max}..................maximum force [N]

l........................distance between supports [mm]

h.......................height of the speciman [mm]

b.......................width of the specimen [mm]

Strength of the wood is in the range of 65 to 150 MPa.

Damaging of wood in bending is usually break caused by maximum applied force. In this case, the failure occures on the tension side of the speciman. Cracks are continue spread across the neutral axis (a), or there is a complete damaging the body, either fibrous (c) or fragile (blunt) fracture (d).

The first damage is on the pressure side, where typical pressure deformation ocurrs (e). Another possible type of damage is crack in the neutral axis created by shear stress (f). By deflection of fibers the basic damage occures by tension (b).

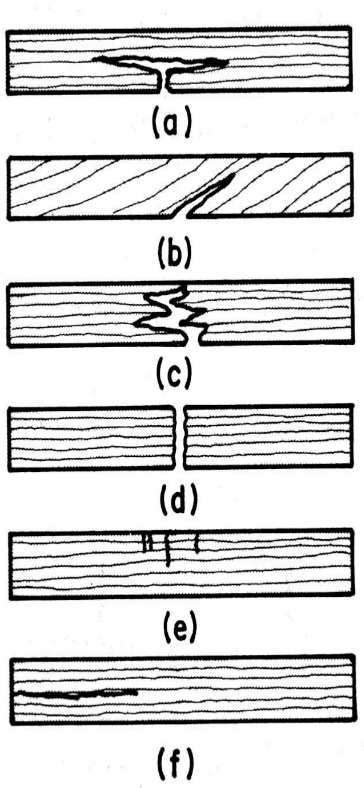


Figure 13: Possible damaging processes during bending of specimen

Experimental setup of specimen in testing machine Instron and placing of acousti emission sensors are shown on Figure 14 and Figure 15. AE sensors are placed on wooden sample by clips and AE contact between sensors and samples was made by ultrasonic gel (grease).

Figure 14: Preparation of specimen on INSTRON testing machine

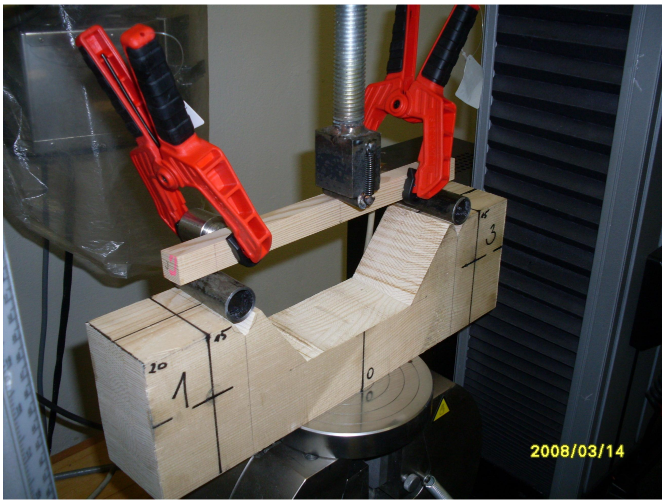


Figure 15: Acustic emission sensors placed on the testing specimen

4.3. Measurement of CT specimens

The second test was proposed to use so called CT specimens (Compact tension). This type of material testing is usually used and normalized to determine the fracture toughness of metal material. Fracture toughness is special material constant and its value is dependant on temperature. Schematic shape of CT specimen is on following Figure 16.

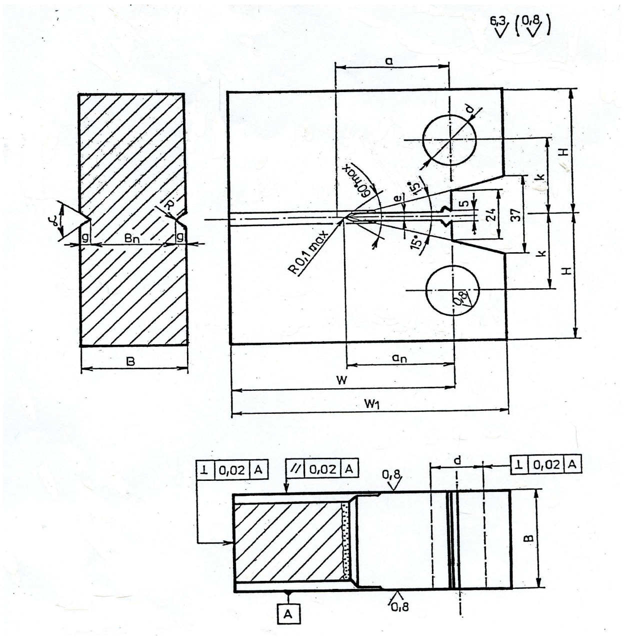


Figure 16: Schema of CT specimen

The main purpose of using CT specimen was to try evaluate similar behavior of fracture toughness like in the metal.

There is an equation for stress intensity factor for Compact Tension specimen (CT):

$$K_I = \frac{\mathrm{LOAD}}{BW^{\frac{1}{2}}} \cdot f\left(\frac{a}{W}\right)$$

K_{IC}.........................Stress intensity factor ï Fracture toughness

Load.......................Loading force

B, W......................Dimension of specimen

f (a/W)...................Special correction function of type of specimen (a=notch)

However one must consider that wood has strong anisotrophy behavior, which influenced the material characteristics in different directions.

For the test, two types of CT specimens were used due to big anisotrophy of structure. First type was with the initial notch in axial direction, second type was with the initial notch oriented in radial direction (to the stem axis).

Fracture toughness is combined with stress in material and defect type crack and allowes to evaluate critical lenght of the crack for certain load (stress). This type of tests are mainly used for various materials as a steel and alloys.

When origin material is degradating during the service (or in time), its properties, like fracture toughness are decreasing and structure becomes more weak and vulnerable in the case of external loading conditions. After the experiments, the failured areas of broken specimen for different type of wood were observed by microscope to investigate the damaging processes.

4.4. Pin Forcing

Third measurement_ was concentrated on forcing the metal pin into the wood specimen. The methodic consist of measurement of force, deflection and acoustic emission response during the process of forcing and pulling out the metal pin. On the figure 17. and 18. there is a view on the experimental loading equipment and acoustic emission measurement.

The special test apparatus was used for injection of metal pin into wood specimen. This apparatus was measuring the force and deflection in time.

This experiment was done at Institute of Theoretical and Applied Mechanics of Academy of Sciences CR with co-operation with Department of Wood Science, Faculty of Forestry and Wood Technology, Mendel University in Brno.

Figure 17: Preparation of the measurement

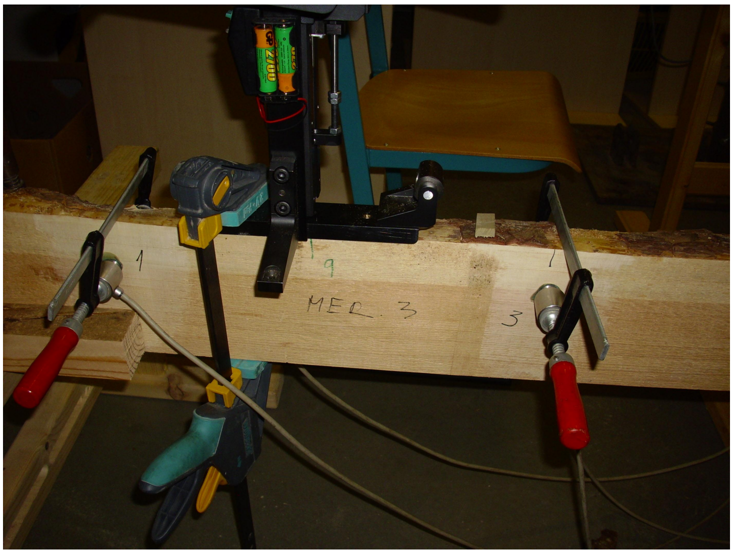


Figure 18: Wood specimen for the test

5. Results and Discussion

5.1. Three-point bending test

It must be said, that experimental results can be influenced by many factors, like age of the wood, density of wood, resin content, position on the trunk (higher density in bottom parts, lower in upper parts) and other factors. From those effects obtained results can show variability, because they are not identical.

5.1.1. Silver fir *(Abies Alba* Mill..*)*

In the figure 19., there is process of bending test on speciman 2.

Figure19: Speciman 2 after bending test

Figure 20: Local damage of Speciman 2 after bending tests

Results of Specimen 2 (representing)

On the Figure 19. and Figure 20. are shown detailed views of damaged areas after the test. It can be seen that the cracks are located in the middle of loading point and also in the middle of the specimen in direction of neutral axis.

Relation between applied force and acoustic emission activity, and also location of acoustic emission events is shown in Figures 21 a) and 21 b) and 21 c).

AE activity with higher amplitude starts when the load reached 0,75 kN and displacement is aproximately two mm. This range of loading corresponds to elastic deformation of specimen and acoustic emission activity is very low.

Next increase of load is represented with high acoustic emission amplitude, up to the point when load reached 1,7 kN and displacement 9 mm. This represents plastic deformation of specimen and creating the micro and macro cracks which are mostly located on the left side (see figure 21 c) - Localization) from the middle of specimen. This is confirmed by evidence of cracks on the figure 20.

Total failure (destruction) of specimen after the maximum load is acompanied by acoustic emission event with very high amplitudes.

Presenence of acoustic emission events with high ampitude means potential failure (creating local big cracks in the specimen). Cumulatin curve of AE events is increasing.

Other Results (in Appendix)

In the Appendix, there are similar result from the others specimens.

In comparison, all three tested specimens on the wood Silver fir are showing similar behavior.

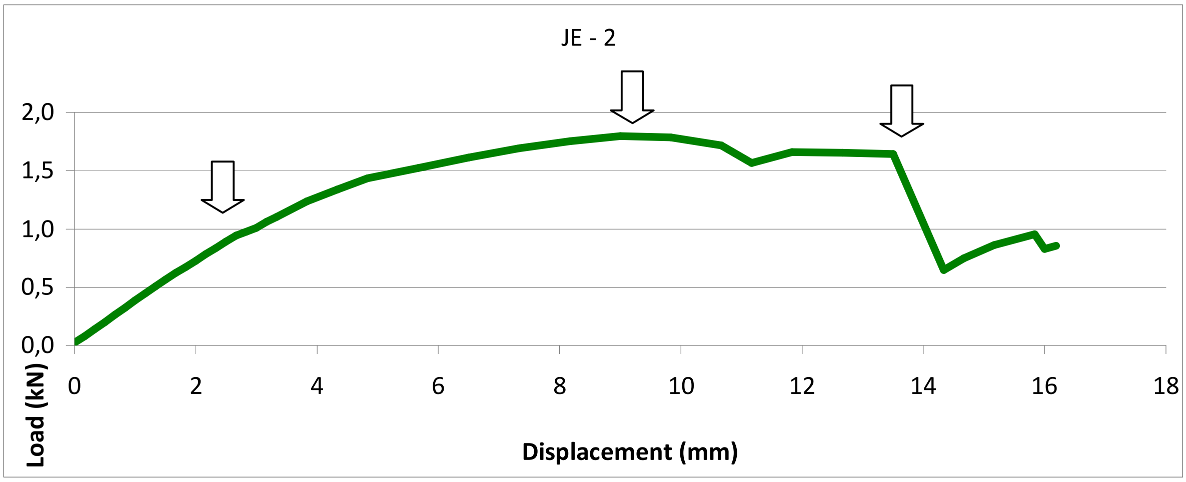


Figure 21 a) ï Working graph

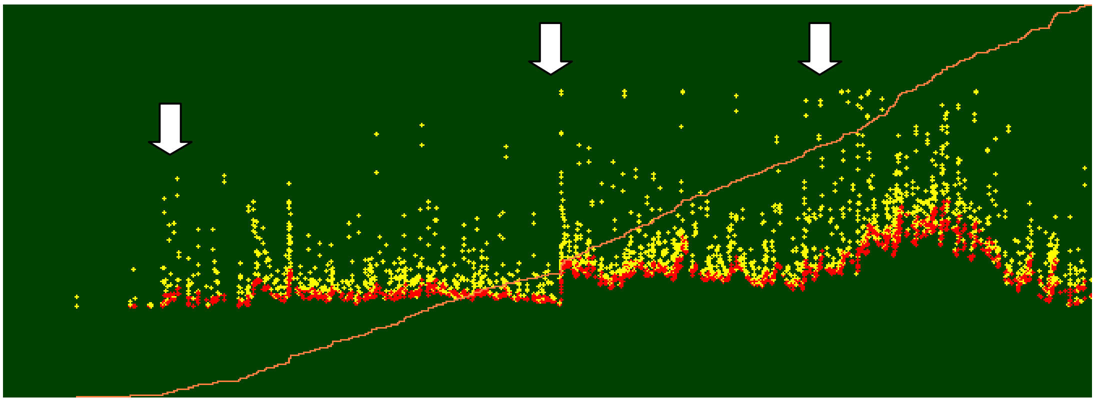


Figure 21 b) - Graph of Acoustic emission activity

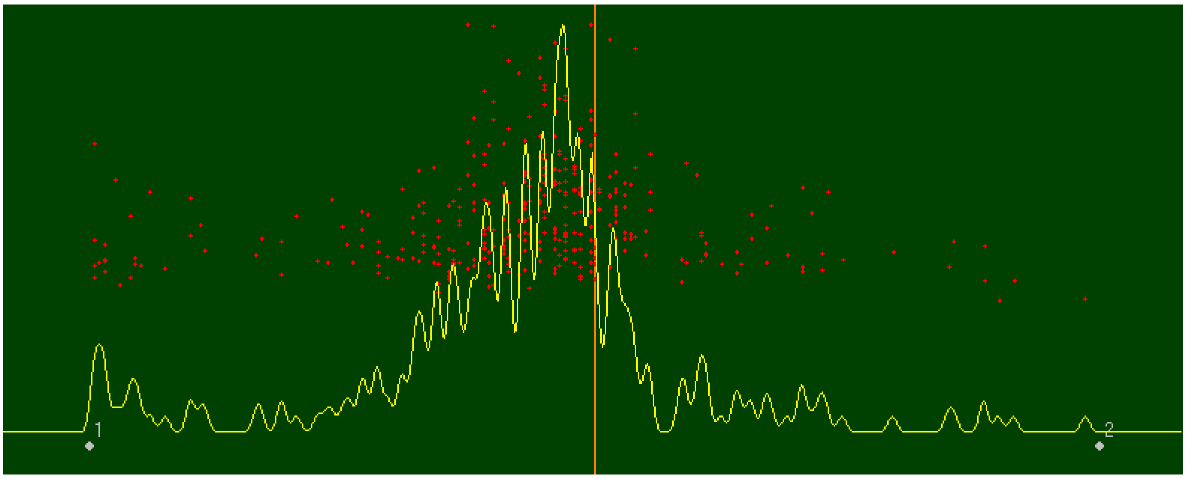


Figure 21c) - Localization of AE events

Sensor 1

Sensor 2

5.1.2. Norway spruce *(Picea abies L.)*

In the figure, there is result of bending test on specimen 2

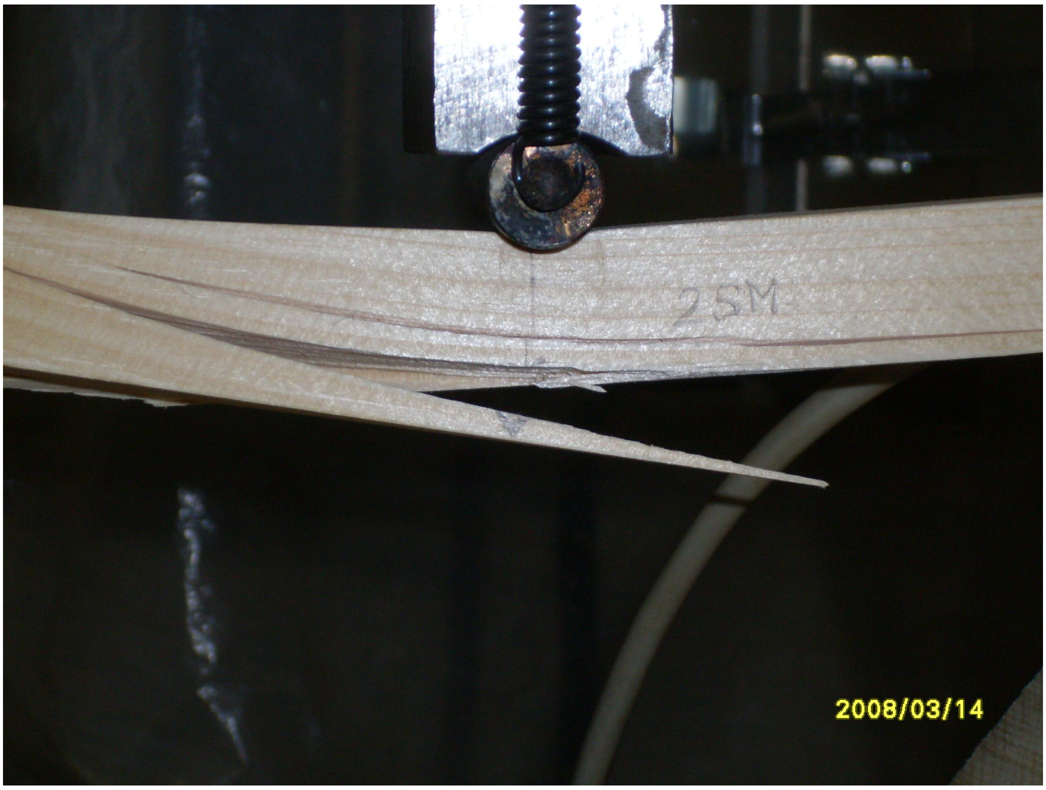


Figure 22: Specimen 2 after bening test

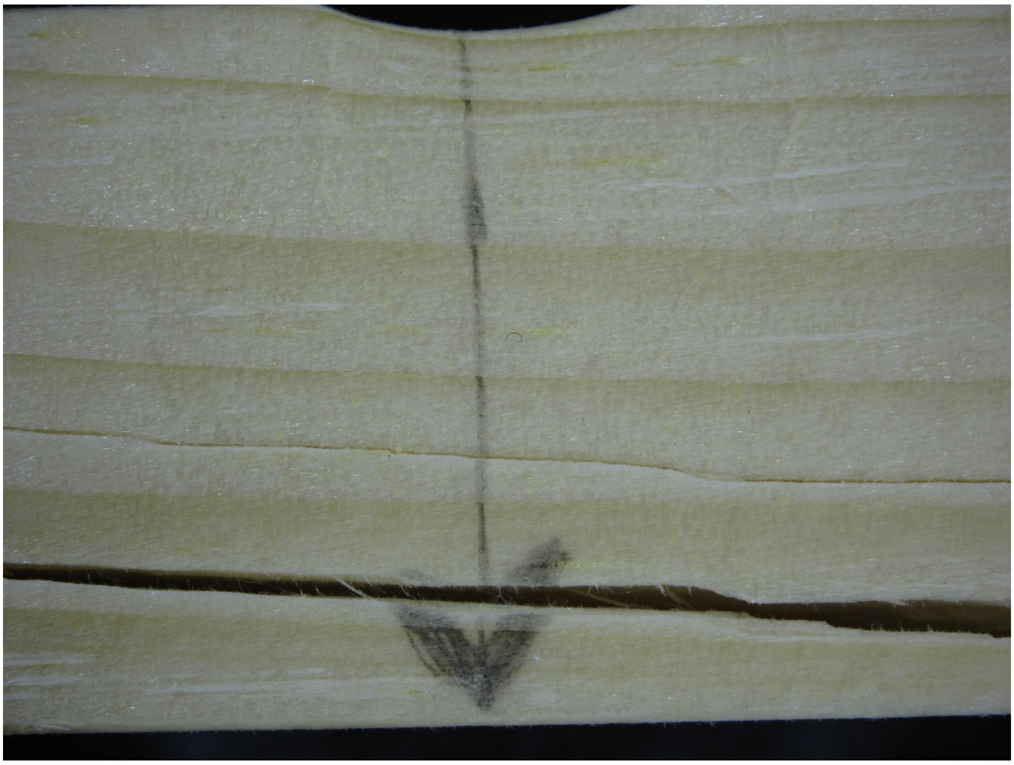


Figure 23: Local damage of Specimen 2 after bending test

Results of Specimen 2 (representing)

On the Figure 22. and Figure 23. are shown in details damaged areas at the end of the test.

Elastic loading of specimens has no active acoustic emission, as can be seen from the Figure 24 b). By increasing the force (in the Figure 24 a)), the acoustic emission activity is increasing as well, and there are AE events with higher amplitude.

Continuous increasing curve of acoustic emission events corresponds to the creating of high amount of small cracks.

Local areas of damage (created cracks), were acompanied with decreasing of the force and by occurence of high amplitudes of acoustic emission.

Cumulative curve of AE events is increasing proportionally. Again during the maximum load there were registered events with highest amplitude. High stressed area on the left side of loaded specimen led to create the magistral crack.

Localization graphs, (see Figure 24 c)) corresponds to created magistral crack determined in Figure 22.

Other Results are shown in Appendix.

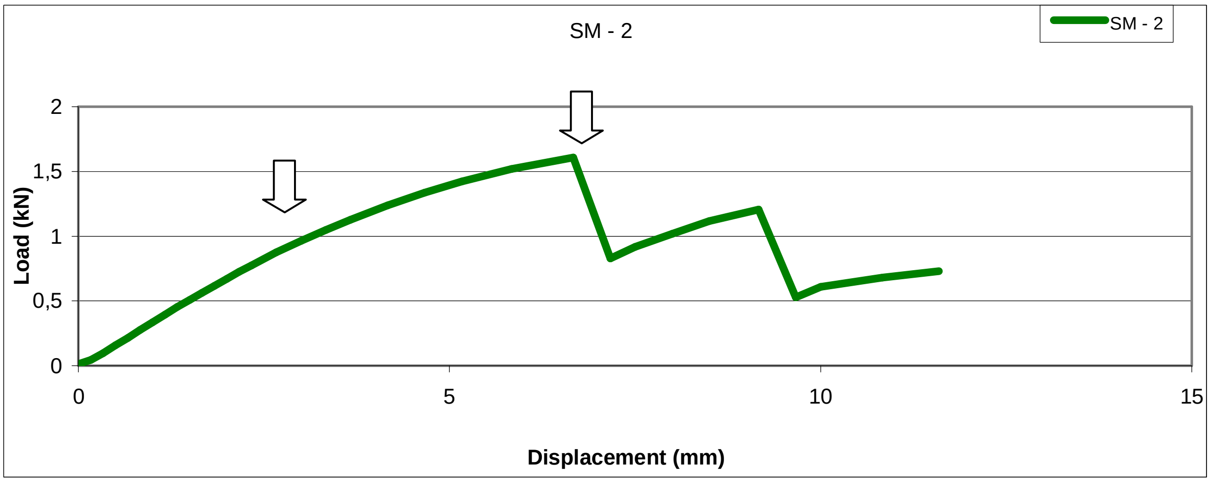


Figure 24 a) ï Working graph

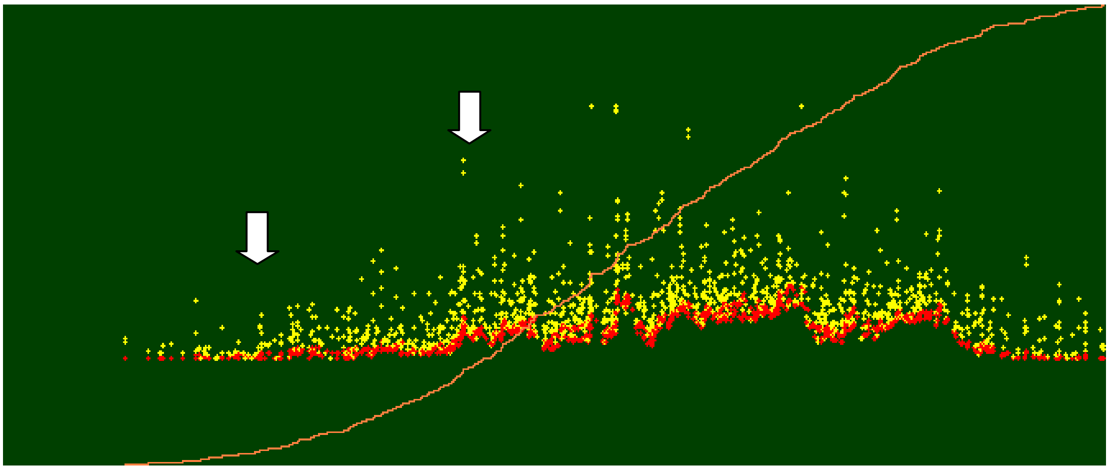


Figure 24 b) - Graph of Acoustic emission activity

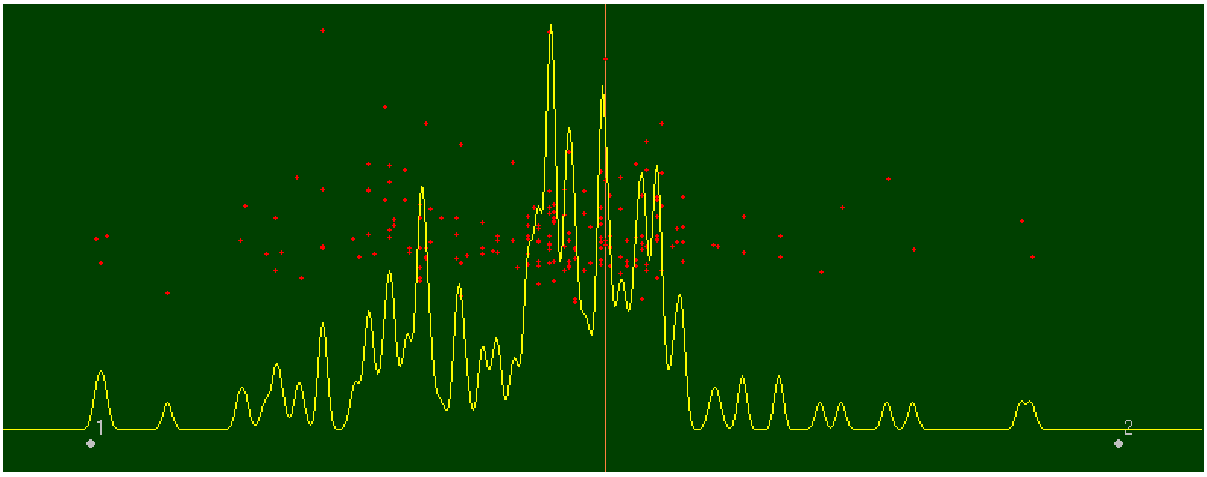


Figure 24c) - Localization of AE events

Sensor 1

Sensor 2

5.1.3. Scots pine *(Pinus sylvestris L.)*

In the figure, there is result of bending test on specimen 1

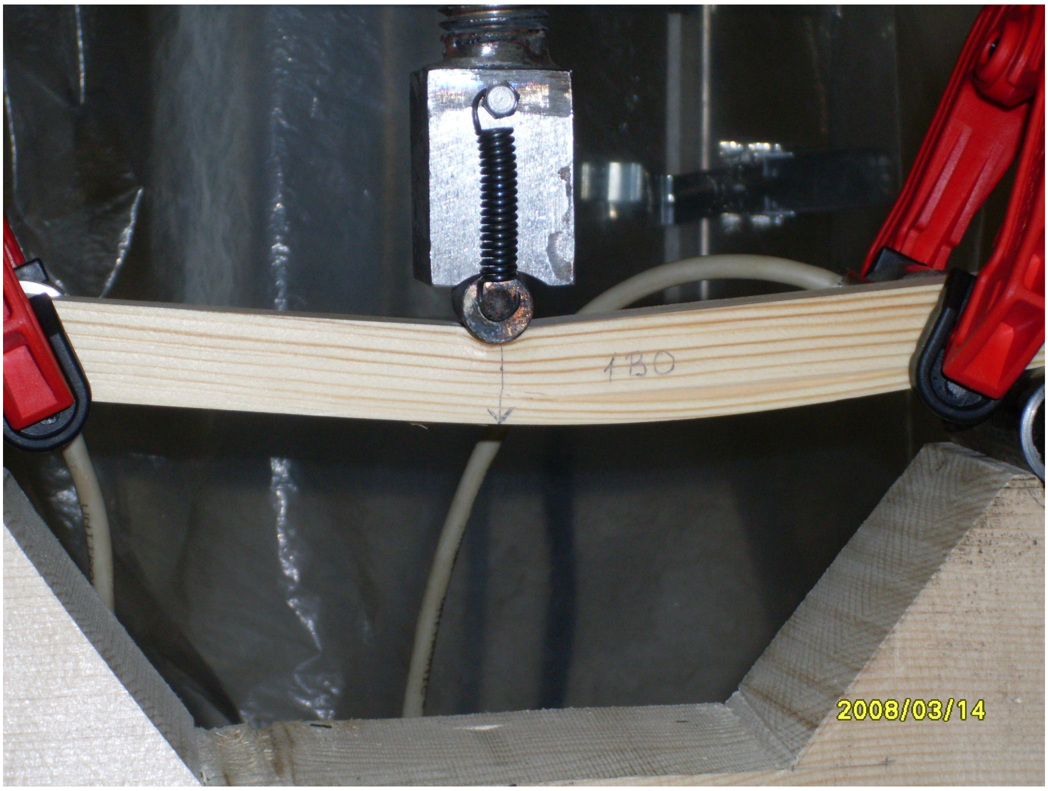


Figure 25: Specimen 1 bending test

Figure 26: Local damage of Specimen 1 after bending test (bottom view)

Results of Specimen 1 (representing)

In Figure 25. and 26. is a view on specimen after bending test. Loading curve on the beginning linear with no acoustic emission event.

When the load is increased, registered acoustic emission signals are with small amplitude and on the transfer point to the plastic area number of AE events is increasing and also with high amplitude.

By reaching the maximum load, the failure of specimens occurs and AE activity is increasing with the highest amplitude.

As it was said before, high amplitude means rising of the cracks which are localized on the right side of specimen, according to localization graph (Figure 27 c)) and proved on Figure 26 (bottom view of the damaged area).

Other Results (in Appendix)

Similar results were obtained in other specimens (see Appendix).

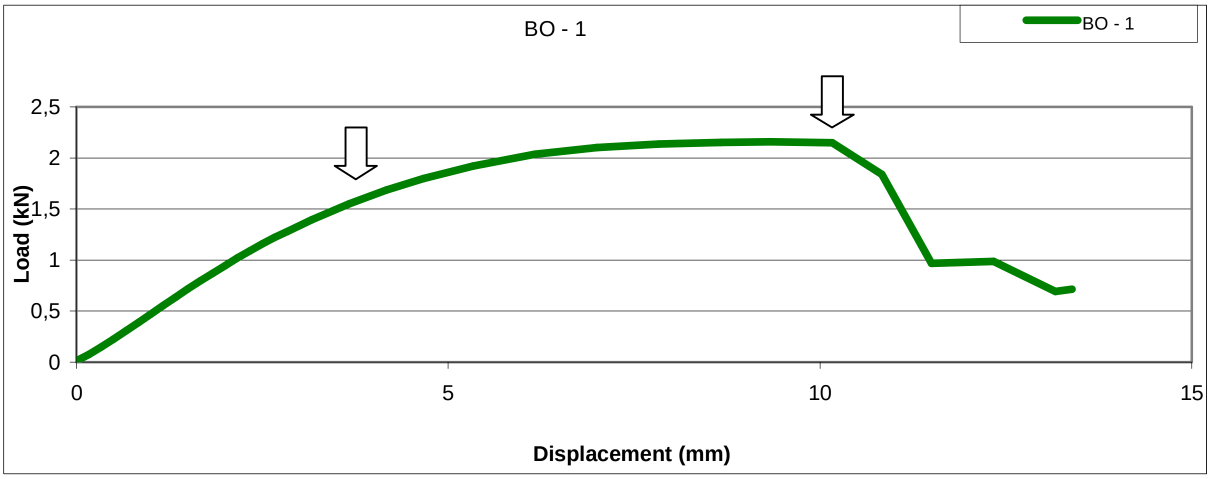
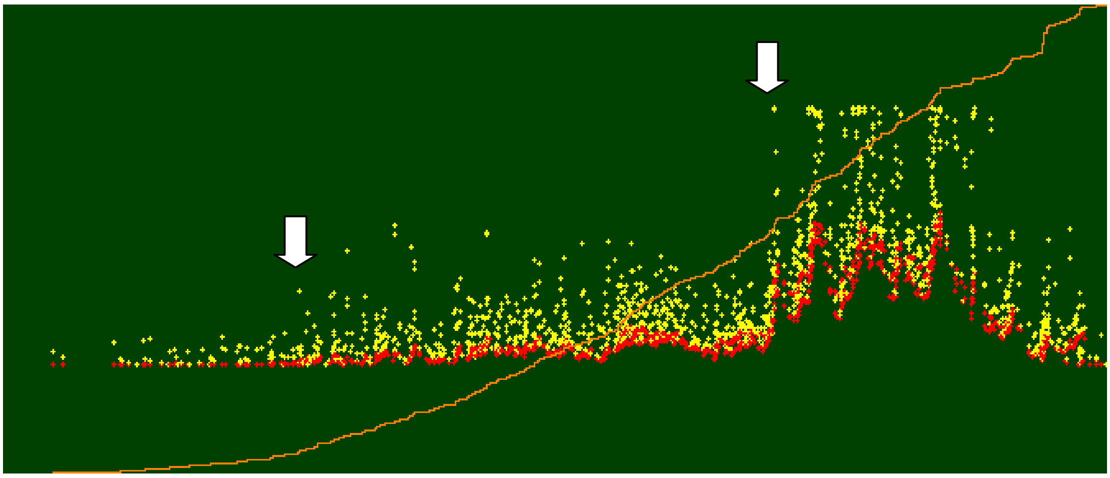
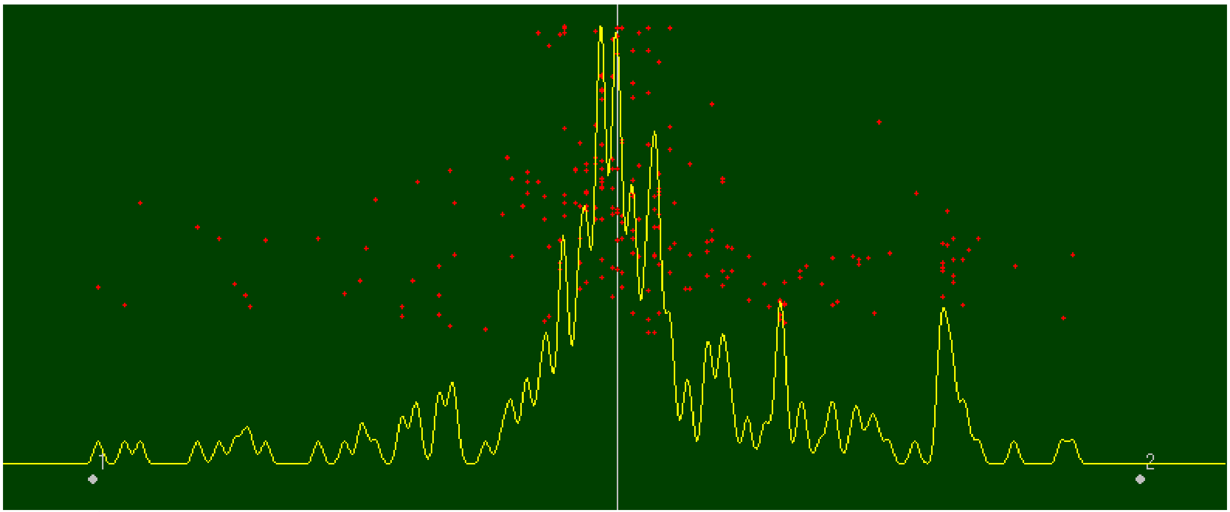


Figure 27 a) ï Working graph



27- b) - Graph of Acoustic emission activity



27 c) - Localization of AE events

Sensor 1

Sensor 2

5.2. Measurement of CT specimens

5.2.1. Axial orientation of the notch

5.2.1.1. Silver fir *(Abies Alba* Mill.*)*

Results of experiments of the CT specimens after loading test are shown on Figure 28 and detailed fracture are is shown on Figure 29.

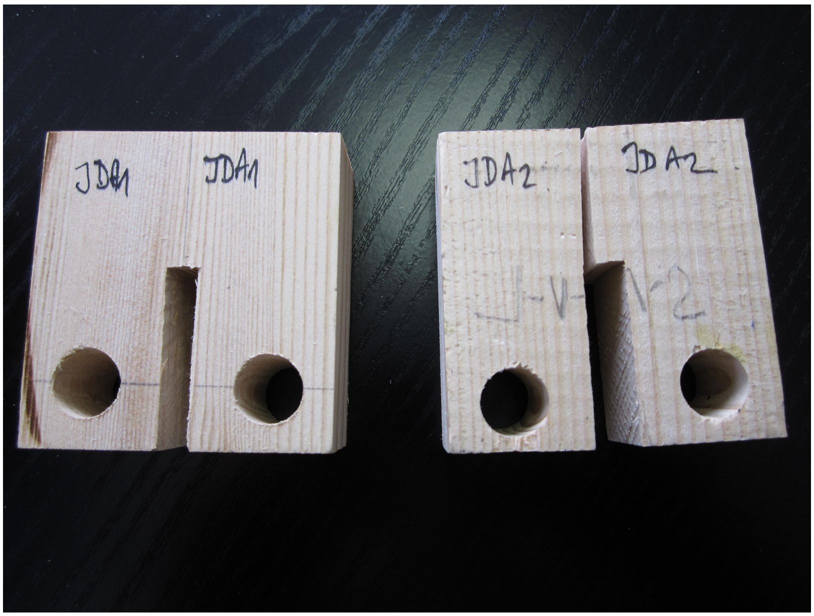
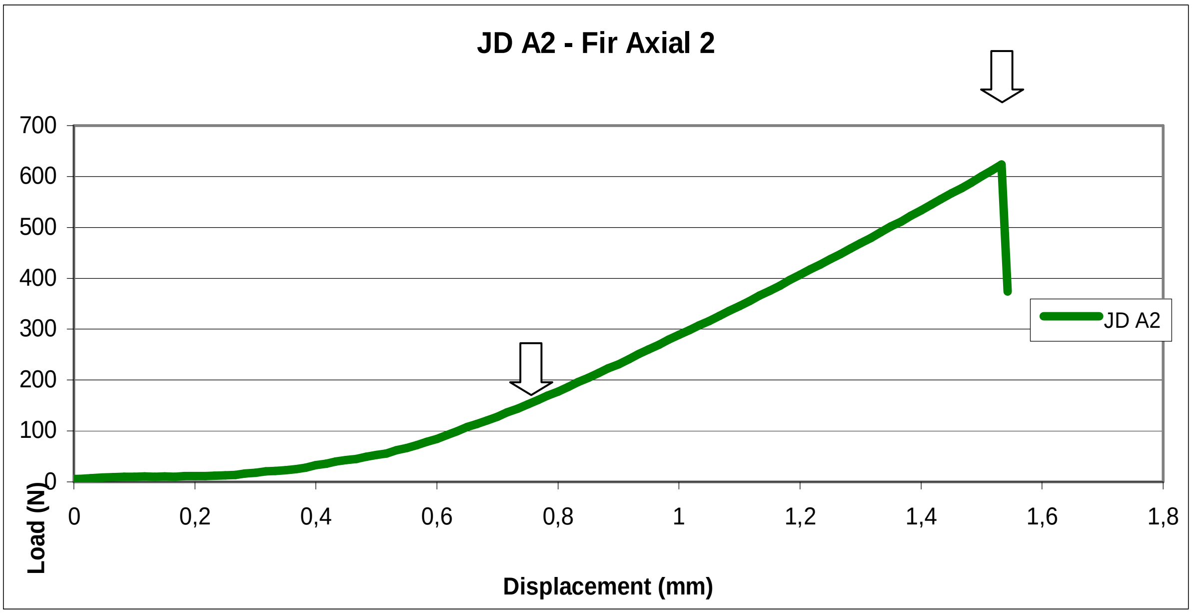


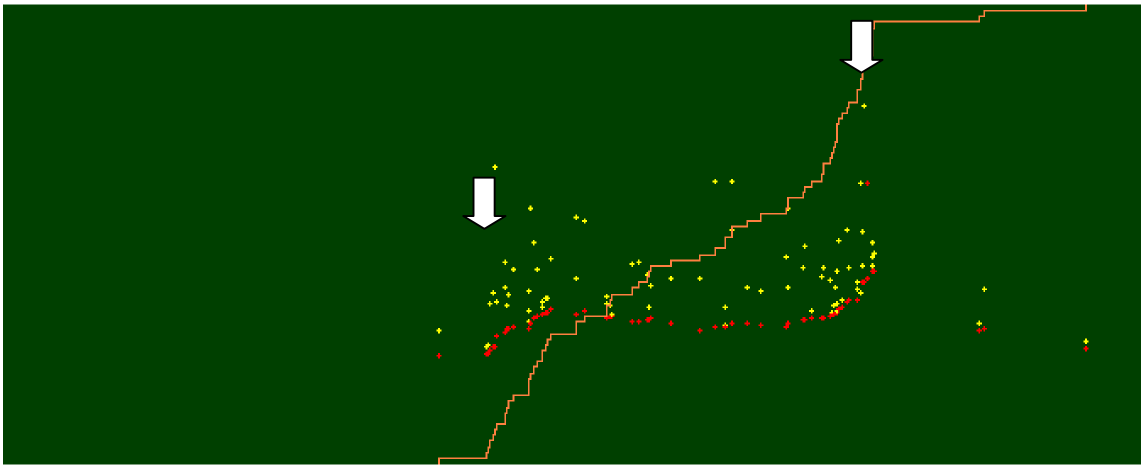
Figure 28: CT specimens after the test

Figure 29: Detail of fracture area, specimen A2

30 a) Working graph



30 b) Graph of AE activity



Relation between the loading force and AE activity is shown on Figure 30 a) and 30 b). After beginning of the loading there were not registered acoustic emission signals. By increasing the load, AE rate increased rapidly, with high amplitude and before the final fracture was registered high amount of acoustic emission signals. Maximum reached force was very low because of the high stress concentration factor at the tip of the initial artificial defect. Beginning of the loading acompanied by the occurence of AE signals gives earlier information of starting point of total damage.

5.2.1.2. Norway spruce *(Picea abies L.)*

Results of experiments of the CT specimens after loading test are shown on Figure 31 and detailed fracture are is shown on Figure 32.

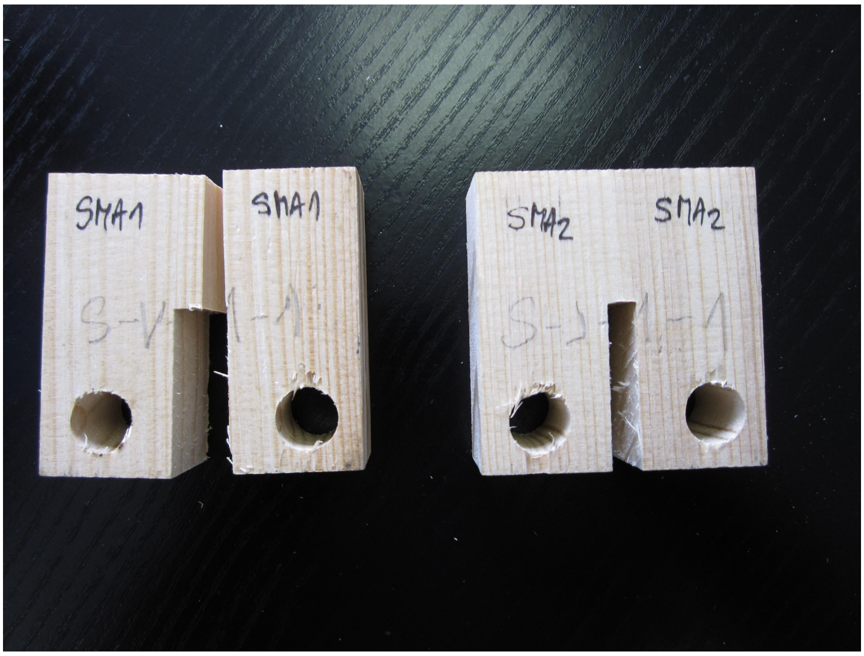
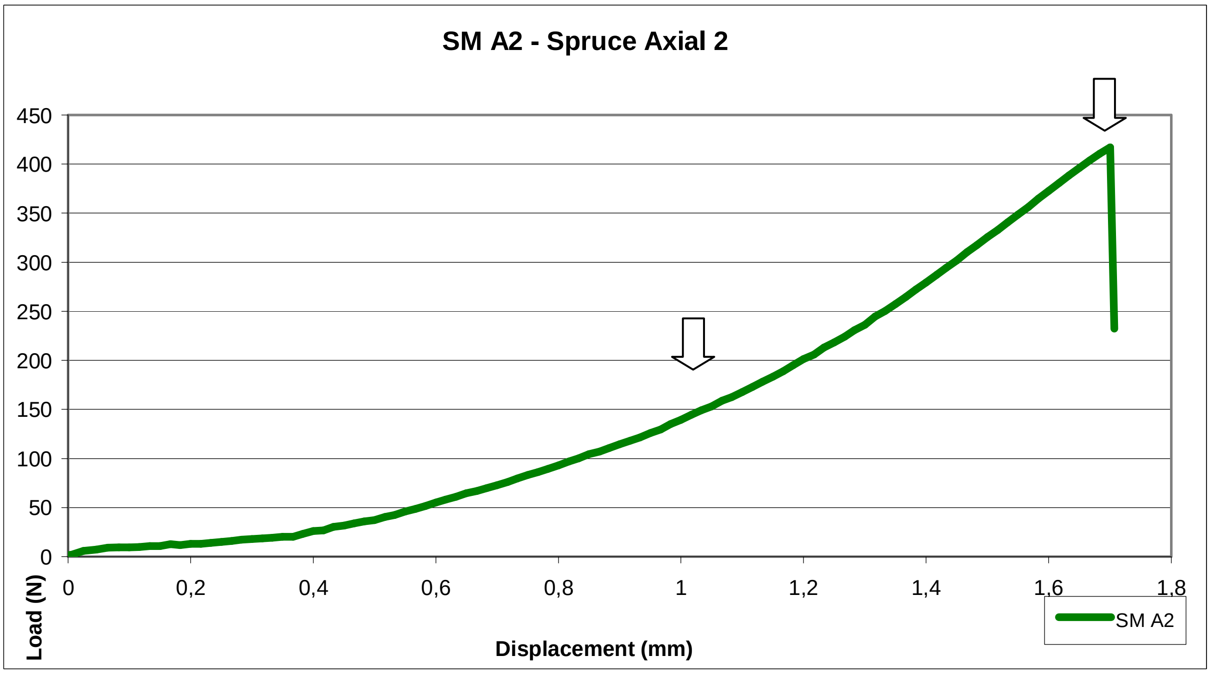


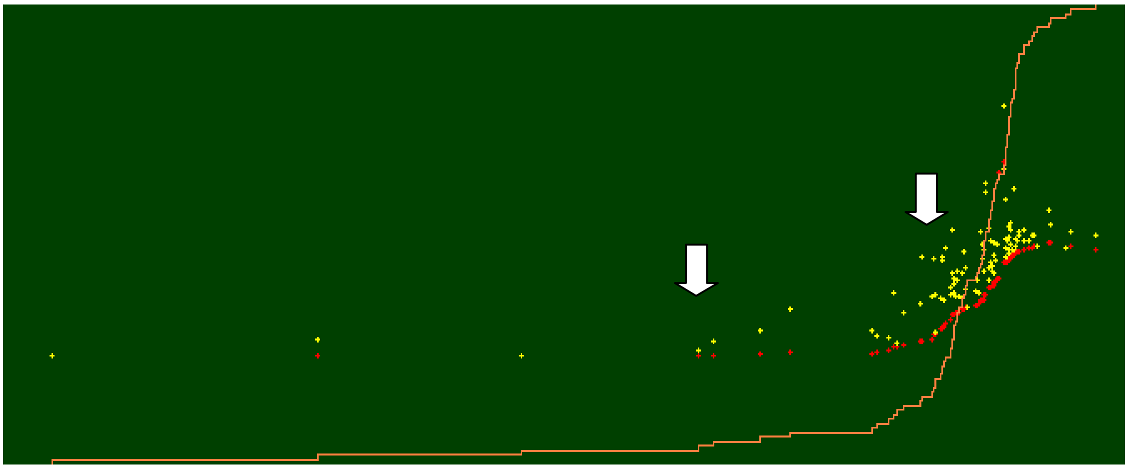
Figure 31: CT specimens after the test

Figure 32: Detail of failure after loading test

33 a) Working graph



33 b) Graph of AE activity



From the Figure 33a) a nd 33b) it can be seen that acoutic emission activity with higher amlplitude starts in the stress concentration place on the tip of intitial artificial defect. By increasing of load, AE activity increased rapidly to the point, when maximum load is reached.

Again there was an occurence of AE activity before final fracture of specimen.

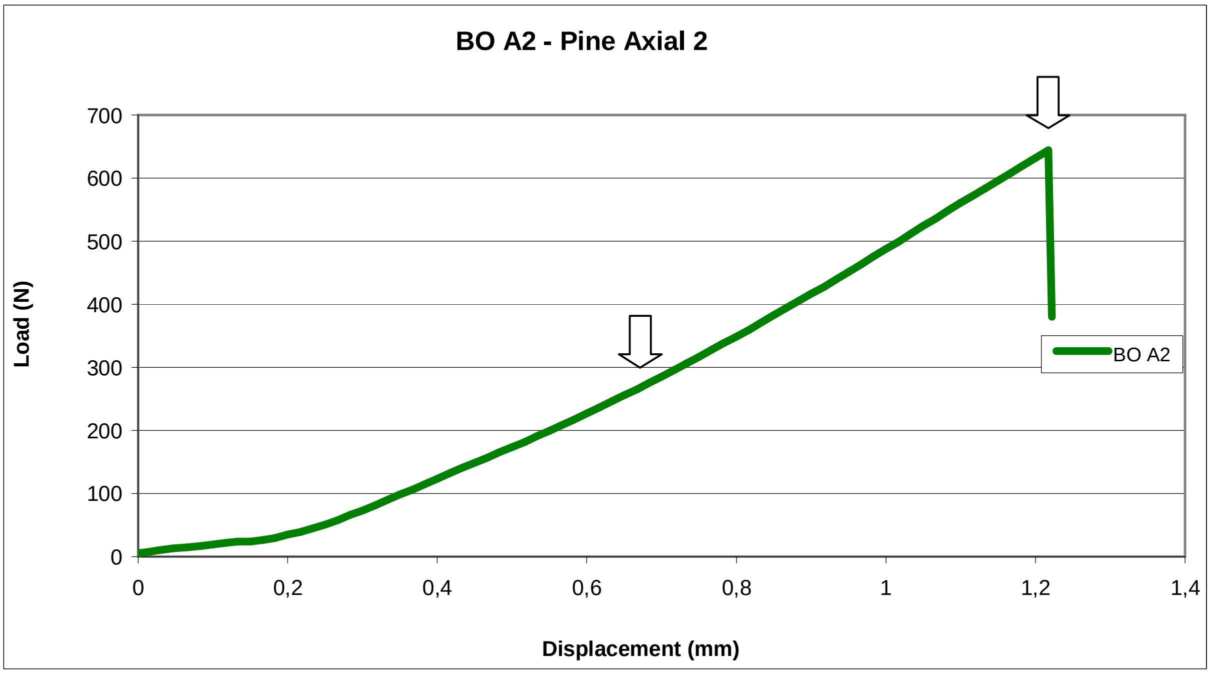
5.2.1.3. Scots pine *(Pinus sylvestris L.)*

Results of experiments of the CT specimens after loading test are shown on Figure 34 and detailed fracture are is shown on Figure 35.

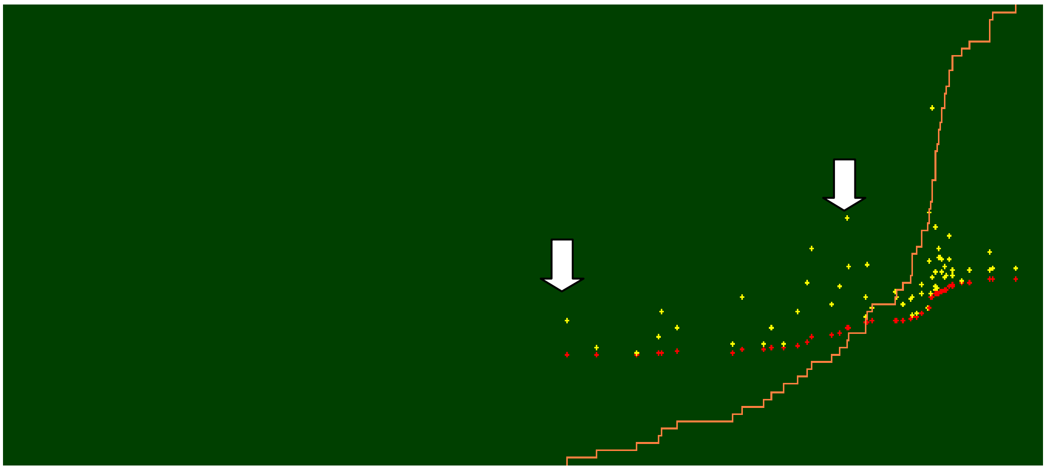
Figure 34: CT specimens after the test

Figure 35: Detail of fracture area, specimen Pine A2

36 a) Working graph



36 b) Graph of AE activity



By comparison of loading force (Figure 36 a) and acoustic emission activity (Figure 36 b), it can be seen that initial damage started when loading force reached approximately half of the maximum load. It corresponds to occurence of acoustic emission with higher amplitude and before the maximum load AE rapidly increased.

Comparison of results of all three wood specimen

For axial direction the maximum force, which caused the failure of specimen, was between 400 - 600 N (40 - 60 kg).

Achieved results are influenced by various factors, mainly as anisotrophy. During the loading of specimens it can be seen that stress concentration factor in the notch is causing very rapid increase of AE signals, even if the load is on the low level.

Displacement at tip of the notch is corresponding to high level of stresses at the area of the notch.

Rapid increase of AE rate is occuring in the tip of the notch due to highest stress level.

From the acoustic emission point of view the high activity was observed on Fir and Spruce before the final fracture, whereas on Pine the acoutic emission activity is lower.

In all cases, acoustic emission gives information about damaging processes before final fracture occurs.

5.2.2. Radial orientation of the notch of CT specimen

Figure 37: Broken CT specimens loaded in radial direction

From the Figure 37 is clearly seen that the proposed experiment on CT specimen with radial orientation of the notch did not give proposed direction of failure. Final failure occures in axial direction in all specimens, see Figure 37.

From the point of Acoustic emission measurement was expected that the failure will occure at the tip of the notch. Due to high anisotrophy of specimens, failure started in axial direction in area outside of the tip of the notch. There was some acoustic emission activity registered, but failure of specimen was influenced by this anisotrphy with very different value of ultimate stress.

Artificial crack didn´t give enough high stress concentration factors to start crack movement perpendicular to the wood fibers.

For this type of experiments, it should be proposed modified CT specimen (not according to standard for steels and other metals). Behavior of modified CT specimens should be in the future experimentally verified.

5.3. Pin Forcing

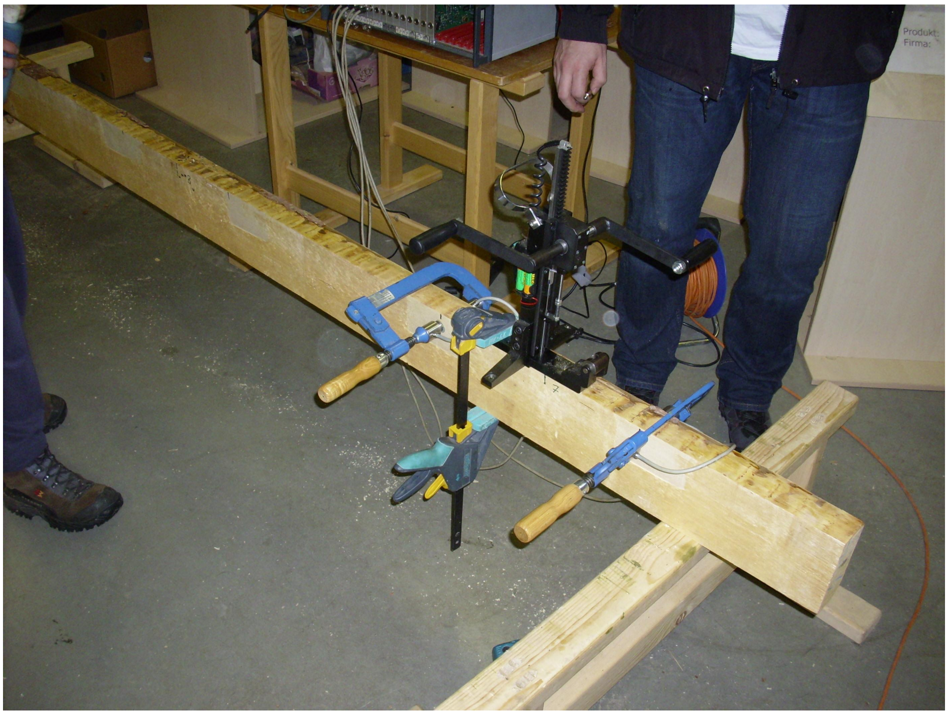


Figure 38: Experimental setup of forcing equipment

5.3.1. Silver fir

On the Figure 39, there is dependance of AE signals on loading force and appropriate deflection of pin penetration into the wood sample in radial direction. In the beginning of loading, when pin penetrates into wood, in the distance from 0 to 20 mm, there is a high AE activity, see cumulative curve of AE events (green color), with lower amplitudes. During continous loading, up to the penetrating deflection 115 mm, smaller amount of AE events is occuring, but with high amplitudes. It corresponds to increase and decrease of force due to damaging across the fibers initiating the cracks around the penetrating pin.

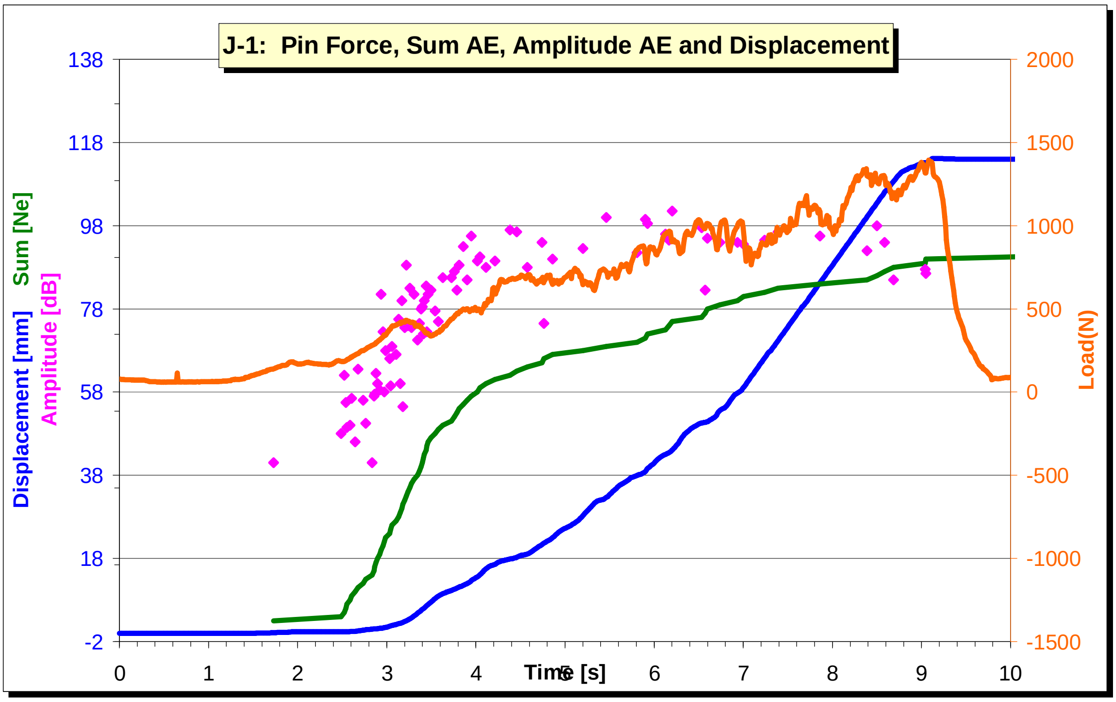


Figure 39: FIR - Relation between investigated features during forcing

5.3.2. Norway spruce

Behavior of Norway spruce wood during the pin force application showed similar results in relation to acoustic emission signals and deflection. Again at the beginning of pin penetration, higher rate of AE, with the low amplitude was observed. Continuous loading showed nonuniform increase of force (local decrease and again increase) which influence the acoustic emission activity (cumulative curve).

There is a difference of penetrating force in comparison to Silver fir - in the case of Norway spruce is the force lower.

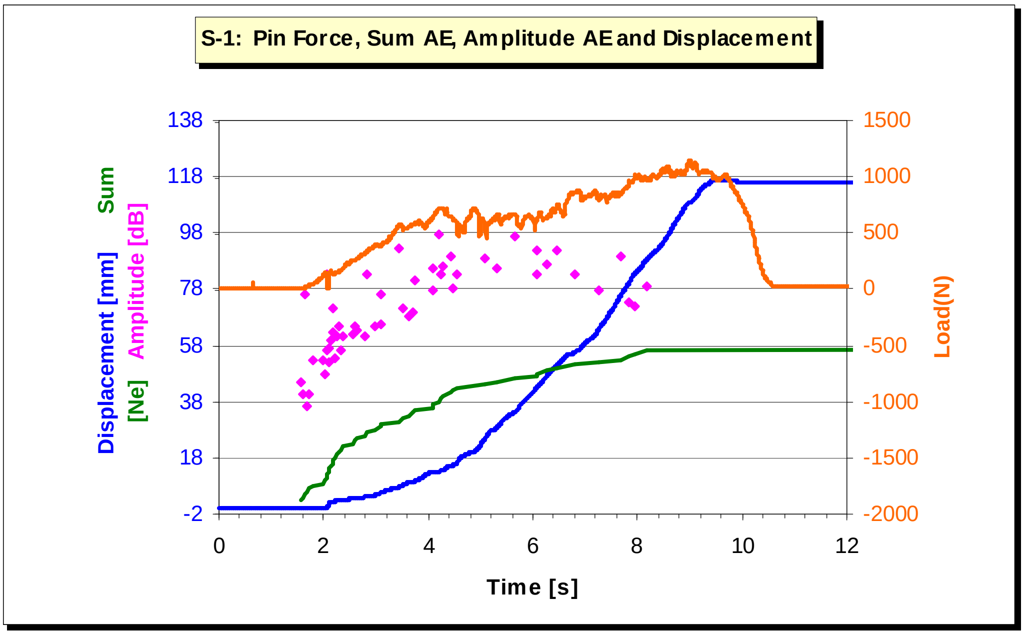


Figure 40: SPRUCE - Relation between investigated features during forcing

5.3.3. Scots pine

The third pin forcing experiment was done on Scots pine. The behavior of registered characteristics is similar to the previous tree species. Continuous loading showed higher nonuniform penetrating force and lower amplitudes. Also the maximum penetrating force was lower. This corresponds to softer structure of wood of Scots pine.

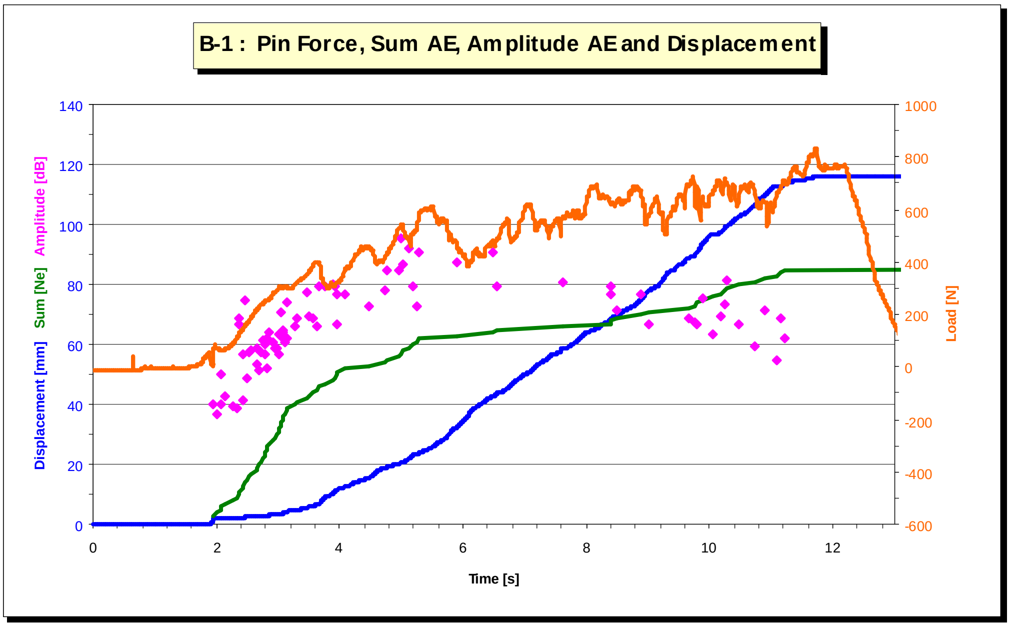


Figure 41: PINE - Relation between investigated features during forcing

5.3.4. Forcing and unforcing of the metal pin

In the Figure 42 is shown whole process of forcing and unforcing during one experiment. It can be seen that pulling out of the pin from the created plain hole gives small amount of acoustic emission with the low amplitueds. To pull out the pin small force is needed (negative force).

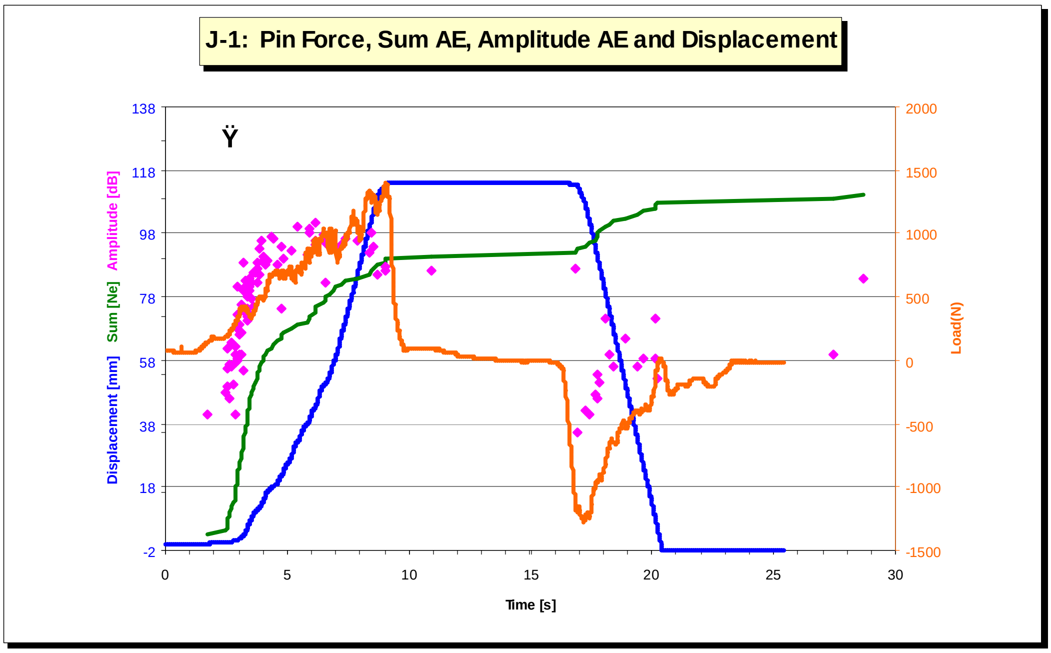


Figure 42: FIR - Relation between investigated features during forcing and unforcing

6. Conclusion

6.1. Three-point bending test

- Measurement of acoustic emission during the three-point bending test have shown few basic findings:

a) During the low loading value the wood material in all specimens showed small rate of acoustic emission activity with the low amplitude

b) With increasing of load higher acoustic emission activity was recorded.

c) During this etap of loading amplitude of acoustic emission was rapidly increased.

d) Highest etap of loading was acompanied with irreversible damaging processes in all wooden specimens and local microcracks were observed and recorded by acoustic emission (with the highest amplitude)

e) Localization of creating local defects like cracks was detected by number of AE events

f) Final fracture (corresponding to the maximum load) was identified by high amount of AE event ahead

6.2. Measurement of CT specimens

a) Loading test on CT specimens with the notch oriented in axial driection showed damage in type of cleavage parallel to the axial direction. For this type of damage maxiumum load is very low. Acoustic emission activity is concentrating at the area of tip of the notch and begins with low force

b) On the other hand CT specimen with the notch oriented perpendicular to the stem axis was not possible to measure because of big anisotrophy of wood structure behavior. During the loading AE signals were registered, but their origins were not only on the notch, but in the place where the final crack was initiated

c) To determine the maximum value of load for specimen with notch in radial direction, modified type of specimen should be used, for example type of SEN specimen (Single Edge Notch)

6.3. Pin Forcing

a) Experiment with Pin forcing into the wooden specimen in radial direction have shown good relation between applied load and acoustic emission activity

b) Highest AE activity was observed on beginning when the pin was forced into the wooden specimen

c) During local decrease of load higher acoustic emission activity was observed

d) Deeper penetrating of pin into the wood was accompanied with acoutic emission event with the higher amplitude and the high amplitude in all cases means creating the local cracks

e) Process of unloading and repeating loading in the same whole was accompanied with AE event with low amplitude, unloading force was low

7. Summary

In general it can be stated that acoustic emission technique can be used for investigating of various damaging processes in wood (during the static loading).

a) Investigated type of wood (Fir, Spruce, Pine) have shown different material characteristics, which corresponds to the the AE activity

b) Position of creating the local cracks in the wooden specimens can be detected at least by two channel acoustic emission system

c) Measured attenuation of AE signal was approximately 10 dB in distance of 300 mm. From practical point of view, for localization of affected area, where the damage will start, the higher amount of AE sensors must be used

d) The very high activity of AE signals was observed before final fracture of specimen

e) This fact can be used in the future for evaluation of existing beams in various old buidings, wood constructions

For the future research in acoustic emission aplication on wood processing it would be usefull to study closer relation between acoustic emission characteristics and damaging processes in wood.

Next possibilites of AE application as a diagnostic tool should be based on experimental verification of AE on healthy wood compared to wood influenced by biotic and abiotic factors - canker, pests or decomposing of old wood - in civil engineering.

8. Appendixs

8.1. List of References

VALLEN, Harmut. Acoustic Emission Testing. Volume 6.Wuppertal: CASTELL-Verlag, 1999, p. 6 -14. ISBN 3-934255-26-4

DROUILLARD, Thomas F. Acoustic Emission - A Bibliography with Abstracts. II. Title. New York: IFI/Plenum Data Company, 1979. ISBN 0-306-65179-3

MAZAL, Pavel. Method of Acoustic emission. In AE Proceedings. Brno: University of Technology, 1999. p. 44. ISBN 80-214-1303-4

ROSNER, Sabine. Acoustic emission of conifer sapwood becomes weaker after each dehydration-rewetting cycle. In Abstract booklet. Vienna: EWGAE and TÜV Austria, 2010

KAWAMOTO,Sumire. Acoustic Emission and Acousto-Ultrasonic Techniques for Wood and Wood-Based Composites - A Review

ROGERS, L.M. Structural and Engineering Monitoring by Acoustic Emission Methods - Fundamentals and Applications. London: Lloyd´s Register of Shipping, 2001, p. 5.

HARTMAN, W.F et al. Acoustic Emission Monitoring of Pressurized Systems. STP 697 Philadelphia: American Society for Testing and Materials (ASTM), 1979.

DUNEGAN, H.L. Elimination of Extraneous Noise Sources from Acoustic Emission Based Termite Detection Instrument by Use of Modal Ratios. San Juan Capistrano, USA, 2001

PHYSICAL ACOUSTICS CORPORATION. Pocket Ae and Pocket Aewin User´s Manual. Princeton, USA, 2007.

SVOBODA, V. Private information, 2011

ASTM Standard E399-83: Standard Test Metod for Plane-Strain Fracture Toughness of Metallic Materials. Philadelphia: Annual Book of ASTM Standards, Vol. 03.01, pp. 519-554, 1984

ASTM E976 ï 10: Standard Guide for Determining the Reproducibility of Acoustic Emission Sensor Response

ĻSN 49 0115 - DŚevo. Metoda zjiġŠování meze pevnosti ve statickém ohybu

8.2. List of Figures

8.3. Other results - Bending test

Silver Fir - *Abies Alba* Mill. - Specimen 1

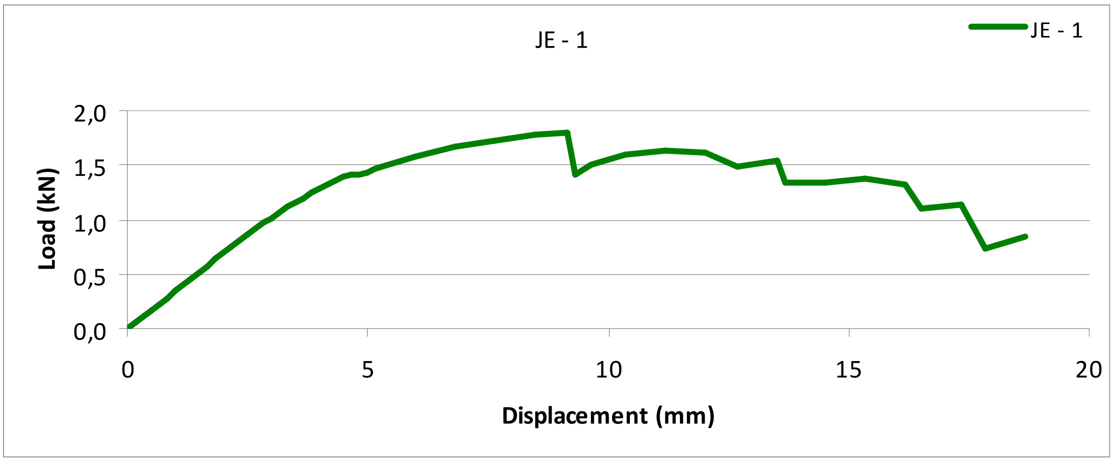


Figure 1: Working graph

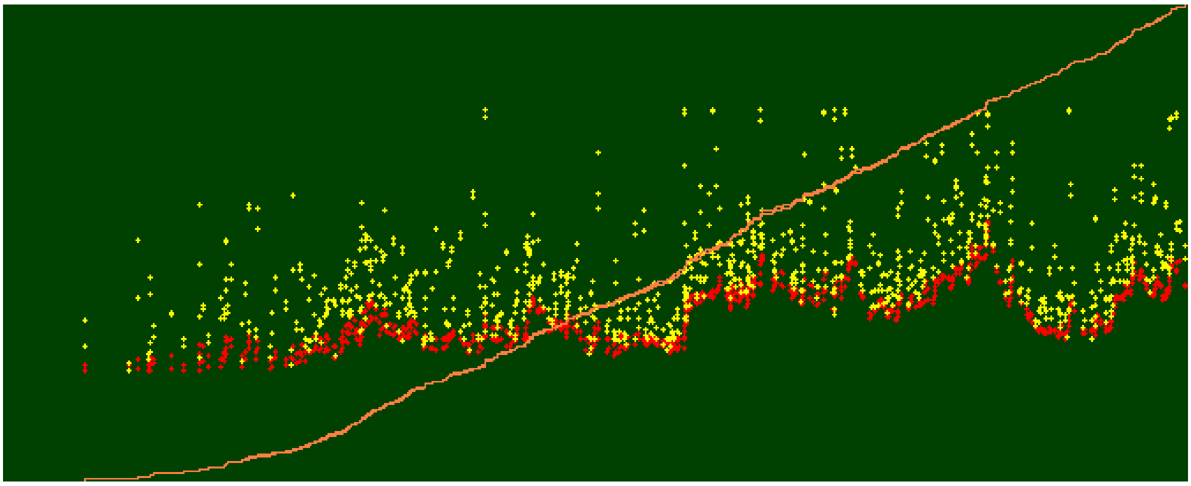


Figure 2: Graph of AE activity

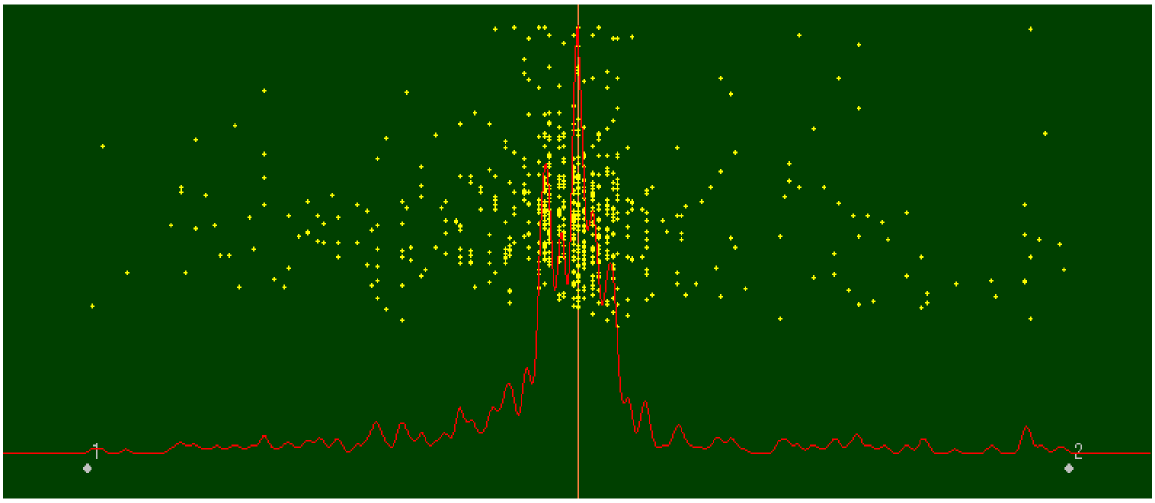


Figure 3: Localization

Silver Fir - *Abies Alba* Mill. - *Specimen 3*

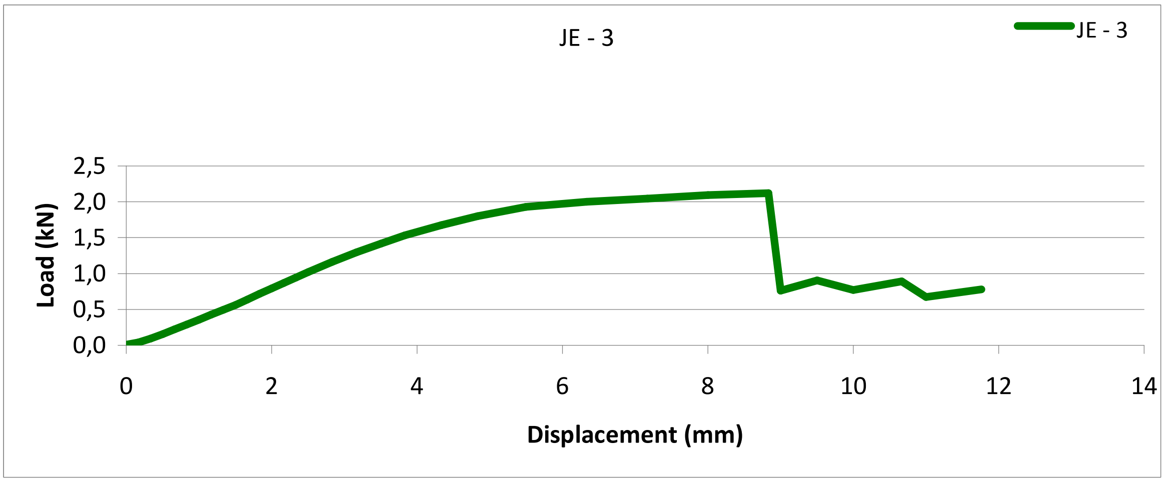


Figure 4: Working graph

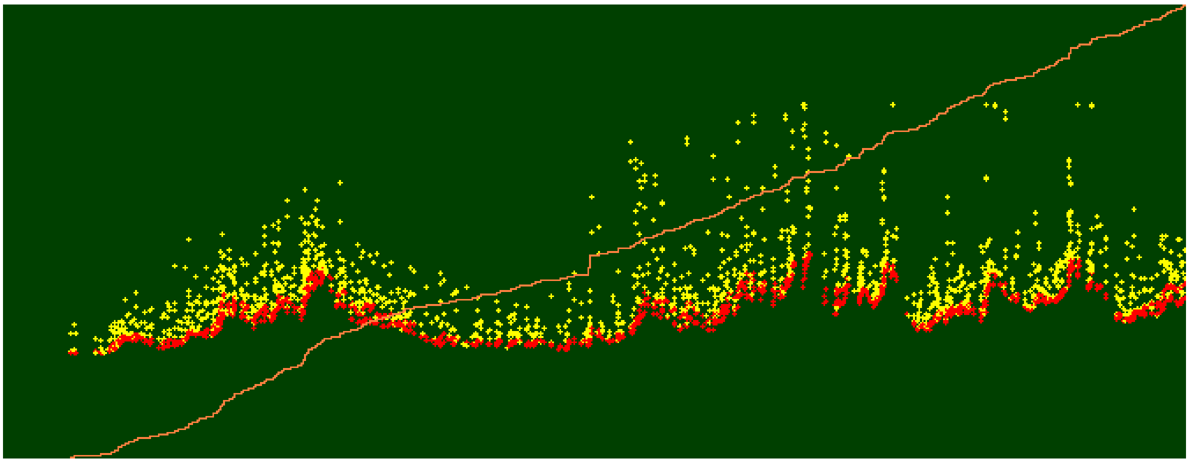


Figure 5: Graph of AE activity

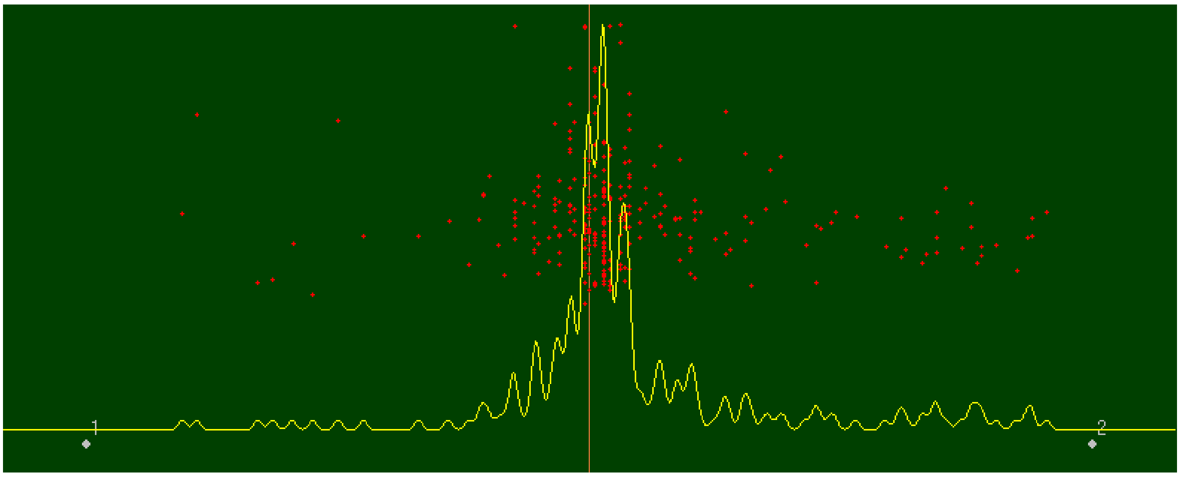


Figure 6: Localization

Norway Spruce - *Picea abies* L. - Specimen 1

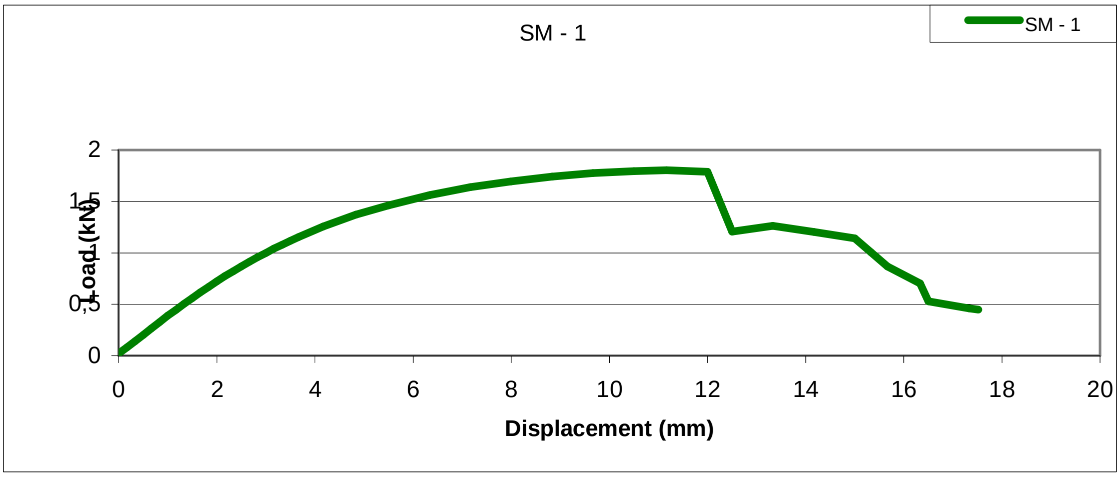


Figure 7: Working graph

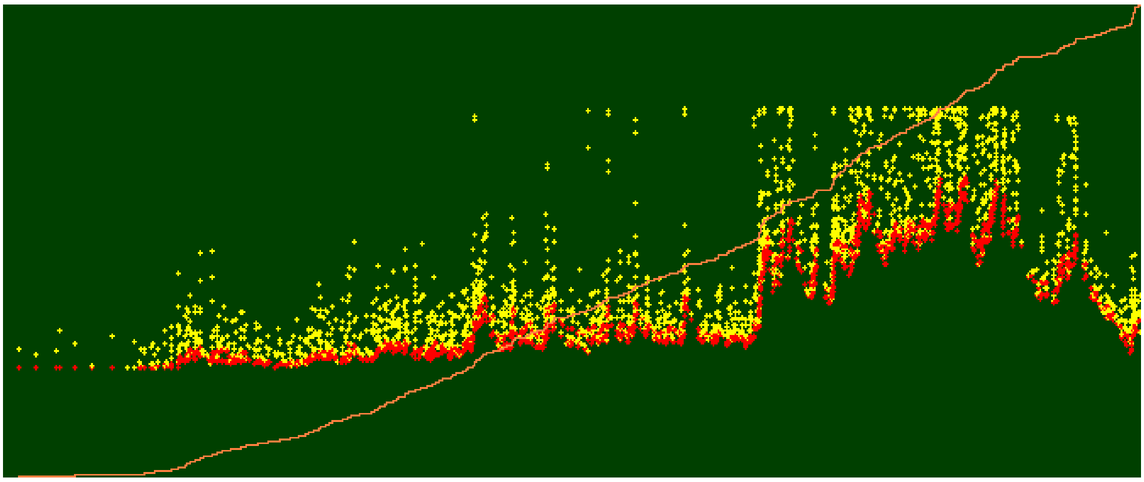


Figure 8: Graph of AE activity

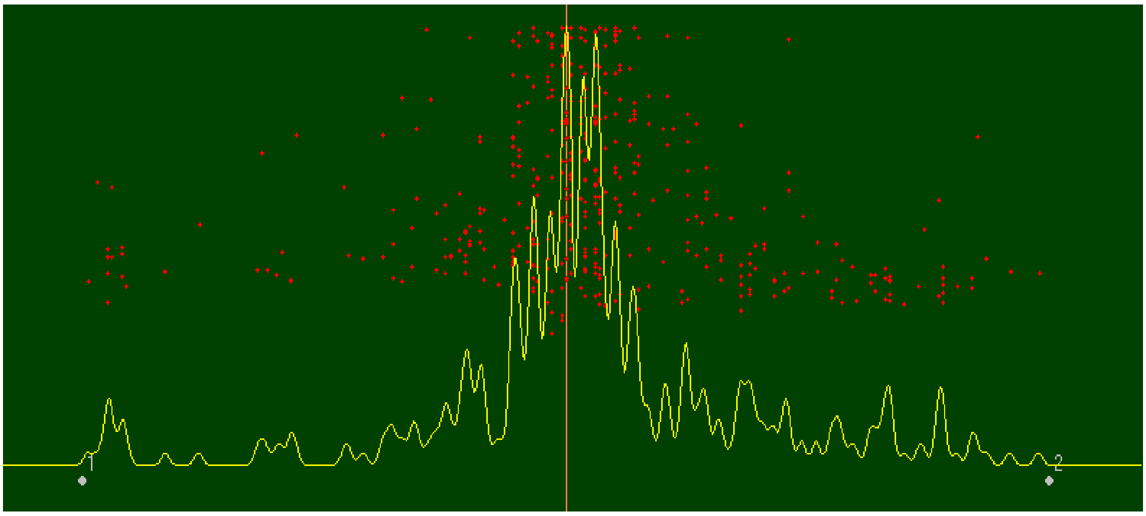


Figure 9: Localization

Norway Spruce - *Picea abies - Specimen 3*

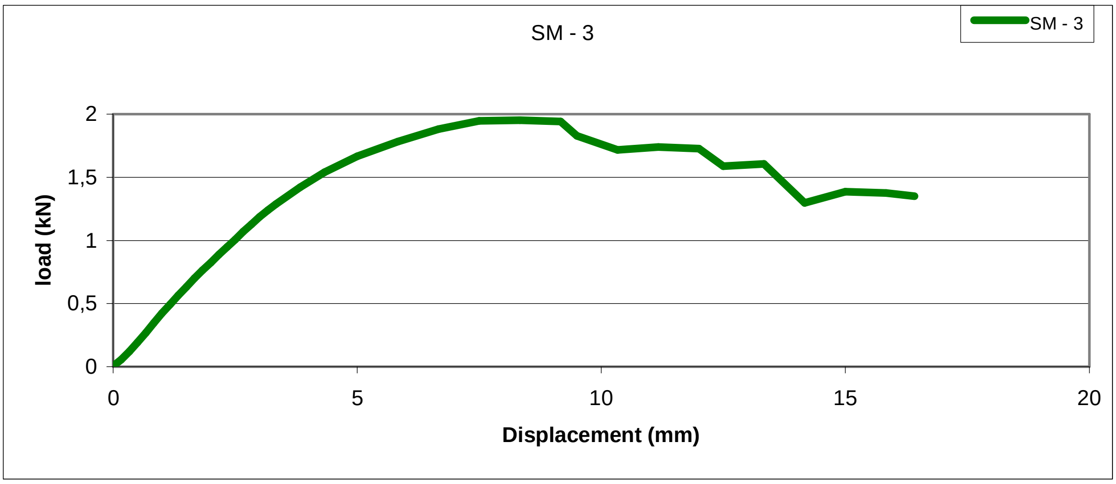


Figure 10: Working graph

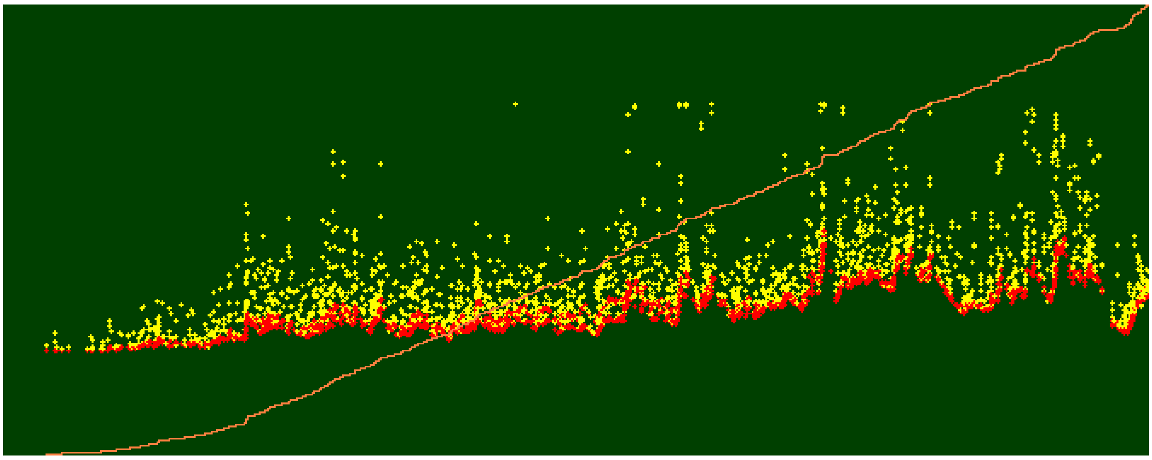


Figure 11: Graph of AE activity

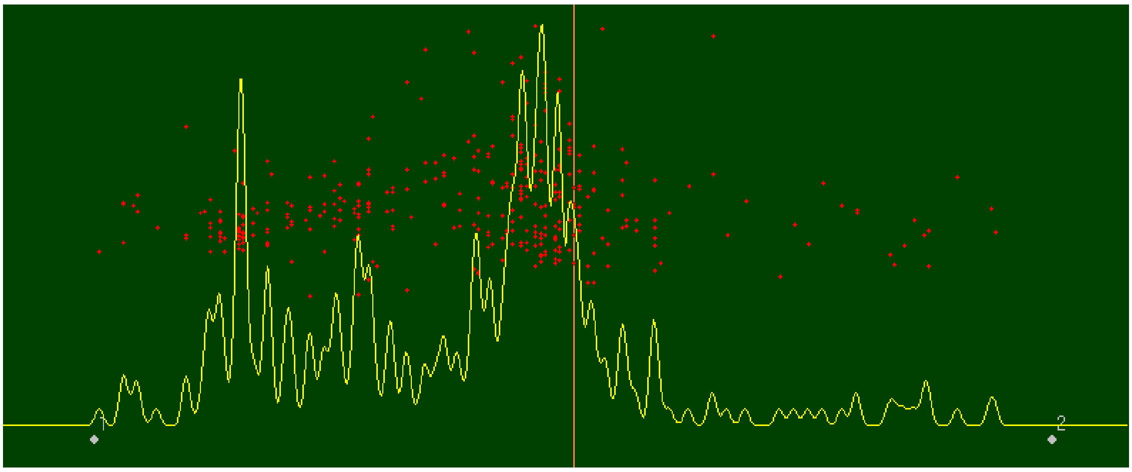


Figure 12: Localization

Scots Pine - *Pinus sylvestis - Specimen 2*

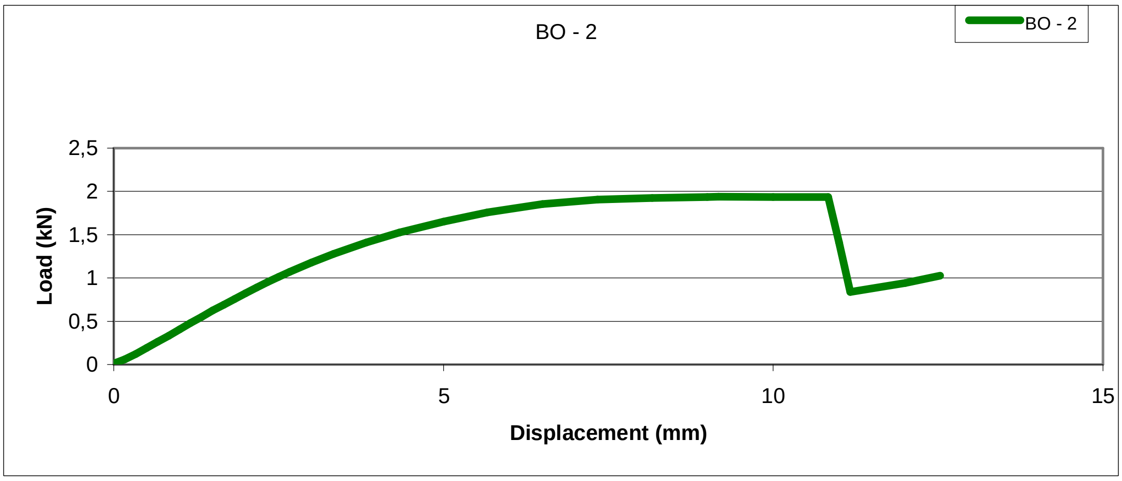


Figure 13: Working graph

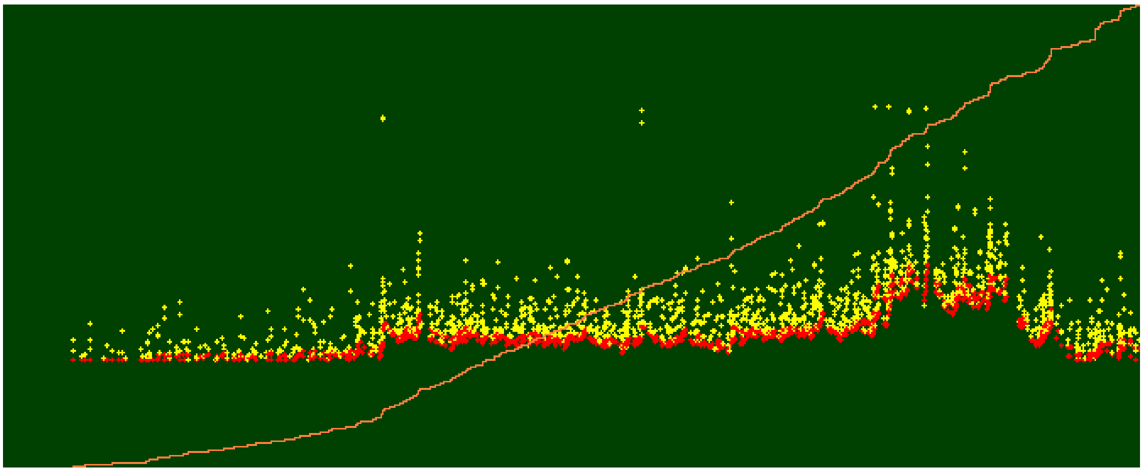


Figure 14: Graph of AE activity

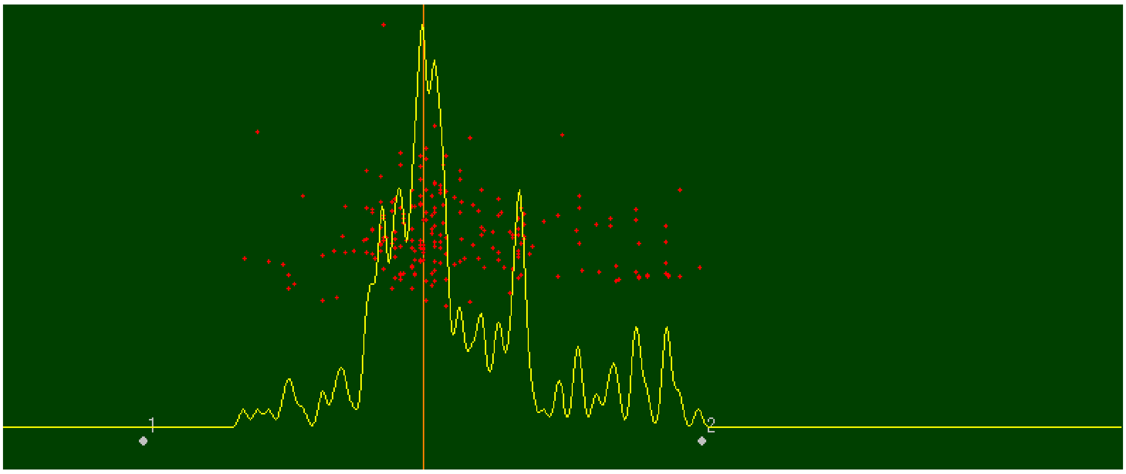


Figure 15: Localization

Scots Pine - *Pinus sylvestis - Specimen 3*

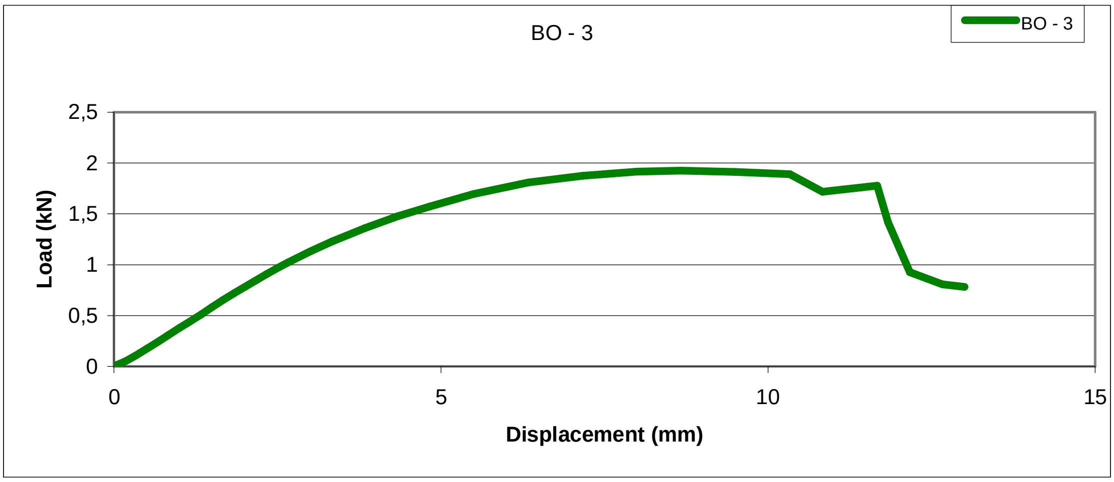


Figure 16: Working graph

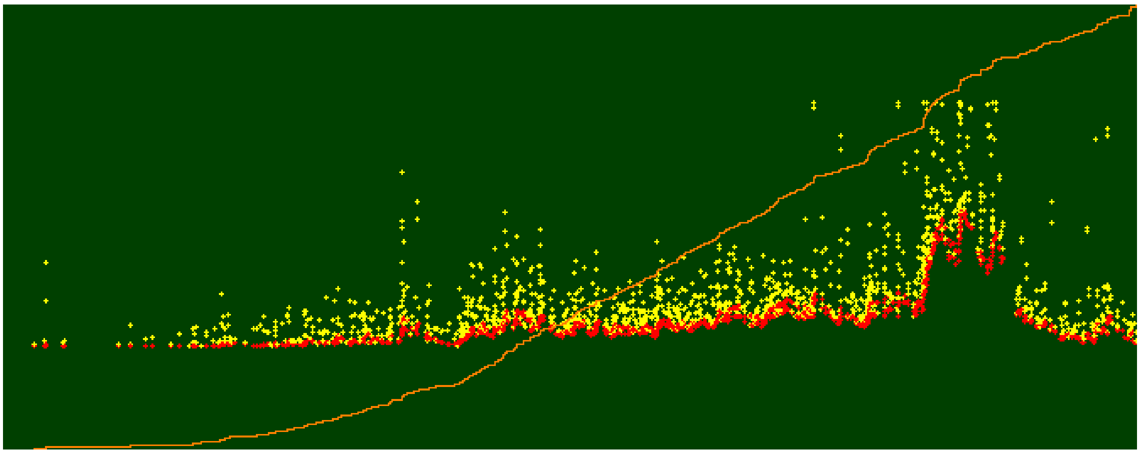


Figure 17: Graph of AE activity

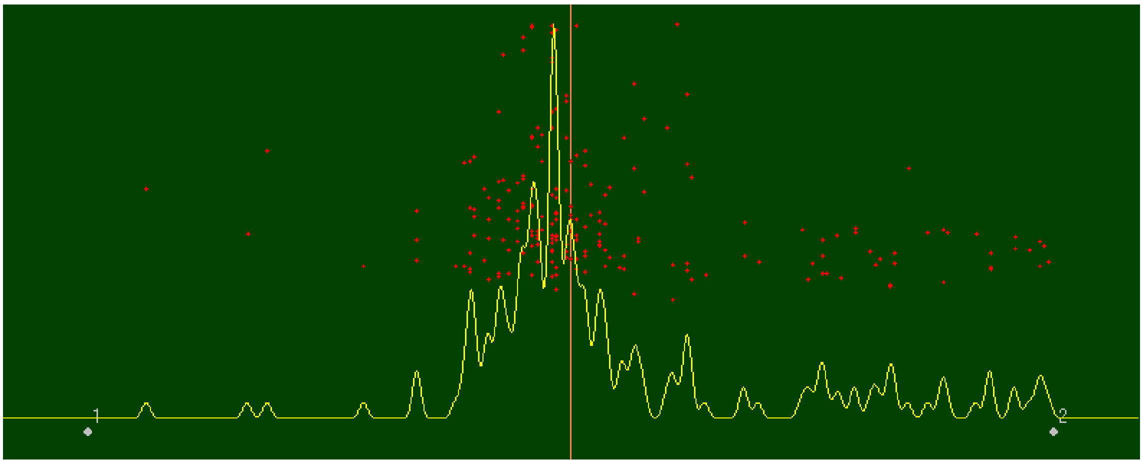


Figure 18: Localization