

Review

Influencing Factors in Acoustic Emission Detection: A Literature Review Focusing on Grain Angle and High/Low Tree Ring Density of Scots Pine

Giulia Boccacci ¹, Francesca Frasca ¹, Chiara Bertolin ² and Anna Maria Siani ^{1,*}

¹ Department of Physics, Sapienza University of Rome, Piazzale Aldo Moro 5, 00185 Rome, Italy; boccacci.1766495@studenti.uniroma1.it (G.B.); f.frasca@uniroma1.it (F.F.)

² Department of Mechanical and Industrial Engineering, Norwegian University of Science and Technology, Richard Birkelands vei 2B, Gløshaugen, 7491 Trondheim, Norway; chiara.bertolin@ntnu.no

* Correspondence: annamaria.siani@uniroma1.it; Tel.: +39-06-4991-3479

Abstract: Among non-destructive testing (NDT) techniques applied to structural health monitoring in existing timber structures, ranging from visual inspection to more sophisticated analysis, acoustic emission (AE) is currently seldomly used to detect mechanical stresses in wooden building assets. This paper presents the results from a systematic literature review on AE NDT applied to monitor micro and macro fracture events in softwood, specifically Scots pine. This survey particularly investigates its application with respect to the tree rings density and grain angle inspection, as influencing factors well correlated with physical and mechanical characteristics of wood. The literature review was performed in a three-step process defined by the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) flow diagram, leading to the selection of 31 documents from different abstract and citation databases (Scopus, Web of Science and Google Scholar). The outcomes have highlighted how laboratory experiments, including several types of tests (tensile, cutting, compressive, etc.), were conducted in most cases, while a very limited number of studies investigated on in situ monitoring. In addition, theoretical approaches were often explored in parallel with the experimental one. It emerges that—for tree ring density studies—a multi-technique approach, which may include microscopic observations, could be more informative. Indeed, although not widely investigated, high/low tree ring density and grain angle were found as influencing factors on the AE parameters detected by the sensors, during condition and structural health monitoring experiments.

Keywords: acoustic emission; Scots pine; non-destructive techniques; grain angle; tree ring density; PRISMA; wood; softwood

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1. Introduction

Deformation and fracture are some of the common problems affecting wood material as it is often used, nowadays as in the past, in the construction of structures and artefacts of cultural value and therefore in need of special care and conservation. Research on wood is conducted by using different non-destructive testing (NDT) techniques mainly aimed at timber grading and assessment of existing timber structures [1].

Among NDT techniques, acoustic emission (AE) has recently been used to detect mechanical stresses in existing timber structures. An overview of the application of AE on wooden materials was already provided by Baensch [2] and Ross [3]. The aim of our review is to analyse the state of the art of the AE NDT technique applied to monitor the occurrence of fracture events in softwoods, specifically Scots pine, focusing on the influence of grain angle and tree ring density on such occurrence. First, the general framework of NDT used on wood samples was initially defined by means of a preliminary survey, designed to study the influence of high/low tree ring density and grain angle

direction on the outcomes obtained through the different methods. After that, the same influencing factors in relation to the AE parameters detected during experiments on wood samples, were investigated in a systematic literature review.

The density parameter as a focus of this work was defined as the ratio between the dry weight of wood divided by the green volume of the same wood (expressed in g/cm^3) [4]. In addition, the tree ring width (TRW) was investigated, as one of the main parameters used in dendrochronology for the reconstruction of climate variability of the past (tree rings usually grow wider in warm, wet years and they are thinner in years when it is cold and dry). Finally, the wood grain angle as the angle between the wood fibre direction and the vector in the axial direction (as shown in Figure 1), was studied together with the density as influencing factors in the AE detection.

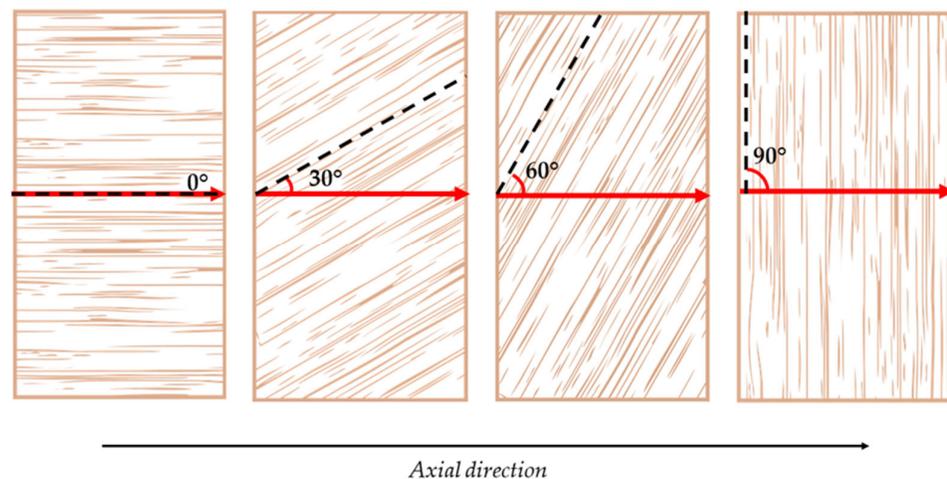


Figure 1. Illustration of samples with different grain angles (0-30-60-90°).

The paper is structured into three sections: following the introduction, the second section (i.e., Methodology) describes the search strategy based on the three-step process that led to the screening of the documents analysed in this review. In the third section (i.e., Results and Discussion), papers were organized by outcomes and into geographical regions, year of publication and subject areas of the research. Discussion on the outcomes is provided here. Then, the last section (i.e., Conclusions) evaluates the aspects mentioned above and identifies gaps in the application of AE on structural health and condition monitoring of softwood material, that might be faced and filled in the future.

2. Methodology

A first step of the literature review included a preliminary survey aimed to pinpoint the most widely used non-destructive testing techniques in the study of wood samples and assets.

Then, the systematic literature review on AE NDT technique applied to monitor the occurrence of fracture events in Scots pine, was performed using a three-step process described by the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) flow diagram [5].

2.1. Preliminary Literature Survey

The preliminary literature survey was carried out by searching useful documents for the definition of the background within which the current research is included. The research was conducted by using the online databases Scopus, Google Scholar and Web of Science. It was conducted through five keyword combinations using the Boolean operator “AND”: (1) “NDT” AND “Grain” AND “Pine”, (2) “NDT” AND “Pine”, (3)

“NDT” AND “Softwood”, (4) “NDT” AND “Grain” AND “Wood” AND “Fracture”, (5) “NDT” AND “Earlywood” AND “Latewood”.

Some of the documents resulting from this search through the above-mentioned databases, and other documents of interest for a total of 13 publications, were reported in Table A1 (see Appendix A).

2.2. Literature Review

2.2.1. Search Strategy and Papers Collection

Figure 2 shows the three-step procedure entailed by PRISMA flow diagram: (i) identification; (ii) screening; (iii) inclusion. Step (i) was performed with five keyword combinations, again using the Boolean operator “AND”: (1) “Acoustic Emission” AND “Grain” AND “Pine”, (2) “Acoustic Emission” AND “Pine”, (3) “Acoustic Emission” AND “Softwood”, (4) “Acoustic Emission” AND “Grain” AND “Wood” AND “Fracture”, (5) “Acoustic Emission” AND “Earlywood” AND “Latewood”.

The search was limited to the published paper in the time interval January 2000–June 2021 and conducted in slightly different ways according to the internal differences among the three databases. The identification step was applied in Google Scholar, sorting the documents by relevance and considering the first three pages viewed (corresponding to the first 30 documents) having all the keywords present either in the title or in the brief subtitle description. The same was applied in Scopus, looking at the research keywords in the “Abstract, Title, Keywords” section. In Web of Science, the documents were first sorted by relevance and then selected by conducting the keywords research in the “Topic” section. Duplicates were removed. The research initially provided a total number of 158 documents, shown separately for each of the different keyword combinations in Table 1. All the included documents were written in English and available online. According to the criteria adopted in the selection of records, the keyword combinations in the considered abstract and citation databases, might not capture that do not fit any combination of the search terms. For example, the combination “Acoustic Emission” AND “Softwood” was not able to capture papers focused on the AE detection on spruce samples, if the term “Softwood” was not explicitly indicated in the keywords or in the title and abstract. However, we focused our search on papers concerning Scots pine.

Step (ii) was carried out by reading 105 documents (i.e., the abstract in case of journal articles or the brief introduction in case of other type of documents, such as chapters of books or conference publications). This led to exclude 74 documents.

In step (iii), a list of 31 papers were included in the review, among them 26 articles in peer reviewed journals, 4 conference papers and 1 book chapter.

Table 1. Number of initial results obtained from Scopus, Web of Science and Google Scholar for each keyword combination.

| Keywords Combinations | Scopus + Web of Science | Google Scholar |
|--|-------------------------|----------------|
| Acoustic Emission Grain Pine | 2 | 8 |
| Acoustic Emission Pine | 43 | 26 |
| Acoustic Emission Softwood | 15 | 22 |
| Acoustic Emission Grain Wood Fracture | 10 | 13 |
| Acoustic Emission | 3 | 16 |

| | | |
|-----------|-----|------|
| Earlywood | | |
| Latewood | | |
| | 73 | + 85 |
| | 158 | |

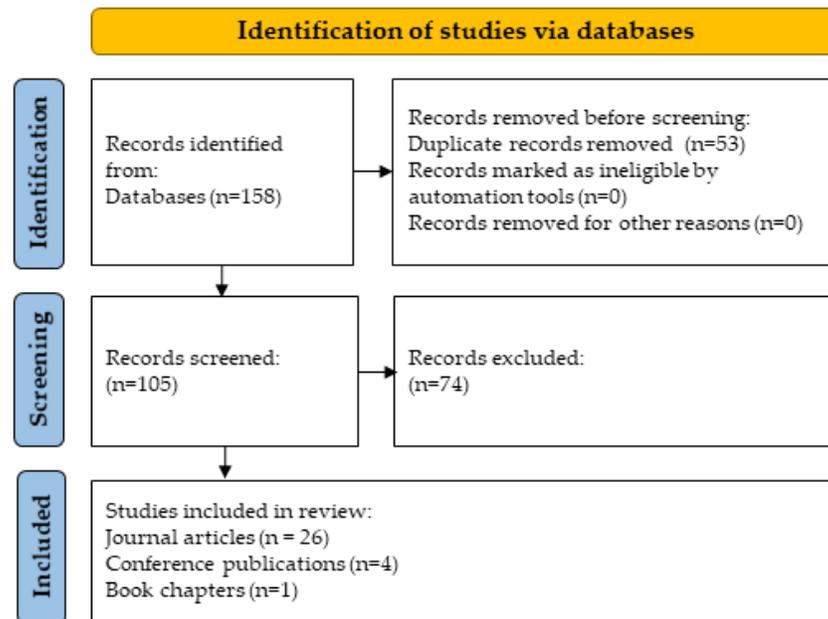


Figure 2. PRISMA flow diagram for new systematic reviews showing the number of documents obtained after each evaluation-step.

Among these 31 documents, 18 were obtained from Scopus/Web of Science (herein-after named only as Scopus if duplicate) and 13 from Google Scholar.

2.2.2. Analysis of Publications

The selected documents were analysed to extract the following information:

- contents of publication;
- geographic distribution;
- year of publication;
- subject areas of the research (of both authors and journals).

A database was created, reporting all the relevant characteristics deduced from the content of the documents. The table was structured reporting the following information for each document: “keyword combination” used to visualise the document in the abstract and citation databases, “reference” of the document, “bibliographic ID number” used as mentioned in writing this paper, “year of publication”, “authors”, “affiliation” of both the first and last authors of the document, “countries” obtained from the affiliation of the first author, “topic” as the expertise of both the first and last authors, “wooden species” studied in the research, “objectives” of the research, “period of study” as the time interval in which the samples were conditioned and/or tested, “instrumentation” used in the experiments, “aspect of the grain or tree ring density” when mentioned in the document, “analysis of parameters” conducted in the research, “analysis method” applied in the works, also considering possible theoretical approaches, “case-study” indicating if the research was conducted in laboratory or in situ and “research date” on which the databases were last accessed to carry out the search. This approach allowed us to collect all the relevant information discussed in the results and discussion section of this review. The subject areas of the authors involved in the research were derived from Scopus, specifically from

the profile page of the first and last authors of each document. The subject areas of the journals in which these documents were published were obtained from the Journal Rank Indicator SCImago. Conference publications and chapters of books were not considered in this evaluation.

3. Results and Discussion

3.1. Preliminary Survey on Non-Destructive Techniques on Wooden Samples

The preliminary survey allowed us to define the techniques mostly exploited in structural health monitoring field when dealing with wood, which are summarised in Table A1 reported in the Appendix A, divided into five categories: visual, acoustic, vibration, probing and other non-destructive techniques. The table also reports, for each technique, the type of outputs obtained in the literature.

Despite their effectiveness, NDT results are affected by several factors related to internal wood structure (grain angle), test conditions (device, sensor positioning, timber-sensor coupling mean, specimen dimensions) or environmental conditions (moisture content (MC), temperature) [6]. On these assumptions it is very important that future investigations should use unified procedures (MC adjustment factors, number of measurements, experimental and monitoring setup and procedure) to enhance the capacity of these techniques [1]. Wood grain angle was proved to be an influencing factor in the variation of wood stiffness (large grain angles can reduce stiffness and shape stability) [7]. In Cyra and Tanaka [8], wood grain angle was investigated together with the slope of grain (SoG), a parameter defined as the deviation of the grain from the edge of the wooden piece. They found that the AE activity in routing of yellow poplar blocks decreased from 0° to roughly 15–30° grain angles and reached the maximum at 150°. Moreover, concerning the SoG, the AE count rate (expressed in counts/0.2 s) gradually decreased from 0° to around 75–105° and reached the maximum at 180°.

Concerning the density parameter, it was assessed that for many softwoods, density is inversely related to tree ring width (TRW), as growth rate affects the width of the earlywood, whereas the amount of the denser latewood remains approximately constant. Therefore, TRW is included in the timber-grading criteria based on visual inspection and it is used as a rough estimate of density and thus of stiffness and strength [9]. However, probing methods are most frequently used to estimate density in existing timber structures, as the most reliable and simplest indicator of the wood mechanical properties. In addition, Lin et al. [10] studied the effects of ring characteristics on the compressive strength and established that it increased with decreasing ring width parameters and increasing ring density parameters.

3.2. Acoustic Emission along Grain Angle Direction in High/Low Tree Ring Density of Scots Pine

The literature review aimed to analyse and clarify the more recent information existing about the use of acoustic emission technique to monitor fracture events, occurring along the grain angle direction in Scots pine samples of low and high tree ring density.

3.2.1. Geographic Distribution

Figure 3 shows the map of the affiliation of the first author of the publications. Studies were performed by researchers mainly from Europe (Poland, Norway, Spain, Austria, Finland, Germany, France, Switzerland and Hungary), from Asia (Japan and China), North America (USA and Canada) and South America (only one document from Chile). The results show that the topic is especially investigated in those countries in which pine wood is more widespread in nature and hence more used as building construction material.

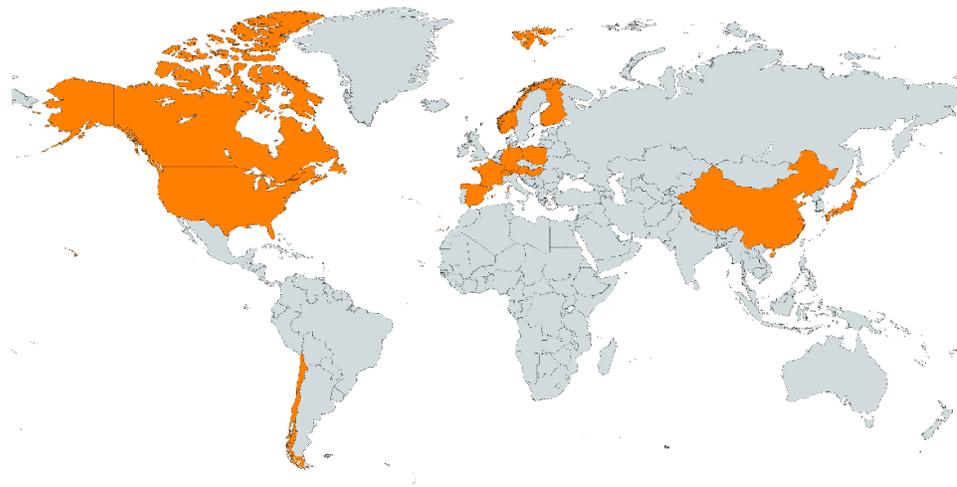


Figure 3. Geographic distribution of the first author’s affiliation involved in the research topic. Created with “MapChart” (Credit: <https://mapchart.net/>, accessed on 30 July 2021).

3.2.2. Year of Publication

Figure 4 shows the number of publications by year. In 2020 up to five documents were published on this specific topic.

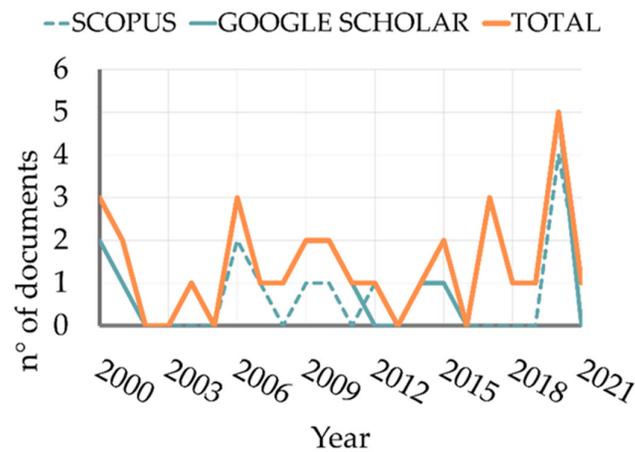


Figure 4. Number of papers by year after the refine diversified by different colours: blue dashed line for Scopus, blue solid line for Google Scholar and orange line for the total number of documents.

3.2.3. Subject Areas of the Research

The expertise and cultural background of both the first and last authors of each document were investigated and results are shown in Figure 5a. The authors are mainly involved in Engineering studies (33%), then in Material Sciences studies (29%), then in Agricultural and Biological Sciences (12%), in Earth and Planetary Sciences (9%) and in other disciplines including Chemistry, Computer Science, Art and Humanities, Physics and Astronomy, Energy and Environmental Science. Figure 5b shows a pie chart reporting the percentage of subject areas of the journals in which this type of research was published. The main macro-areas are Material Sciences (34%), Engineering (24%), Forestry (18%), Physics (8%) and other disciplines including Waste Management and Disposal, Agronomy and Crop Sciences, Biotechnology, Nanoscience and Nanotechnology, Plant Sciences and Metals and Alloys.

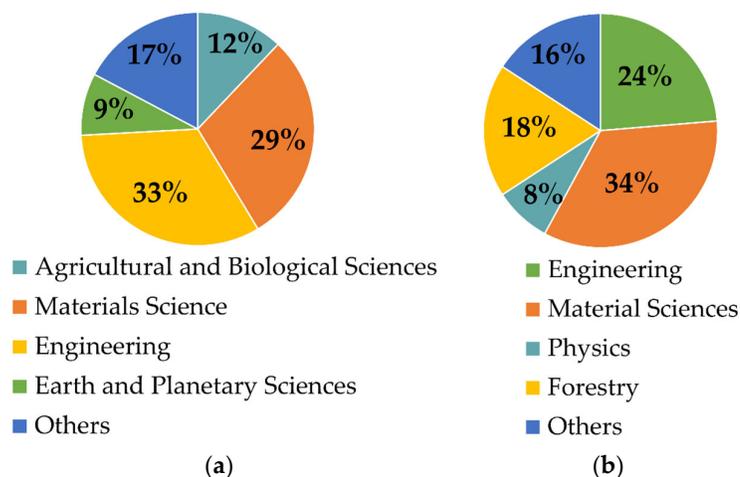


Figure 5. (a) Percentage of subject areas of expertise of the authors representing their research field and cultural background; (b) Percentage of the main subject areas of the journals.

Table 2 reports the name of the journals in which the documents were published, their corresponding main subject areas (as the macro-areas in which specific disciplines are included) and the related journal quartiles, that allow us to understand which are the most prominent journals within each specific discipline. The last column shows the number of documents published for each of the listed journals (N° of docs). Conference publications as well as chapters of books were not considered in this diagram or in the table below. Moreover, for two journals there was no detailed information available, so for this reason only 24 documents instead of 31 were included in this investigation.

Table 2. Journal’s names, corresponding main subject areas, journal’s quartile and number of published documents for each journal.

| Journal | Subject Area | Quartile | N° of Doc |
|--|-------------------------------|----------|-----------|
| Archives of Civil Engineering | Engineering | Q4 | 1 |
| Bioresources | Engineering | Q3 | 1 |
| | Waste Management and Disposal | Q3 | |
| Construction and Building Materials | Engineering | Q1 | 3 |
| | Materials Sciences | Q1 | |
| European Journals of Wood and Wood Products | Forestry | Q2 | 1 |
| | Material Sciences | Q2 | |
| Folia Forestalia Polonica–Forestry | Forestry | Q2 | 1 |
| Holzforschung–Wood research and Technology | Forestry | Q4 | 2 |
| | Material Sciences | Q4 | |
| Insight–Non-Destructive Testing and Condition Monitoring | Engineering | Q3 | 1 |
| | Material Sciences | Q3 | |
| | Metals and Alloys | Q3 | |
| Journal–Faculty of Agriculture Kyushu University | Agronomy and Crop Sciences | Q4 | 1 |
| | Biotechnology | Q4 | |
| Journal of Material Science | Material Sciences | Q2 | 1 |
| | Engineering | Q1 | |
| Journal of Tropical Forest Science | Forestry | Q3 | 1 |
| Journal of Wood Science | Material Sciences | Q3 | 1 |
| Material Science and Engineering | Physics | Q1 | 1 |

| | | | |
|-----------------------------|-----------------------------------|----|---|
| | Material Sciences | Q1 | |
| | Engineering | Q1 | |
| | Nanoscience and Nanotechnology | Q1 | |
| Forests | Forestry | Q1 | 1 |
| Materials | Physics | Q2 | 2 |
| | Material Sciences | Q2 | |
| Physical Review Letters | Physics | Q1 | 1 |
| Wood Research | Forestry | Q2 | 1 |
| | Material Sciences | Q3 | |
| Wood Science and Technology | Forestry | Q1 | 4 |
| | Engineering | Q1 | |
| | Material Sciences | Q2 | |
| | Plant Sciences | Q2 | |

3.2.4. Content of Publication

Figure 6 reports a scheme that summarises the main information extracted by the selected reviewed documents. As a result, 27 over 31 documents explored softwoods behaviour, especially of pine, spruce, hemlock, fir and cedar; 10 of them also explored the behaviour of hardwoods such as alder, oak, ash, poplar, chinkapin, birch and lime wood; while one document considered wood products such as medium-density fibreboard (MDF), oriented strand board (OSB), plywood and particleboard. In most cases, the AE technique appeared to be used in laboratory experiments and in only one case among the reviewed documents, it was applied for an in-situ monitoring focused on movable objects only [11]. The tests conducted on the samples were of various type (mainly fracture tests, but also tensile, cutting, coating, compressive, drying and torsional tests) and they sometimes involved an acclimatisation process (e.g., climate chamber [12–14] and laboratory chamber dryer [15]).

The acoustic emission instrumentation was often found coupled with the testing machine to perform mechanical tests and the digital image correlation often used to record images during the tests. Among the analysed documents, only 7 included microscopic observations of the surface by means of scanning photography technique, scanning electron microscopy, optical microscopy, stereomicroscopy and electron microscopy.

Finally, among the selected publications, 12 documents had both an experimental and theoretical approach, also performing numerical modelling or simulation and in some cases suggesting general mathematical formulations.

The investigation showed that the most monitored acoustic Emission parameters were amplitude (A), energy (E) and counts (C), which were frequently studied against time, crack length and load (even in their cumulative form) with their distribution often highlighted. Among the parameters less frequently studied there are the frequency characteristics [11,16–21], other parameters such as the energy release rate (G) [22], the fracture toughness (K) [23,24], root mean square of the signal voltage (RMS) [25–27], density surface energy value (DSV) [16,23], stress (σ), strain (ϵ) [20,28–32] and modulus of elasticity (MoE) [32,33].

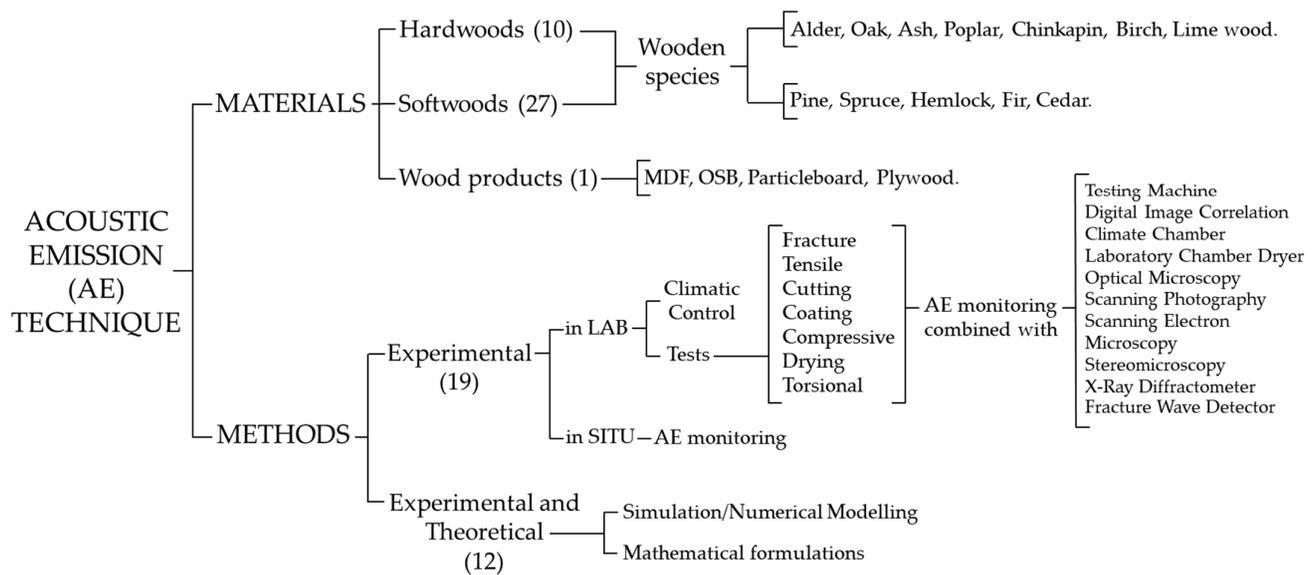


Figure 6. Information extracted from the selected documents. In these works, the Acoustic Emission technique was used alone or combined with other techniques. In brackets the number of documents.

In many cases, wood samples were subjected to pre- or ongoing experimental settings, such as acclimatisation at some temperature (T) and relative humidity (RH) conditions in a climate chamber or simply moistening them in water [19,34,35]. In more than half of these documents, the time information related to the preconditioning period was missing even when the acclimatisation setup was specified, causing a problem in the reproducibility of the experiments. The AE parameters were often related to the moisture content (MC) of the tested sample, as in the case of Rosner et al. [19] who demonstrated in their experiments that the AE count rate lower than 175 kHz of fresh, never dried sapwood beams appeared to be much higher than that of once or twice pre-dried sapwoods. Sometimes the AE parameters were also related to the RH condition of the environment in which the tests took place. Bertolin et al. [14] carried out an investigation where the AE signals were recorded during two stages of an experimental procedure that occurred in a climate chamber at two different relative humidity levels and it was noted that the AE activity was concentrated over the first days after the hygric change and successively, as the sample equilibrated with the new environmental conditions in the chamber, it suddenly decreased. Some publications include a theoretical approach aimed to perform numerical simulation and modelling of wooden fracture behaviour, by using Finite Element Analysis through different software such as the Abaqus CAE 2019 software [23], the AutoCAD 2012 software [36], the Adina v. 8.4 Finite Element Method (FEM) program [33] and the ANSYS software package [13]. In a work by Aicher et al. [30] Linear Elastic 2D Finite Element Simulations of wood specimens were performed to obtain some insight on the most probable source region of AE signals. Nagy et al. [37] used a 2D statistical lattice model based on morphological simulations of microscopic damage evolution in wood. In some cases, comparison between experimental analysis conducted by AE and numerical modelling are presented, for example to show the capability of AE technique to monitor the crack tip growth within wood material [38].

Other works propose mathematical formulations for example as model to express the relationships between surface roughness and chip thickness [25], to compare experimental data to the theoretical ones [16], or to define the location algorithm used for the burst source location in wood specimens [30]. In Shao et al. [39] a theoretical approach was presented in the study of the fractal theory applied to examine the fracture surfaces of five types of woods. In Zhao et al. [22], based on thermodynamic approach, a theoretical model

for predicting crack instability was established and the model was verified by double cantilever beam (DCB) tests.

Although the multi-techniques approach used in these documents appears to be lacking in microscopic observations, they have proved to be effective in the fracture surface analysis. In addition, their efficacy when coupled with AE system was demonstrated in a work by Kossakowski et al. [33], where a scanning photography technique made it possible to distinguish fracture patterns at different magnification, both in radial–longitudinal (RL) and tangential–longitudinal (TL) orientations; or in Niemi et al. [32] who used a stereomicroscope to study the fracture characteristics of different wood products. In other works, the scanning electron microscopy system was adopted [13,18,39–41], as in the case of Shao et al. [39] who used it to identify different modes of wood fracture during three-point bending tests of samples.

A few documents investigated the influence of the grain angle on the AE activity monitored on wood samples [25,29]. Aguilera et al. [25] in their studies identified changes in cutting conditions and surface quality of Scots pine samples. It was assessed that the effect of changing the slope of grain was reflected by a significant variation in the acoustic emission signals. The failure process of red Iauan and Sitka spruce specimens under static and fatigue torsional loading with different grain angle rotations was monitored by Chen et al. [29] and important differences in AE counts for hardwood and softwood were found. It was assessed that the test-piece grain angle influences the total AE counts, up to the fracture. As a result, AE counts decrease as the grain angle increases from 0 to 45 degrees and increase as the grain angle increases from 45 to 90 degrees.

The tree ring density property has also been investigated in some publications, for the way it can influence the variation of AE parameters [12,19]. Rosner et al. [19] in their experiments found that spruce latewood emitted much more AE at a given volume, because the tracheid number was higher than in spruce earlywood. This was proved by the AE count rate that appeared to be generally higher in latewood. Perrin et al. [12] highlighted in their work that wood species having a significant difference in the density values between latewood (LW) and earlywood (EW), are more likely subjected to stress concentrations at the EW/LW interfaces. It was proved that when the differences between EW and LW density values are very small, the damage mechanisms are quickly initiated but evolve progressively until the rupture (the signals are numerous but not very energetic).

4. Conclusions

This literature review has investigated the role that the grain angle direction and the high/low tree rings density have in detecting acoustic emission burst on Scots pine. Very few documents have analysed the relationship between these two parameters and the acoustic emission detection. Nonetheless, results provided a basis for four potential future research lines that are highlighted here:

- The AE activity emitted by wooden samples and assets under stress with different grain angle direction and tree ring density, can be investigated to assess if these two parameters might become fingerprints useful in forecasting mechanical decay. Such research might be used in the monitoring of structural health of wooden building envelopes, thus assuming a crucial role in the preventive conservation of them from mechanical stresses. In addition, such analysis might open interesting perspectives to investigate the influence of moisture content (MC) in the simultaneous assessment of mechanical and biological risk of decay on wooden samples. In fact, the MC variation is strictly related to drying/wetting events (i.e., risk of mechanical decay) while high MC provides optimal conditions for mould growth on wooden substrate (i.e., risk of biological decay).
- Future studies could investigate the relationship between AE activity and the tree rings density and the grain angle in pine samples (as widely used building construction materials), to obtain insights on the durability of pine materials, leading to a

higher and prompt capability to address appropriate retrofitting interventions in wooden historical buildings in the era of climate change.

- The multi-technique approach used in these documents proved to be lacking in microscopic observations, but in view of their efficacy in obtaining helpful information, it is suggested to consider the microscopy techniques in fractography i.e., in the study of the fracture surface of wood during the experimental tests.
- Finally, the information related to the preparation and acclimatisation stages of the tested samples should be improved, especially in terms of the duration of the conditioning period (an information that is often missing in the existing documents). In this way, the correct reproducibility of the experiments would be ensured.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1 summarises the non-destructive testing (NDT) techniques mainly used in structural health monitoring field when dealing with wood.

Table A1. Non-destructive techniques mainly used for timber grading and assessment of existing timber structures and their corresponding outputs.

| Technique | Output |
|--|--|
| <i>Visual techniques</i> | |
| Visual Strength Grading (VSG) | Examination and recording of wood features, defects, signs of damage or deterioration (cannot predict the influence of non-visible defects; needs to be coupled with other NDT) [9]. |
| <i>Acoustic techniques</i> | |
| Acoustic Emission (AE) | Identification of the onset time of crack nucleation [42]. |
| Micro Hammer (IML) | Estimation of modulus of elasticity (MOE) [1]. |
| Ultrasound and stress wave | Estimation of modulus of elasticity (MOE), dynamic modulus of elasticity (Edyn) and bending strength (MOR). Assessment of strength and stiffness [1]. |
| <i>Vibration techniques</i> | |
| Portable Lumber Grader (PLG)–also coupled with microphone | Estimation of modulus of elasticity (MOE) and bending strength (MOR) [1]. |
| Mechanical Timber Grader (MTG)–also coupled with accelerometer | Estimation of modulus of elasticity (MOE) and bending strength (MOR) [1]. |
| <i>Probing techniques</i> | |
| Resistography | Estimation of defects such as knots, fissures, decay or even termite attack existing in hidden surfaces. Estimation of density (abnormal density variations associated with |

| | |
|---|---|
| | mass loss, caused by biological degradation), mechanical strength, modulus of elasticity (MOE) and water content of timber [1,9,43]. |
| Pyloidin | Estimation of density [1,44]. |
| Screw Withdrawal Resistance Meter (SWRM) | Estimation of density [1,44]. |
| <i>Other ND techniques</i> | |
| Acoustic tomography | Study of the influence of pith distance on velocity [1]. |
| Ground penetrating radar (GPR) | Assessment of the variation of the Moisture Content [1]. |
| Infrared thermography (IRT) | Species recognition, physical properties prediction and evaluation of degradation level. Detection of MC differences [1,45]. |
| Near Infrared-hyperspectral imaging | Determination of the ratio of juvenile wood to mature wood [1]. |
| Thermal Imaging techniques | Display the origin of crack nucleation and its progress. In static torsional testing of wood, the temperature change produced by thermal radiation will decrease a little when a sample is loaded but increase quickly after cracking takes place. The thermal imaging of softwood indicated that earlywood exchanged more thermal energy than latewood [42]. |
| Stress-wave Toc Tomography | Detection of decay and defect in the interior of the wood material (including knots of little size) [45,46]. |
| CdZnTe-Based X-Ray Spectrometer | Determination of absolute density [47]. |
| Microwave-focused beam | Detection of grain angle for arbitrary grain inclination in 3D space [7]. |
| Synchrotron radiation micro-computed Tomography (SR μ CT) | Detection of the microscopic structure of wooden specimens under initial, crack evolution and final fracture development [48]. |

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