Acoustic Emission (AE) Signal Classification from Tensile Tests on Plywood and Layered Wood

Franziska RITSCHEL *, Markus G. R. SAUSE **, Andreas J. BRUNNER ***,
Peter NIEMZ *
* ETH Zürich, Wood Physics Group, Institute for Building Materials, Zürich, Switzerland,
** University of Augsburg, Experimental Physics II, Augsburg, Germany
*** Swiss Federal Laboratories for Materials Science and Technology, Empa, Dübendorf, Switzerland

Abstract. Even today, a detailed description of the damage progress in wood or wood materials under tensile loading is still a challenge. The complexity of the damage behaviour results from the various mechanisms occurring simultaneously at several length scales. So far, few studies focused on mechanical behaviour of wood or wood materials by analysing acoustic emission (AE), although AE can provide information on multi-scale damage mechanisms and damage accumulation. The high time resolution of AE measurements is beneficial for detection of micro-mechanisms, their interactions and accumulation leading to macroscopic failure.

For the AE analysis presented here, several types of industrial plywood and layered wood materials made from spruce were subjected to quasi-static tensile loads and simultaneously monitored by AE. Since polymer-composites and wood can be assumed to behave analogously, especially regarding their anisotropic properties, application of pattern recognition methods for fibre reinforced polymer-matrix composites are expected to have also high potential for AE signal classification of wood fracture.

Such unsupervised pattern recognition, e.g. based on the frequency domain of the AE signals, are purely mathematical approaches to perform signal classification and to identify natural classes of AE signals, respectively. Within the present investigation, a signal classification approach originally developed for fibre-reinforced composite laminates is explored for plywood and layered wood materials. Problems and challenges are identified which have to be solved for a detailed understanding of their damage behaviour.

The different layered structures of plywood all yield two AE signal clusters which can roughly be differentiated in signals of relatively high shares of low frequency and high frequency content, respectively. These occur essentially over the whole test duration and yield comparable AE signal amplitudes and energies. The challenge is to assign the features of the detected signals to their microscopic source mechanism.

Introduction

The combination of in-situ acoustic emission and synchrotron X-ray micro-tomography on miniature specimens of spruce wood has yielded promising insights into the damage behaviour of wood under tensile loading [1,2]. An essential element of the analysis was the application of an unsupervised pattern recognition and classification method [3] that originally had been developed for fibre-reinforced polymer-matrix composites. In the investigation on polymer composites, the damage mechanisms yielding the different signal clusters were identified via detailed finite element simulations [4]. For the miniature wood specimens, the pattern recognition essentially yielded two distinct clusters for both types (radial and longitudinal orientation of wood with respect to tensile load axis). These clusters differed mainly in their relative low frequency (around 300 kHz) to high frequency content (between about 600 and 700 kHz) in the power spectrum.

For the miniature wood specimens, the correlation between acoustic emission signal clusters and X-ray micro-tomography images was used for identification of the damage mechanisms and the damage accumulation. Detailed X-ray image sectioning and analysis even yielded a rough correlation between acoustic emission signal amplitude and crack size in these specimens. It is noteworthy that acoustic emission (minimum detectable crack length around 2 micro-meter with an effective crack size around 10 micro-meter squared for typical 5 micro-meter cell wall thickness at the selected detection threshold of 31 dB_{AE}) proved more sensitive for damage detection than the spatial resolution available from X-ray micro-tomography. For further information on the damage mechanisms yielding the two observed acoustic emission signal clusters, finite element simulation of selected damage mechanisms in miniature specimens is currently under way.

The analysis of the damage accumulation based on acoustic emission signal parameters, e.g., yielding differences in amplitude distributions, for the model layered wood and the industrial plywood have previously been published [5,6]. In view of the results on the miniature wood specimens noted above, it is of interest to perform the unsupervised pattern recognition also on the layered wood and plywood specimens. Selected results of this analysis are reported and discussed in this contribution.

Materials and Test Set-up

In the present investigation, several types of spruce wood model layered wood (3 layers) and industrial plywood (3 to 6 veneer layers, labelled “PLY3” through “PLY6”), respectively have been subject to quasi-static tensile testing to failure with simultaneous acoustic emission monitoring and digital image correlation based on an earlier study [7]. The model layered wood specimens were made from 3 mm thick layers, planed down from wooden planks, in order to avoid damage from veneer cutting. The orientation of the wood layers was aligned in the loading direction (0°,0°,0°, i.e., unidirectional labelled “UD”) for one type of model layered wood and with the middle layer perpendicular (0°,90°,0°, i.e., cross-ply labelled “CP”) for the other. The same tests were also performed on specimens of solid spruce wood (labelled “SOLID”). All specimens (size and shape adapted from DIN 52377, see [5,6] for details) were tested on a universal test machine (type Zwick Roell 100, load cell 100 kN) with a constant cross-head speed of 2.5 mm/min.

The acoustic emission monitoring of the tensile tests model layered wood and the industrial plywood specimens has been performed with commercial equipment (type AMSY-6 from Vallen Systeme GmbH) using three types of sensors (two each of type SE-150M, SE-45H and SE-1000H from Dunegan Engineering Corp.). In this contribution, only the results from the SE-1000H sensors will be presented and discussed. The reason for this is that the frequency response of those sensors fits best with that of the miniature sensors (type M31 from Fuji Ceramics Corp.) used in the experiments on miniature specimens. For the tests on model layered wood and solid wood, the two sensors were mounted 10 cm apart (and 15 cm from the bottom and top, respectively) on the same side of the specimen. For the tests on the industrial plywood, the two sensors of type SE-1000H were mounted 3 cm apart (and 17 cm each from bottom and top, respectively). Average signal attenuation determined from lead pencil breaks amounted to about 1 dB_{AE}/cm.

Results and Discussion

The clusters from pattern recognition are all presented with the same set of features for ease of comparison. These are the so-called weighted peak frequency (WPF, the geometric mean between peak and centre of gravity frequencies of the power spectra) and the amount of partial power 2 (PP2, spectral power between 200 and 400 kHz). A weighting scheme in the pattern recognition algorithm identifies the "best" partitioning in terms of feature combination and this combination turned out to be among the best (if not the top-most) for all analysed specimen types (at least for the sensor type used in the analysis).

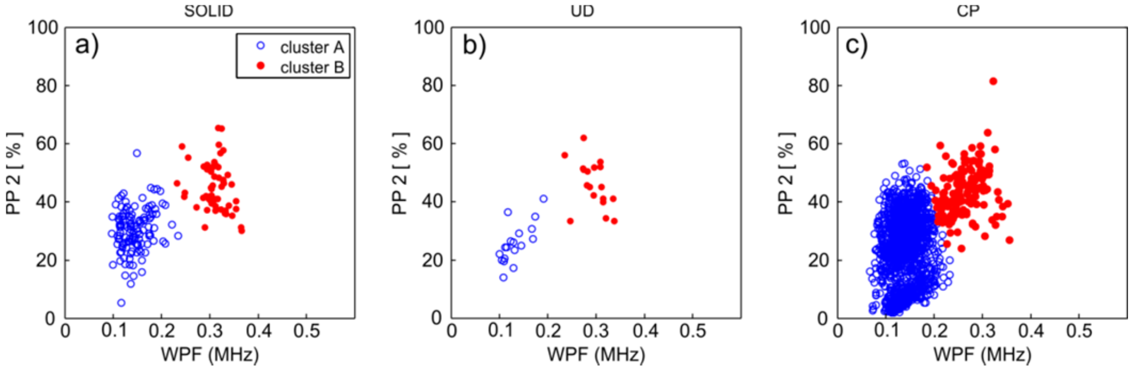

Fig. 1. Cluster from pattern recognition of acoustic emission signals for a) solid wood (SOLID) and the model layered wood specimens with b) all layers aligned with the tensile load (UD) and c) with the centre layer normal to the tensile load (CP), only signals from the first hit sensor type SE-1000H are shown, open/blue circles belong to cluster A, full/red circles to cluster B.

The clusters obtained from unsupervised pattern recognition from the solid wood (labelled SOLID) and model layered wood specimens (UD and CP) are shown in Figure 1. Figure 2 shows the corresponding clusters for the industrial plywood. All graphs in Figures 1 and 2 show essentially two clusters with weighted peak frequencies around 150 and 300 kHz, respectively. The clusters at higher weighted peak frequency (around 300 kHz) yield a higher contribution from partial power 2 compared with the cluster at lower weighted peak frequency. The former ranges from about 30 to about 70 percent for all specimen types, the latter from about 0 to 50 percent, except for the "SOLID" and "UD" specimen types. The "CP" type with the centre layer oriented normal to the tensile load compares well with the clusters from the industrial plywood. The number of first-hit signals observed in "SOLID" and "UD" is significantly lower than for the other specimen types. It is likely that this is due to the different mesoscopic and macroscopic failure patterns observed in the tests. However, the identification of two clusters with comparable weighted peak frequency ranges and similar amounts of partial power 2 raises the question whether the underlying microscopic damage mechanisms are the same in all types of specimens.

Previous waveform analysis of tensile tests on model layered wood and solid wood specimens simply plotting centre of gravity frequency versus peak frequency had already yielded indications of two clusters [8]. Even though this could not be interpreted in terms of underlying mechanisms, it was noted at that time that signals from both clusters seemed to occur over the whole test duration from initiation of tensile loading up to failure. Tentatively, it was hypothesized that waveforms seemed to belong to either a class with a higher contribution of the spectral power at lower frequencies or to a class with a higher contribution at higher frequencies. As a further hypothesis, this was interpreted to indicate different damage mechanisms. Whether this related to mechanisms acting on different time-scales, e.g., “fast” and “slow”, remained unclear at that time.

The appearance of two distinct clusters for each of the layered wood and plywood specimens with similar characteristic with respect to weighted peak frequency and the partial power in the frequency range between 200 and 400 kHz for separating the clusters points to the similarities between the different specimen types. This similarity, on one hand, consists of the same size and shape of the specimens (dog-bone type, based on DIN 52377), and – except for solid wood - on the other of the adhesively bonded, layered structure. The main difference between model layered wood and industrial plywood is the amount of damage introduced by manufacturing. Model layered wood specimens were manufactured from selected wooden planks with few defects and irregularities and planed down to the required thickness (3 mm), whereas the industrial plywood was manufactured from veneer which intrinsically has a larger amount of damage, e.g., from lathe checks.

Considering the similarities it has, however, to be noted that the acoustic emission signal parameter analysis yielded distinct differences among the different specimen types [5,6]. For the industrial plywood, only acoustic emission signals from two other sensor types (SE-150M and SE-45H) were analysed and compared in [6], but not the signals from the SE-1000H type sensor so far. The sensors type SE-1000H had yielded significantly lower number of acoustic emission signals than the other two sensor types in the tensile tests on the model layered wood specimens [5].

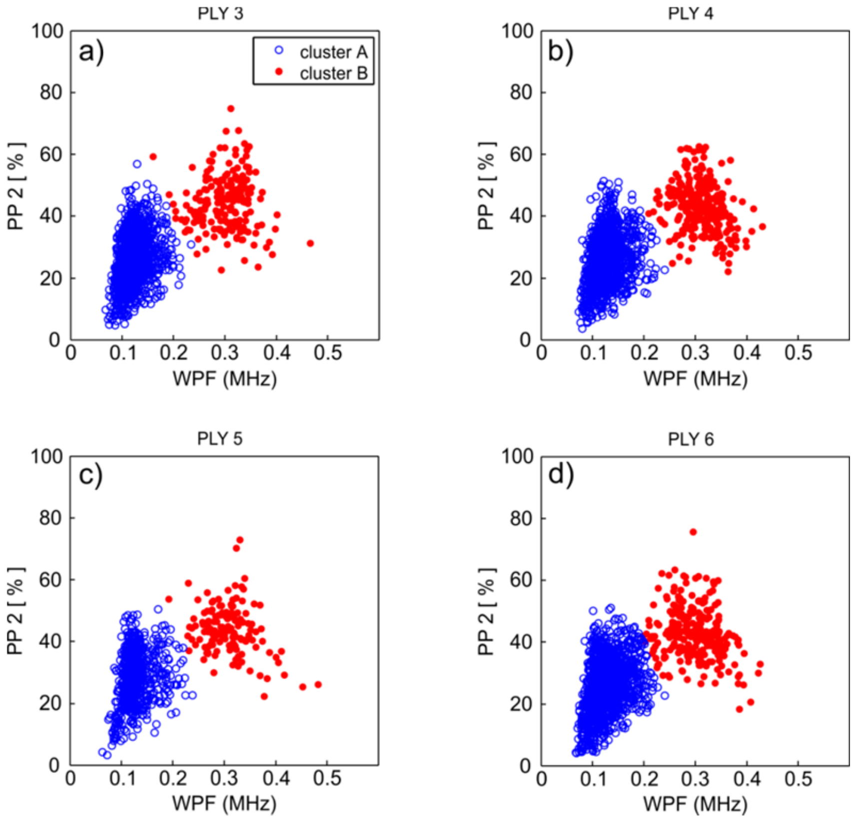

Fig. 2. Cluster from pattern recognition of acoustic emission signals for the industrial plywood specimen types, a) 3 layers, b) 4 layers, c) 5 layers, d) 6 layers, only signals from the first hit sensor type SE-1000H are shown, open/blue circles belong to cluster A, full/red circles to cluster B.

As noted in the introduction, unsupervised pattern recognition of tensile tests on miniature specimens made of solid spruce wood with radial and longitudinal orientation (total length around 3 cm) have also yielded two clusters, however at different weighted peak frequencies (on average around 270 and 630 kHz) and with partial power 4 (PP4, spectral range 600-800 kHz) as best feature combination for cluster separation. These tests have been monitored with miniature sensors (type M31) which qualitatively (but not quantitatively) have a similar frequency dependent sensitivity as the SE-1000H. In the case of the solid wood miniature tests specimens, the two clusters have tentatively been attributed to interwall cracks (low frequency component cluster) and to cell wall cracks in the tracheids (high frequency component cluster). This was consistent with the evidence from X-ray micro-tomography which showed a rather complex damage pattern. Further investigations using finite element simulation of model sources considering different location, orientation and rise time of the source are currently under way. These are expected to yield more insight into the mechanisms and to validate the identification of mechanisms based on X-ray micro-tomography imaging.

Such modelling results are not available for the model layered wood and plywood specimens. Hence, other approaches have to be investigated for identifying the mechanisms relating to the two clusters. Since the question whether signals from the clusters obtained from the tensile tests on miniature specimens showed distinct differences either in their appearance in time (i.e., correlating with lower or higher loads) or resulted in signals with differences in acoustic emission signal parameters (e.g., amplitude or energy) had shown that no significant differences could be found, the same analysis was performed for the solid, the model layered wood and the plywood specimens.

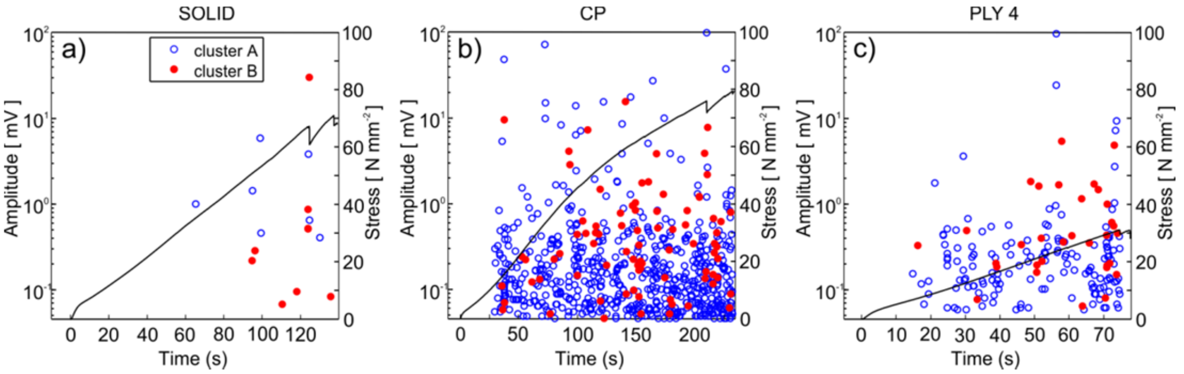

Fig. 3. Distribution of acoustic emission signal amplitudes from cluster A and cluster B, respectively for selected specimen types as a function of time and stress, respectively, a) solid wood (SOLID), b) model layered wood with centre layer normal to tensile load (CP), and c) industrial plywood with 4 layers (PLY4) , only signals from the first hit sensor type SE-1000H are shown, open/blue circles belong to cluster A, full/red circles to cluster B.

Fig. 3 shows amplitude distributions as a function of time of selected tests on single specimens where the signals belonging to each cluster are identified by different symbols (open and full circles). The tensile stresses are also shown for comparison among different material types. The distributions for all specimen types (including those not shown) do not indicate significant differences in the occurrence in time and in the amplitude range of signals belonging to the two clusters. This implies that both mechanisms (if the clusters really represent different mechanisms) are acting essentially simultaneously. This is consistent with the results from tensile tests on miniature specimens of solid wood noted above, where the complex microstructure of wood yields complex crack paths and damage patterns involving different mechanisms acting simultaneously throughout the duration of the test.

The question of how the layered structure of the model layered wood and plywood specimens affects damage behaviour compared with solid wood also deserves attention. For the industrial plywood, the failure stress and failure strain is lower than that of the corresponding solid wood specimens [6] and the same holds for the model layered wood [5]. The clusters from pattern recognition do not seem to be affected by the adhesive layer, since two clusters at comparable frequencies and with comparable range of the partial power contributions (PP2), at best with minor differences, are obtained. In the “CP” type model layered wood and in the industrial plywood, there are layers oriented parallel and normal to the tensile load axis (one in “CP” and “PLY3”, two each in “PLY4” to “PLY6”).

In layers oriented normal to the tensile load axis, brittle cell wall cracking as well as cell separation phenomena will occur generating crack areas parallel to the cell axis. Furthermore, the rolling shear induced by the adjacent layers (oriented parallel to load application) will affect crack propagation oriented normal to load and normal to the cell axis of these cross layers. In the layers oriented parallel to the tensile load, the cell wall will be damaged either by brittle cell wall breakage producing the crack area normal to cell axis or by cell wall cracks running parallel to the cell axis. Overall, the meso- and macro-scale damage behaviour in these layers is quite complex, but quite likely originates from microscopic damage mechanisms in the sub-cellular and cellular structure of the wood material.

There is an experimental aspect that has to be noted in the analysis of the signals. The sensors were always mounted on the “wide” side of the specimens [5,6]. Preliminary results from the finite element simulations in miniature spruce wood specimens yield indications for several effects that influence the clusters from pattern recognition. Depending on the location of the source inside the specimen and its orientation with respect to the loading axis, different modes or mode mixes (symmetric versus anti-symmetric) can be excited, yielding different frequency contributions in the signals. Considering the overall frequency dependent sensitivity of the sensor, certain frequency ranges (in this case lower frequencies below about 100 kHz) may not be recorded with the same sensitivity than higher frequencies. These effects could lead to a preferential recording of signals with specific frequency content and hence have an effect on the frequency range of the clusters from pattern recognition as well as on the number of signals in each cluster. Again, these effects will have to be investigated in detail.

Conclusions

It has been shown that acoustic emission signal classification by an unsupervised pattern recognition approach yields two signal clusters for tensile tests to failure for both, miniature and laboratory scale solid wood specimens as well as for model layered wood and industrial plywood made from spruce wood. The signals in the two clusters essentially differ with respect to higher shares of low and high frequency components, respectively. The average low and high frequency components for the two clusters, however, seem to depend on specimen size. Miniature specimens yield somewhat higher weighted peak frequencies for the clusters than laboratory scale, but this might also be affected by the sensor characteristic and possibly by signal attenuation. There is no indication of a separate, third signal cluster that can be attributed to the adhesive layer in the layered wood specimens in comparison with solid wood. Even though the macroscopic mechanical properties of the different specimen types as well as their meso- and macro-scale failure behaviour (fracture pattern) are clearly different, this is not reflected in the clusters obtained from pattern recognition. It is well known that larger size damage in composite materials in general, and hence also in wood and layered wood (e.g., cracks or delaminations) typically yield several or many acoustic emission signals (see, e.g., [9]) representing microscopic mechanisms acting locally. It is hence speculated that the same microscopic mechanisms, i.e., inter-wall and trans-wall cracks identified in X-ray micro-tomography images of miniature specimens produce the acoustic emission signals during damage accumulation under tensile loads also in the laboratory scale specimens (solid, layered and plywood specimens). This tentative conclusion, however, will have to be verified by further investigations. Finite element simulation of signal sources, signal propagation and signal recording is expected to provide crucial information for reliably assessing signals from the different microscopic damage mechanisms.

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References

[1] F. Ritschel, M.G.R. Sause, A.J. Brunner, P. Niemz: „Damage Evolution in Wood – Pattern Recognition based on Acoustic Emission Frequency Spectra”, Holzforschung, submitted (2014).

[2] F. Ritschel, M. Zauner, S.J. Sanabria, B.R. Pinzer, M.G.R. Sause, A.J. Brunner, M. Stampanoni, P. Niemz: „Damage Evolution in Wood – X-Ray Microtomography and Complementary Evidence for Interpreting Acoustic Emission Behavior“, Holzforschung, submitted (2014).

[3] M.G.R. Sause, A. Gribov, A.R. Unwin, S. Horn: “Pattern recognition approach to identify natural clusters of acoustic emission signals”, Pattern Recognition Letters, 33, 17-23 (2012).

[4] M.G.R. Sause, T. Müller, A. Horoschenkoff, S. Horn: “Quantification of failure mechanisms in mode-I loading of fiber reinforced plastics utilizing acoustic emission analysis“, Composite Science and Technology, 72, 167–174 (2012).

[5] F. Ritschel, A.J. Brunner, P. Niemz: „Nondestructive Evaluation of Damage Accumulation in Tensile Test Specimens made from Solid Wood, Plywood and Laminated Veneer Lumber (LVL)“, Composite Structures, 95, 44-52 (2013).

[6] F. Ritschel, Y. Zhou, A.J. Brunner, Th. Fillbrandt, P. Niemz: „Acoustic emission analysis of industrial plywood materials exposed to destructive tensile loads”, Wood Science and Technology, 48, No. 3, 611-631 (2014).

[7] P. Niemz, A. Brunner, O. Walter: “Investigation of the mechanism of failure behaviour of wood based materials using acoustic emission analysis and image processing”, Wood Research, 54, No. 2, 49-62 (2009).

[8] F. Ritschel, P. Niemz, A.J. Brunner: (in German) „Wellenformanalyse von Schallemissionssignalen ausgewählter Zugversuche an Vollholz- und Sperrholz / LVL-Prüfkörpern“, 18th Colloquium Acoustic Emission, Proceedings BB-131 CD (ISBN 978-3-940283-37-5), Presentation No. 04, 8 pp. (2011).

[9] ISO/DIS 18249, Non-destructive testing - Acoustic emission testing - Testing of fibre reinforced polymers - Specific methodology and general evaluation criteria, International Organization for Standardization (2014).