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AE in Polymeric Composites

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Abstract. Polymeric composites comprise a wide range of materials consisting of continuous or discontinuous fibers, various particles, or combinations of these embedded in a polymer matrix. Beside technical polymer composites, bio-based composites with biopolymers or natural fibers, or natural polymer composites such as wood are finding increasing use in structural applications. The complex, multi-scale morphology yields distinctly different mechanisms generating AE under thermo-mechanical loads or environmental exposure. Storage tanks and pressure vessels made from fiber-reinforced composites were among the first components for which AE testing yielded reliable assessments of structural integrity. The empirical Felicity-ratio is important for quantitative predictions of structural damage and remaining service life. Recent advances in AE signal analysis now contribute to improved source location accuracy and to the unambiguous identification of the underlying microscopic signal source mechanisms. AE testing of infrastructure and components tends to move from periodic inspection to continuous structural health or condition monitoring. This also applies to infrastructure made from polymeric composites as well as to structures or parts in the transportation industry. AE implemented for process monitoring related to polymeric composites shows potential for development of AE-based process control. This chapter first reviews the mechanisms generating AE in polymeric composites, then discusses progress in AE signal analysis for source location and identification of mechanisms and presents selected examples of established AE applications from the micro- to the macro-scale. This includes prediction and quantification of damage in materials and structures, and closes with prospects for developments of AE condition monitoring and process control.

Keywords: Polymer-matrix composites, AE signal source identification, AE source location, Structural integrity assessment, Condition and process monitoring.

1 AE sources in polymeric composites

Polymeric composites consist of at least two, sometimes several, phases or components, each with distinct properties. The polymeric phase, either a thermoplastic or thermoset, is usually the continuous matrix into which the second phase is embedded. The second phase, consisting of, e.g., particles of various sizes and shapes, short, or continuous fibers, often is stiffer than the polymeric matrix and hence acts as a reinforcement. Short or continuous fiber-reinforced polymer (FRP) composites may include different types of fibers as well as different matrix phases. AE source mechanisms (based on the definitions in [1]) are (cite) *"a dynamic process or a combination of processes that produce AE by the rapid release of energy from localized sources within the material"*. In polymeric composites, such processes are various damage mechanisms. They do generate AE when the material is, e.g., subject to thermo-mechanical stresses, impact of foreign objects, environmental exposure or ageing. These processes comprise matrix cracks, debonding between the polymer matrix and the reinforcement phase(s), or failure of any other phase, e.g., fiber breaks, fracture of particles, etc. (see Fig. 1).

These AE sources related to defect initiation or propagation are called primary sources [1]. Specifically, initiation and propagation of delaminations, i.e., planar separations inside a layer (so-called laminae) or between layers of the laminate, are also considered a damage mechanism in FRP [2]. However, there is clear evidence from AE monitoring that delamination is the result of a large number of small, often microscopic matrix cracks [3] and possibly fiber-matrix debonds rather than a single AE source mechanism. Damage propagation or growth in polymeric composites can be affected by residual defects from processing and manufacturing operations, e.g., matrix porosity, internal stresses, or edge delamination as well as by discontinuities, e.g., at ply drop-off positions. Secondary sources of AE generated by defects already present in the composite comprise, e.g., friction between crack surfaces at debonded fiber-matrix interfaces, or fiber pullout after fiber breaks.

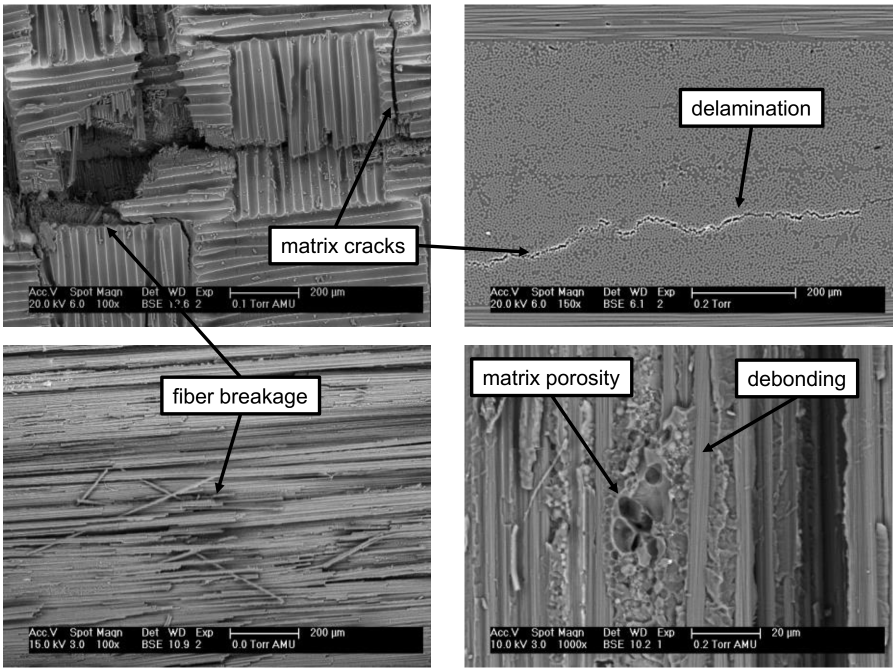


Fig. 1. Microscopy images of fracture zones of a carbon/epoxy composite material indicating matrix cracks, delamination, fiber breakage, matrix porosity and debonding.

The morphology of polymeric composites is complex, covering a range of length scales and that also holds for the defects present in the material or generated by damage mechanisms during damage accumulation. The matrix porosity ranges from the sub-micrometer level up to several hundred micrometers or even millimeter size sinkholes. Matrix cracks and fiber-matrix debonding cover a comparable length scale range, whereas delaminations produced by impact, even if barely visible on the surface, can have initial lengths or widths of several centimeters [4] and then propagate to even larger size depending on the applied global stresses or loads and their interaction with the composite morphology and the internal stresses. Fiber breaks often occur simultaneous with fiber matrix debonding around the failure location and, due to redistribution of stresses, may promote the occurrence of further damage in their vicinity.

In FRP composites with continuous fiber reinforcement, the amount of fibers (fiber volume fraction) and their lay-up plays a significant role in damage initiation and accumulation. One specific feature of damage initiation and accumulation in FRP composites is that initially small defects are generated statistically distributed in the volume of the test object or the in-service components or structures. Further loading, often by cyclic loads or stresses, with constant or variable amplitude and/or frequency spectra yield defect growth or propagation. This then results in coalescence of defects into larger damage zones that frequently leads to localization of mesoscopic or macroscopic damage during further loading stages and finally, to failure. FRP failure models reflect that in a damage index, e.g., stiffness reduction [5], which shows a non-linear behavior as a function of time or load. This non-linear behavior is typically reflected in the observed AE activity and AE intensity.

Based on the multitude of possible AE sources, polymeric composites are well known to generate an enormous amount of AE signals during loading. This makes inspection of these materials quite challenging in terms of data handling, but at the same time quite useful. The information provided by the AE signals is a unique opportunity to study the microscopic initiation, growth and accumulation of damage inside polymeric composites.

2 Identification of AE source mechanisms

From near the beginning of the use of AE for fiber composites there has been interest in using the signals to identify the source type of each detected AE event [6]. Based on the various different damage mechanisms occurring in composites, there is the natural challenge associated with the task of source identification. Since the complexity faced in classification of damage mechanisms is not yet resolved in mechanics, e.g. delamination vs. matrix crack, it is consequently even harder to label the corresponding AE signals appropriately. In particular, no damage mechanism is truly isolated, so a fiber break will always incorporate aspects of fiber debonding and possibly matrix cracking in its surrounding. Accordingly, the AE signal from such fiber breaks will include contributions from all other mechanisms that are involved. Likewise, a macroscopic crack propagation such as delamination of a certain length will microscopically involve matrix cracking, fiber debonding, fiber pull-out and even fiber breaks. Again, the corresponding AE signal is shaped from the contribution of all these mechanisms. Nevertheless, the approach to perform identification of AE source mechanisms is a task that has seen serious advances in recent decades.

To categorize the established AE analysis techniques, it is useful to distinguish between signal classification and source identification tasks (see Fig.2). The first task is the grouping of AE signals based on their similarity. After this step, the second task is to assign a group of AE signals to a specific source mechanism.

2.1 AE signal classification

In the past, many authors proposed the use of single AE feature values, such as amplitude or peak frequency to perform source classification for polymeric composites. Due to its simplicity, such an approach seems promising, but has not turned into a commonly accepted procedure. The reason for that is the huge bias included in a single feature value, which originates from the particular testing setup, material type, sensor choice, sensor location and many other factors. Therefore, such classification approaches are not transferable to other testing conditions and many times neglect the known relationships between feature values and source mechanisms. Therefore, it became apparent that single features were typically not a reliable means to identify sources. This conclusion was echoed by the conflicting results that were reported in the literature.

To overcome these deficiencies, pattern recognition techniques were widely examined by the research community. Conceptually, pattern recognition methods consist of two approaches, supervised and unsupervised pattern recognition, both trying to classify the AE signal based on a set of AE features instead of a single feature.

The task of unsupervised pattern recognition is to separate a set of given objects into distinct groups according to their similarity relative to each other. Various approaches with a focus on detection of characteristic similarities of the recorded AE signals have been published [7, 8, 17–22, 9–16]. As a distinctly different approach, supervised pattern recognition techniques consist of two subsequent stages. In the supervised stage, a set of objects with known assignment to the respective classes is prepared. This assignment is usually denoted labelling. For this stage, an algorithm is trained to recognize these types of objects based on a given set of features. In the subsequent stage, the algorithm is applied on objects with unknown assignment and classifies them based upon their similarity to the object classes provided in the supervised stage.

Among the successful applications, discrimination between noise and non-noise acoustic emission signals is achievable by unsupervised pattern recognition techniques [7, 8]. In combination with the use of suitable experimental considerations and finite element simulations the respective signal groups can also be associated with specific damage mechanisms in FRP [9, 11, 26, 12–16, 23–25].

2.2 AE source identification

Whilst grouping of AE signals significantly benefits from the advances in the field of data sciences, the source identification task is left to the AE community. As seen in Fig.2, one can identify three distinctly different approaches for this task.

Single source specimens. In the past, significant research efforts were made where the focus was on a specific test sample or loading condition that was designed to isolate the AE sources to a single type. This approach was undertaken with the idea that the recorded AE information (e.g. frequencies, amplitudes, energies) from this single source could be translated to other experimental conditions where multiple source types would be present. Among these approaches there is the use of model composites (e.g. single fiber fragmentation test, fiber strand testing, …) as well as micromechanical settings (e.g. filament testing, fiber pull-out, …).

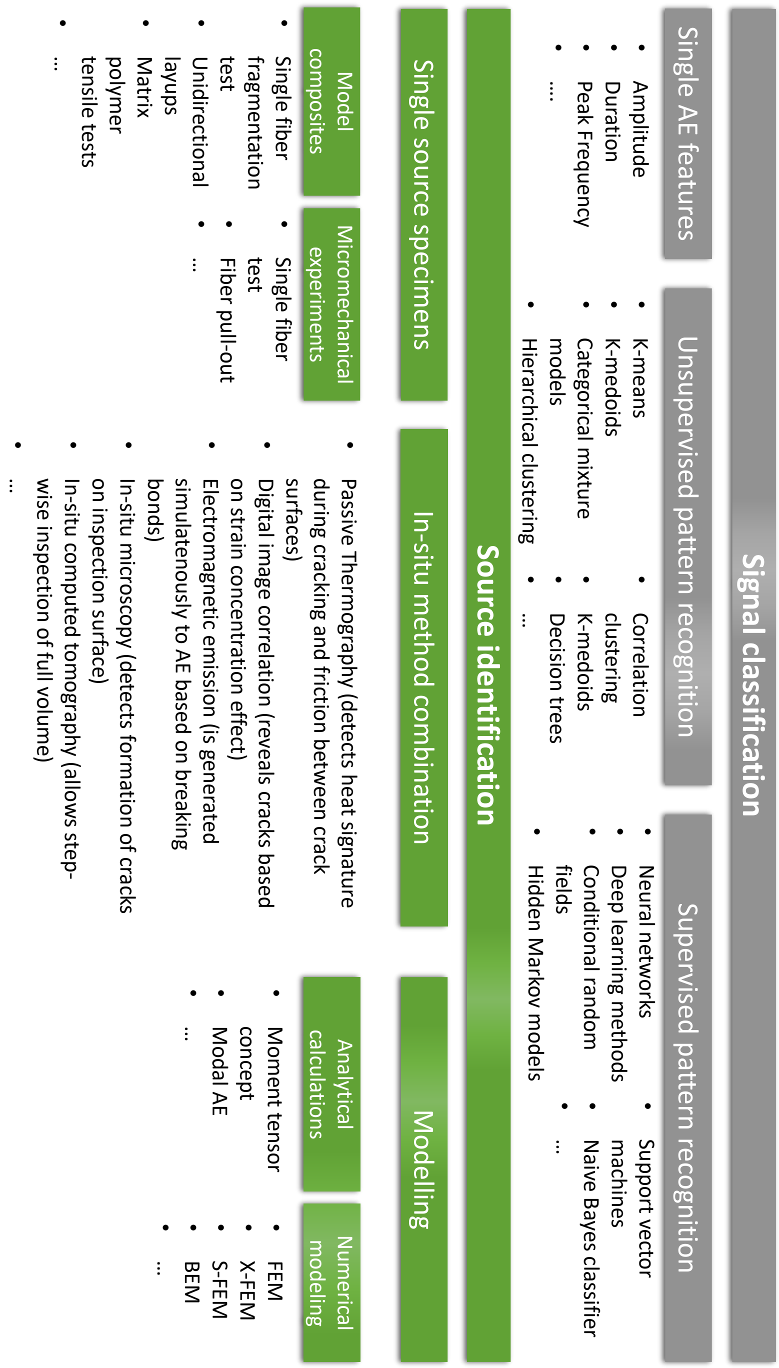


Fig. 2. Categorization of tasks involved in identification of AE source mechanisms and potential approaches and methods for each step.

Whilst interesting results were achieved in many cases, the key drawback still rests in the lack of transferability. With significant advances in modeling of AE, we nowadays precisely understand the massive influence of different propagation conditions, geometrical constellation and residual stresses. Thus, such single source experiments are a highly interesting tools for basic research experiments, but are not feasible to create “fingerprint” AE signals for a particular source type that is expected to happen in a real polymeric composite [27, 28].

In-situ method combination. For the cases, where realistic specimens with multiple AE sources are present, the established way to perform source identification is by means of phenomenological observations [29], by comparative measurement of test specimens with known types of AE sources [11, 30] or by post-mortem microscopy [31]. With modern experimental setups, better approaches are nowadays available, which allow an in-situ comparison of AE signals and secondary observations. Fig. 2 lists some of the established ways of correlation with an extensive coverage of that topic found in [32]. The most promising experimental approach for source identification available today is likely the in-situ combination of high-resolution computed tomography using X-Ray or Synchrotron Radiation together with AE. This allows studying microscopic damage mechanisms (e.g. fiber breaks) with a visual volumetric inspection method and to compare that result to the occurrence of particular types of AE signals [33].

Modeling. As another independent approach, modeling has been used to provide an assignment of particular groups of signals to particular damage mechanisms. For volumetric media, a suitable approach to derive the source type is the use of moment tensor inversion, originally developed in geophysics and then applied to concrete (a composite material). A comprehensive overview of this topic is found in chapter 7 and 8 and the original work [34–36], so it is not repeated here. For AE sources in composite laminates, further refinement is found in [37, 38]. Another classification technique more adapted to composite materials is the analysis of guided waves, termed “Modal AE” due to the analysis of the guided wave modes. Although this approach is an experimental procedure, the relationship between certain source types and the type of guided wave modes found in thin structures is heavily assisted by modeling attempts using analytical or numerical tools [29, 39–47]. The aim is to find characteristic ratios of certain guided wave modes, which are characteristic of a particular source type.

With the advent of powerful computers and advancements in numerical methods it is now feasible to perform a direct computation of the AE signal released by a particular damage mechanism. Such numerical procedures have been demonstrated throughout various publications [15, 16, 32, 48–52]. One approach for using modeling in source identification was presented in [48]. The procedure is carried out in three subsequent steps:

1. the volume of interest is defined and modeling of different source signals is carried out at representative source and sensor positions
2. the same feature extraction procedure is applied to the modeled signals as for the respective experimental signals and
3. feature value positions of the modeled signals and the experimental signals are compared.

Based on the known AE source type of the modeled signals this allows to assess the origin of signal groups and has a reasonable or high possibility to relate the occurrence of one signal group to one AE source type.

2.3 Limitations of AE source identification

Meanwhile, robust approaches have been proposed to identify natural clusters of AE signals [16] and have been adopted by various other research groups for composite materials, wood fracture and in plant science [20, 53–56]. Factors of influence such as propagation effects, sensor types, damage formation within the propagation path and test object geometry have been concisely elaborated [32, 48, 57, 58].

Although many approaches have been proposed in literature, none of them has made it to accepted standards so far. A majority of the published work reports the aspect that damage mechanisms in polymeric composites are distinguishable based on their frequency characteristics (see e.g. [59, 60]). However, wave propagation over a certain length compromises the frequency information due to frequency selective attenuation and dispersion [61]. In addition, changes in laminate thickness, fiber orientation and many other factors impose additional challenges to successful source identification. Specifically, the transfer from lab-scale specimens to component level requires some specific attention and new approaches to deal with the change in signal information [32].

3 AE source localization in polymeric composites

Since fundamentals of source localization procedures are introduced in chapter 5, this section has its focus on the specific implications in the context of polymeric composites. Here, the primary challenge for AE source localization arises due to the type of wave propagation. Many engineering materials are isotropic, so source localization assumes a constant sound velocity. In contrast, in polymeric composites the orientation of the fiber reinforcements introduces anisotropy (see Fig. 3), which requires different algorithms.

In addition, these materials are typically fabricated as thin, plate-like structures, which results in the formation of guided waves. Hence, the wave velocities are strongly dependent on frequency and therefore need explicit consideration. Moreover, for these guided waves every wave mode has an individual dependency of propagation velocity as a function of frequency. Finally, the formation of such guided waves reduces a 3D localization problem to a 2D localization problem, since the depth position of the AE source cannot be localized based on measurement of the arrival time (Δt-values) at the AE sensors.

As seen in Fig. 3, dependent on the specific stacking sequence, composite laminates may exhibit more or less pronounced anisotropy. To address the specific requirements of such anisotropic media, source localization algorithms with multiple sound velocities have been proposed (see chapter 5).

Another strategy to overcome the problem of acoustic anisotropy in source localization procedures was proposed and is referred to as Δt-mapping [62, 63]. This approach requires a discretization of the test object into distinct zones. For a given sensor network, a theoretical Δt-value is calculated for each sensor combination for each zone. This effectively results in a Δt-map of the structure. For the Δt-values of the experimentally acquired event, the nearest combination of Δt-values can then be estimated by automatic search algorithms. [62, 64, 65]. The advantage of this approach is the applicability to arbitrary geometries and acoustic properties.

Other approaches use artificial neural networks for source localization in geometrically complex metallic structures [66, 67]. For these approaches, the basic strategy involves two subsequent stages (training stage and application stage). Similar to the Δt-mapping, artificial neural networks can be used to establish a symbolic relationship between input data (Δt-values) and output values (source position coordinates). For the training phase Δt-values for known source positions must be available. These can be achieved by experiments or by corresponding modeling work (see [68]). While the modelling approaches require an exact knowledge of the acoustic properties, the experimental approach with test sources does not even require knowledge of the sound velocities in the material. Based on training data, an artificial neural network can be used to establish a functional relationship to the AE source coordinates. In the second phase, this trained network can then be used to approximate the AE source coordinates. For composite materials, it is thus feasible to localize AE sources in arbitrary 3D geometries without knowing the sound velocities with high accuracy, provided sufficient input data is provided in the training phase [32, 69, 70].

Based on the aspect that loading of polymeric composites typically provides a huge number of AE signals, the source localization results are highly interesting to identify potential hot-spot areas in the material or structure.

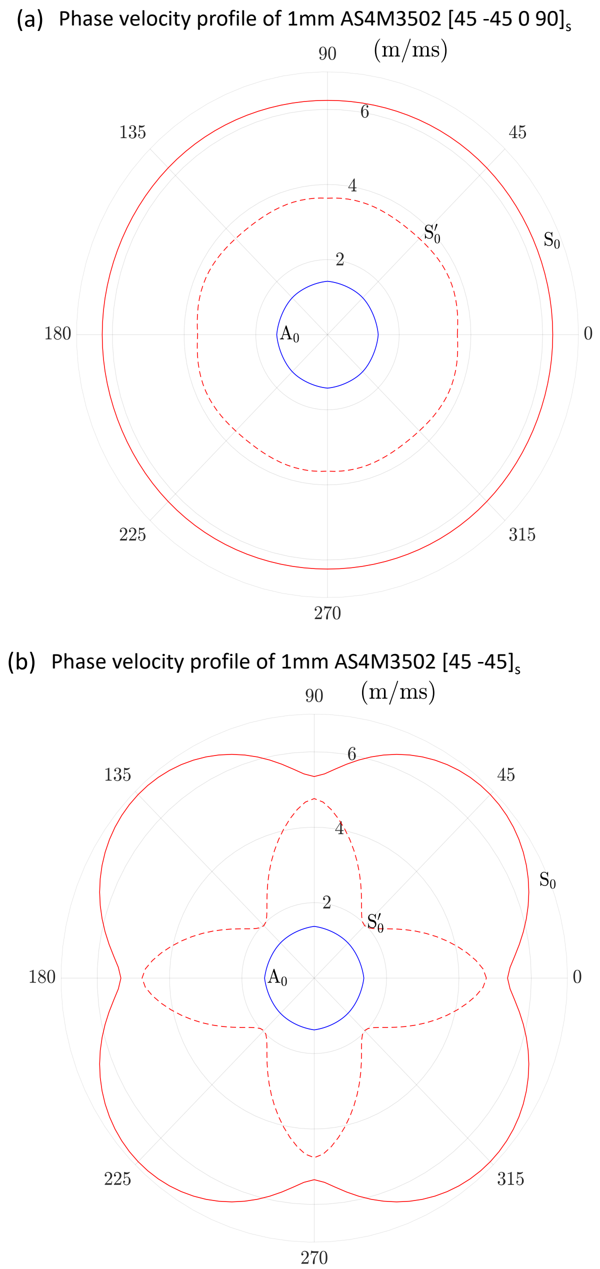


Fig. 3. Phase velocities of fundamental Lamb wave modes (S0, A0) and shear horizontal wave mode (S0') calculated with the Dispersion Calculator (based on [62]) for 500 kHz and quasi-isotropic stacking (a) and cross-ply stacking (b).

4 Kaiser and Felicity Effect, Felicity- and Shelby-Ratio

AE of many materials under increasing loads or stresses shows a behavior that first has been observed and described in metals, namely, that AE occurs only, if the level of load or stress exceeds that attained previously. This is the so-called Kaiser-effect [71, 72], essentially indicating a "memory" for stresses applied to the material. A similar phenomenon has later been noted, first in fiber reinforced polymer (FRP) composites, but also found in other composite materials, such as, e.g., wood or concrete. AE in composites, contrary to that in metals or metal alloys, may occur before the previous maximum load or stress level has been reached. This is called Felicity-effect [73] and both, Kaiser and Felicity effect as well as the so-called Felicity-ratio calculated from the observation of the Felicity-effect, play a significant role in industrial applications of AE. The Kaiser effect can be used to determine the maximum stress level experienced previously by test objects (see, e.g., [74]) and Joseph Kaiser had patented this as a materials' characterization method in 1950 [75]. The Felicity-ratio, i.e., the load level at which the Felicity-effect is observed in tests, divided by the previously attained load, provides an empirical criterion for assessing (global) structural integrity. Typical values of the Felicity-ratio indicating critical loads in FRP composite components or structures are around or less than 0.95 [76]. The exact values may depend on the type of FRP material, the geometry, and the design of the FRP component or structure as well as on the sensitivity of the AE measurement. Quantitative evaluation of the remaining service-life, therefore, is typically using a test database from a sufficiently large number of nominally identical test objects, such as, e.g., the MONPAC-system for chemical process equipment [77]. The Felicity-ratio as an indicator for structural damage can be complemented with additional criteria, e.g., derived from AE activity or AE intensity measurements [78, 79]. Such measurements provide data on signal strength to be used, e.g., for calculating a Severity-index [80] or a Historic index [78, 81]. It can be noted that, besides Severity or Historic index, the so-called b-value derived from geophysics and frequently applied to damage evaluation in concrete [82] is also applicable to other composites, as, e.g., shown by [83] for wood (a natural fiber composite material) as well as for FRP composites [84, 85]. However, to date, there are no standard test procedures for AE monitoring of FRP composites that use the b-value analysis.

The Shelby-ratio defined and discussed by [86] is in a sense analogous to the Felicity-ratio, but looking at AE recorded during the unloading part of the stair-step load pattern (in this case the pressure testing of a vessel). There is a Shelby "count-up" and a Shelby "count-down" ratio that can be determined as damage indicator. A two-step loading pattern (loading from zero to proof load and holding before unloading to a minimum pressure and holding with reloading to the same proof pressure (looking for the Felicity effect), short hold and then unloading to zero is applied. The Felicity-ratio (if amounting to one or less than one) can be evaluated as discussed above. For the Shelby-ratio, the AE activity from the second unloading is analyzed. The AE activity can either be counted from the top (count-down ratio) to a lower pressure level or counted up from a lower pressure level after unloading up to a higher pressure level (count-up ratio). When plotted as a function of consecutive pressure decrements and increments, respectively, the AE activity either shows cumulative numbers that are clearly increasing or not changing much with pressure. The AE activity count-down or count-up values are then compared to a predetermined AE activity evaluation level.

In the paper describing the Shelby-ratio [86], the authors analyzed the correlation between burst pressure and the Shelby-ratio determined either from all hits at all sensors, or from the first hits from all sensors, or the first hit from the most active sensor. Some of these correlations turned out to be (cite) *"very good"*, and impacted pressure vessels could be distinguished from non-impacted ones. The authors also note that a significant fraction of the AE waveform from unloading showed characteristic friction type signals with relatively low frequency and low amplitudes. However, the Shelby-ratio is not used in current standard procedures for AE testing of pressure vessels or other components made from FRP composites.

The current definitions of Kaiser and Felicity-effect and Felicity-ratio in standards on AE terminology [1, 87, 88] are all debatable. In the form stated above, the Kaiser and Felicity effects are seemingly simple. However, several issues have to be considered when determining whether the Felicity-effect is observed as well as for evaluating the Felicity-ratio. Due to their relevance in practical testing, these are discussed more detailed below.

A first aspect is noted in [1], namely that AE for the evaluation of Kaiser- or Felicity-effect has to be detected (cite) *"at a fixed predetermined sensitivity level"*. This implies that the same measurement chain (i.e., sensor, sensor cable, pre-amplifier, cable, and data acquisition channel), with the same data acquisition settings and the same quality of sensor coupling (in principle to be verified) has to be used for the previous and the subsequent loading(s). Depending on the time between load applications, the sensor coupling can be a critical factor, since there is limited literature on degradation of the couplant and the resulting coupling quality at best. However, it is well known, that coupling quality can change significantly over time.

A second aspect related to that is the applied stress to the test object, again, this shall be the same (e.g., implying the same loading set-up or device and the same load-rate), but this is not mentioned explicitly in any of the standards. For test objects subject to multi-axial loads or stresses, the multi-axiality has to be preserved in the reloading.

A third aspect for determining the Felicity-ratio is the number and the intensity (amplitude or energy content) of the AE signals considered in the evaluation. As the only standard, [88] states a definition of the Felicity-effect as (cite) *"appearance of significant acoustic emission"*, but does not define what "significant" means, except for adding a note that this will depend on the application. Standard [78] on the other hand relates "significant" AE to the onset of lamina damage (at least for GFRP composites and the determination of their design stress) and defines it through the Historic index attaining a value of 1.4 for the first time upon reloading (referring to [89] and [90]). The historic index according to [78] is calculated with "MARSE" (Measured Area of the Rectified Signal Envelope) as signal strength parameter and incorporates an empirical K-factor depending on the number of AE signals. Therefore, the numerical value may change, if other AE signal strength or intensity parameters are used for the calculation. In the form stated in [78], the Historic index is noted to yield a sensitive indication of the "knee in the cumulative AE curve" and of the onset of new damage mechanisms. If there is one single dominant damage mechanism, the cumulative curve of various AE signal parameters (e.g., hits, AE counts, AE signal energy) versus time or load (at constant load or displacement rate) often shows an exponential increase that may look like an apparent "knee point" (see, e.g., [91]). The exponential behavior essentially reflects damage growth proportional to the already existing amount of damage resulting in catastrophic failure, unless the loading is stopped in good time. "Significant AE" is also discussed in [76] and guidelines on how to determine "significant" (for FRP vessels) are discussed. Another definition for "significant" AE based on a combination of AE activity (specified number of AE hits per unit time or at least a continuously increasing number of hits) and AE intensity (requiring minimum AE signal amplitudes) by [92] has been shown to yield Mode I fracture toughness values in carbon-fiber thermoplastic laminates comparable to those determined according to [93]. In this context, the question arises whether signals from all sensors or only those from selected sensors, e.g., at specific locations, shall be evaluated for the Felicity-ratio. The draft version of the CARP guideline for pressure vessel testing [94] noted that evaluation of the criteria in Table 12.6.1 that includes Felicity-ratio (cite) *"shall be on a per channel basis"*. This Table requires the Felicity-ratio to be >0.95 for acceptance, however, the note on per channel evaluation has not been implemented in either [95], nor in [76] that were based on the original CARP procedure. In practice, the evaluation of the Felicity-ratio can use data from all channels for a global assessment of structural integrity, and selected channels or a single channel for a local assessment (e.g., a structural detail or critical part of a larger structure). The structural integrity assessment via Felicity-ratio depends on the choice of sensors and it is hence important to explicitly state the channel or channel groups used in the evaluation of the Felicity-ratio.

A final aspect in determining the Felicity-ratio is the types of AE signal sources. This is not discussed in any of the standards. Even if "significant" AE according to one of the definitions above is observed, the Felicity-ratio calculated from the respective loads or stresses may be misleading. This is the case, if the recorded AE contains signals caused by sources outside the test object, e.g., noise introduced from the ambient (e.g., electromagnetic interference) or from the loading device (e.g., frictional contact or servo-hydraulic operation), or by AE signals from secondary sources, e.g., friction between existing crack or delamination faces. Therefore, identifying the underlying source mechanisms (see section 2 above for details on this) of the AE signals used to calculate the Felicity-ratio may help to eliminate signals from non-relevant source mechanisms and thus to improve the predictions derived from the Felicity-analysis. As another approach or complementary to AE signal source identification, AE signal source location can also contribute to detect non-relevant signals. AE signal source location in FRP composite materials or structures is limited in accuracy, but recent developments in artificial intelligence applied to signal source location indicate the feasibility of this approach (see, e.g., [96] for more details). The issue of identification of the AE signal source mechanisms and their validation by non-destructive test methods for Felicity-ratio calculation is briefly discussed by [97]. The question is whether AE signal source mechanism identification for improved Felicity-ratio evaluation is applicable on larger-scale elements or structures. So far, this concept has been evaluated on laboratory-scale materials and components, but the application to larger-scale components is under investigation and preliminary results look promising.

FRP composite materials, elements or structures often are tested with a so-called stair-step load pattern, examples of that are shown in [98]. If the load or stress at which AE fulfilling the criteria for Felicity effect is noted and its ratio to the previous maximum load or stress is calculated, values larger than one may be obtained at low levels of load or stress (typically below 50% of the failure load or stress). This is an indication that further generation of AE and hence possibly of damage, required higher loads than those previously attained. Typically, these formally calculated values will decrease with increasing number of load steps and reach one or a value below one, i.e., showing the Felicity-effect as defined in [1]. Often, Felicity-ratio values below one are observed at loads or stresses higher than 50% of the failure load or stress, analogous to the "knee in the AE curve" for cumulative plots of selected AE signal parameters.

The time between load or stress applications relates to an additional aspect besides the possible aging or change of sensor coupling noted above. For the Kaiser effect, it is known that the "memory" of the previous stress level will not persist indefinitely, once the test object is unloaded (before reloading). This is discussed more in literature on rocks (see, e.g., [99, 100]) than for composite materials [101]. There are clear indications that the Kaiser effect "memory" of the maximum applied load or stress lasts for a finite time, i.e., the effect cannot be observed anymore after a sufficiently long time in the unstressed state. If the test object is normally subject to certain levels of service stresses or periodic variations below a maximum service stress (as, e.g., in pressure vessels), the proof testing for observing the Kaiser effect has to be performed at higher stress levels. For example, [102] for refillable gas cylinders and tubes requires periodic inspection at or above 110% of the service pressure and recommends test repeats after at least 20% of the retest period. This corresponds, e.g., to at least one year after the last inspection for the five years retest interval for the pressure vessels according to [102]. Analogous to the Kaiser effect, a limited duration of the memory is possibly the case for the Felicity-effect as well, even though there is virtually no literature discussing or reporting data on that (except [101] for concrete).

5 Failure prediction in FRP

The first generally known application of AE based failure prediction to polymeric composites was in 1964 [103]. This approach was chosen because the AE recorded during the mechanical testing of composite materials provides a measure of the accumulated damage due to the various mechanisms causing the final failure. Different approaches have been tried or developed to correlate certain aspects of AE data with later failure loads. The fact that AE monitoring provides detailed information about the acceleration of damage or the presence of existing damage (due to frictional AE from the interaction of damage) speaks for this application. Since many composite components or structures are proof-tested prior to their service life, such testing provides a convenient way to monitor using AE and to obtain the required data [104, 105].

A general pattern of damage initiation and accumulation in FRP composites under increasing or cyclic varying stresses is that first small, localized damage is initiated. This is typically distributed stochastically in the volume of the FRP composite. Further application of stresses then lead to growth or propagation of damage from the initial source location, coalescing into meso- or larger scale, often localized damage. Further loading then results in failure [106, 107].

This behavior provides several approaches for AE-based damage and failure prediction. Evaluation of AE and respective general criteria from FRP composites is discussed in [108]. Standard [79] discusses behavior of AE activity, e.g., cumulative number of AE signals or AE signal parameters as a function of time or applied stress as "inactive" (few, sporadic AE signals), "active" (roughly linearly increasing with time or stresses), or "critically active" (increasing faster than linearly, e.g., exponentially with time or stress). Analogous to activity based on the number of AE signals per unit time or load increment, the AE source intensity (a measure of magnitude, e.g., amplitude or energy) is classified as being "low", "intense" or "critically intense". On-line evaluation of criteria based on AE activity and/or AE intensity during proof tests or possibly also during long-term monitoring can indicate critical loads or critical structural integrity prior to failure.

Another approach is monitoring the location of AE sources (and these could be evaluated for their criticality as outlined above) and observing whether local clusters of AE sources develop with time and increase in size and/or criticality. Clusters can indicate the location of coalescence of microscopic damage into mesoscopic or larger damage. Again, these can be assessed with qualitative or quantitative criteria, but are intrinsically linked to the accuracy of the source localization approach (see section 3).

As discussed in section 4 on Kaiser and Felicity effect, the Felicity-ratio determined from the application of special "loading-unloading" load patterns as a function of load provides a global (using all sensors) or local (using a single sensor or a local sensor group) criterion for criticality. Extrapolation of the values as a function of load even indicates expected failure loads and possible locations. NASA White Sands Test facilities proposed such an approach to adopt the extrapolation of the Felicity-Ratio as tool to predict the burst strength of pressure vessels [109, 110]. This was recently refined using artificial neural networks for the prediction procedure based on the trends of Felicity-Ratio, Shelby-Ratio and energetic ratios [70, 111]. This, however, only holds, if no major load redistribution due to damage accumulation occurs during the further load steps. In commercial or industrial applications, the Felicity–ratio and AE activity and AE intensity criteria are, even though empirical, currently the most important criteria for assessing structural integrity or remaining service life.

Therefore, quantitative prediction of damage development and failure loads, or of remaining service-life or definition of re-test intervals based on AE monitoring and analysis is feasible, in principle, for test items ranging from standard FRP composite specimens, to parts or components and large-scale structures.

6 Applications

After more than 50 years of research in the field of AE of polymeric composites, there are many well-established applications, some mature testing standards and various good practices available. An extremely large number of applications has been described since the first use of AE applied to composites in [103]. In early 1986 a survey paper [112] listed already 30 different applications in published literature that were based on > 500 papers or reports from 1970 forward [112]. In the following decades, two more noteworthy reviews on applications were made in 1987 [113] and in 1992 [114]. Two further reviews cover the 2000s [115], [116] and another comprehensive review was published in 2012 [117]. Just recently, in 2016 and 2017 the use of AE for polymeric composites has seen comprehensive coverage in two book chapters to cover the fundamentals for this field [118, 119]. At present, in early 2020, Google Scholar lists > 19.000 scientific publications associated with AE of composites.

The full coverage of all reported AE applications for the field of FRP composites is beyond the scope of this chapter, so we provide some best-practice cases as an inspiration to the reader alongside with a listing of successful applications. Wherever applicable, we refer to some of the fundamental literature or some examples as supplementary literature.

Based on the potential interest of the reader, we grouped the following sections according to specific fields of application.

6.1 Micromechanics testing

Since AE is sensitive to microscopic damage mechanisms, AE monitoring has been applied to different micromechanical tests for the occurrence of damage. One example is the single-fiber fragmentation test (SFFT) for assessing the adhesion between fiber and polymer matrix [120–122]. This has also been used to assess environmental ageing effects on fiber-matrix adhesion [123, 124]. Other aspects include the monitoring of fiber breakage, microscopic resin fracture and fiber pull-out [27, 125].

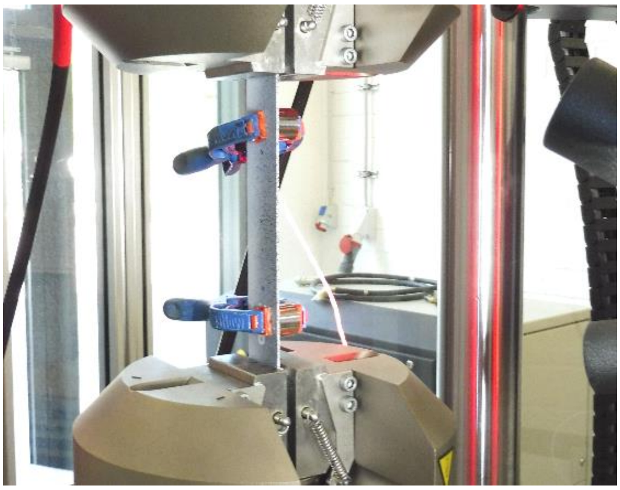
6.2 Lab scale testing

Since standard mechanical tests typically only provide macroscopic data such as load versus strain, the addition of AE monitoring provides a real time and full volume record of microscopic damage initiation and accumulation. The following sections thus present applications centered on the aspect of accompanying these tests with AE in order to obtain an improved set of information.

Quasi-static testing. For quasi-static testing of polymeric composites, AE measurements are frequently applied. In some cases, the focus is on the detection of initiation of damage like first ply failure [126–128] , as well as on the initiation and growth from particular discontinuities like edges and notches [127, 129]. Practically all mechanical test procedures were already accompanied with AE testing, ranging from classical tensile testing to compression tests [130], shear testing [131], flexural testing [73, 132], split-disc testing [133, 134], connectors [135] and many more.

Fig. 4 presents some exemplary results from tensile testing of a carbon/epoxy cross-ply laminate. As seen in Fig.4-a, two clamps are used to attach the AE sensors to the tensile sample. One typical evaluation procedure is linear source localization between the sensor positions, which can be used to identify spots of high AE activity as seen from the density plot in Fig.4-b. Other typical evaluation plots are features plotted superimposed to the recorded mechanical data.

(a)



(b)

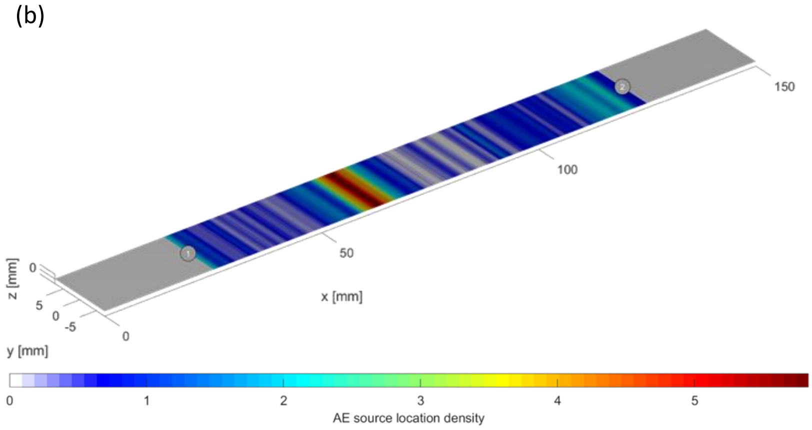


Fig. 4. Typical tensile test setup with two AE sensors (a) and calculated source location positions as density plot (b).

In Fig.5-a the AE amplitude is presented. The extrapolation of the original sample stiffness clearly reveals the “knee” in the curve to coincide with the onset of the majority of AE signals. For the cross-ply layup, this corresponds to the growth of transverse matrix cracks cracks causing a significant reduction in stiffness. However, the most damage occurs towards the end of the test, as clearly revealed by the cumulative energy sum seen in Fig.5-b. This coincides with a noticeable signature in the force-time curve and was confirmed from simultaneous high-resolution imaging as onset of delamination.

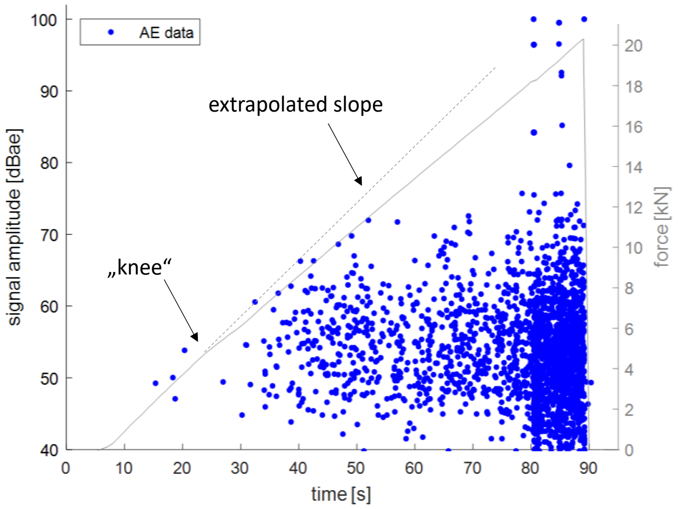
In composite fabrication, many variables can be altered in the design or process choice stage. AE is well suited to detect changes in the damage initiation and progression due to material choices, layups/stacking sequence, geometry and the arrangement of the fibers. Fundamental studies of damage accumulation as function of laminate design were performed early on [136], and the characteristic “knee” in stress-strain curves was successfully correlated with significant changes in AE [137, 138]. Material factors such as influence of fiber changes with the same matrix was studied [139], as well as hybrid fiber architectures [140] or fiber/matrix combinations to find most damage tolerant combinations [141]. Other studies include the determination of an optimal of fiber sizing to delay matrix cracking [142] or AE monitoring to evaluate effectiveness of fiber diameter choice [143].

Moreover, quasi-static testing in combination with AE also allows to interpret the damage state of the material, e.g. after and during impact damage [144, 145]. The limitations of damage identification in FRP composites with AE analysis are discussed by [146]. Such classical lab-scale tests also allow evaluating the degradation of the material as function of environmental factors and the resulting changes to damage initiation and growth. This includes tests as function of temperature [147], performance of wet versus dry composites [148], or aspects of chemical degradation [149].

AE testing in combination with lab-scale mechanical tests is also particularly well suited to analyze the residual capacity of polymeric composites after initial damaging due to overloading or after impact [150].

Fracture mechanics. Next to quasi-static testing, combination of fracture mechanics of polymeric composites with AE testing is an approach with significant benefits for the interpretation of the results. Fracture mechanics tests aim for the detection and quantification of damage initiation and growth, which is an aspect directly related to the generation of AE and can be studied in, e.g., mode I delamination [151], as well as mode II delamination [152, 153]. Such information is of increasing significance, when testing of ductile matrix materials is planned, since plastic deformation effects may render mechanical response of the sample useless [154]. AE source localization information may also be used to track the position of the crack tip and can be used to construct the fracture resistance curve [155, 156]. In fatigue fracture testing, unsupervised pattern recognition with AE signals has been used to distinguish fatigue noise from crack initiation and growth [157].

(a)



(b)

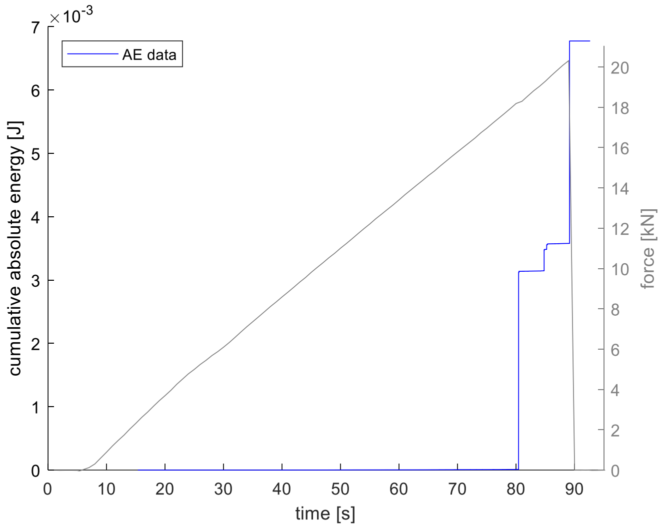


Fig. 5. Typical tensile test setup results presented as AE features, such as AE amplitude superimposed to the load-time curve (a) and cumulative AE energy superimposed to the load-time curve (b).

Estimates of the total delamination size in fracture mechanics tests monitored by AE also allow for determining average size of the microscopic damage created by the AE source mechanisms based either on the number of recorded AE signals [158] or their AE signal amplitude [159] or possibly their AE energy content. This analysis may provide a basis for quantitative damage models for FRP composite materials, components and structures [160].

Fig. 6 presents some exemplary results from fracture mechanics testing of a unidirectional carbon/epoxy laminate. Fig.6-a shows the setup for a Mode I delamination resistance test in the double-cantilever-beam configuration with three AE sensors attached (only the two sensors marked are necessary to perform source localization). Fig.6-b presents the source location results, which show significant densification around the crack position as function of time. This can be used as alternative to optical tracking of the crack tip [161], but also to determine the onset of crack growth based on the onset of AE.

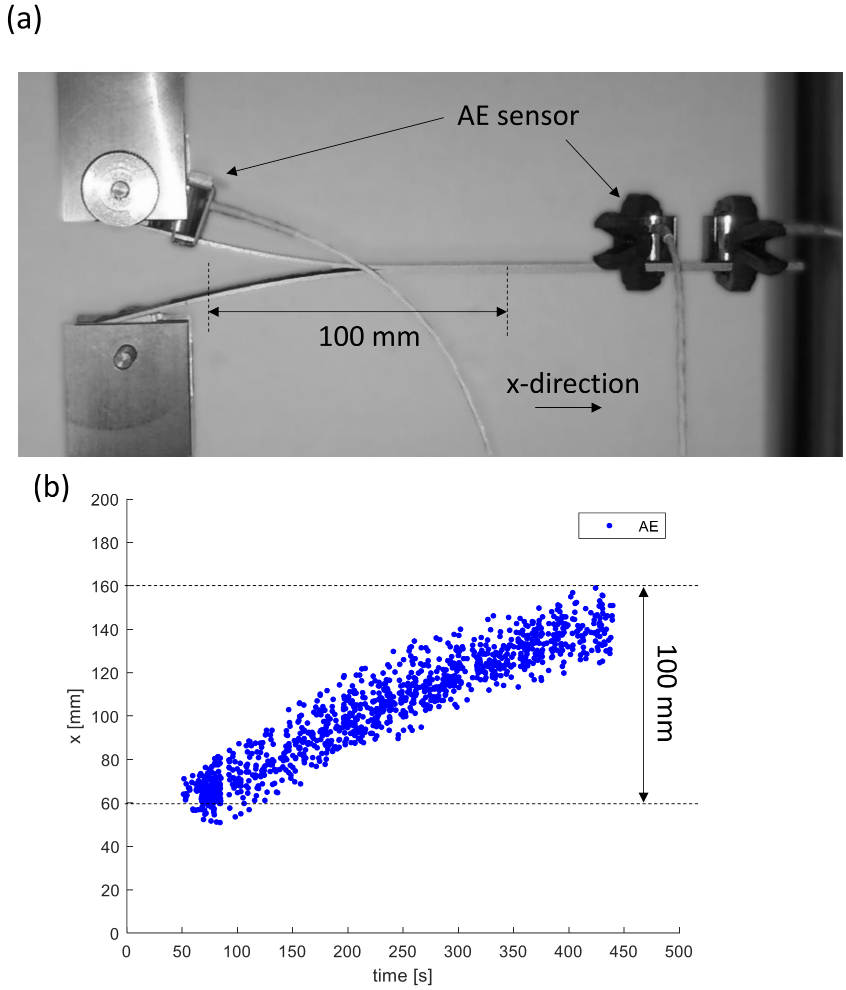


Fig. 6. Typical setup for Mode I fracture toughness test (a) and corresponding source localization result (b).

In Fig.7-a the typical setup for Mode II testing in the end-notched-flexure geometry is shown with the AE sensor attached to the test sample. Fig.7-b shows the corresponding measurement of the AE onset using the Historic index evaluation as tool to identify the correct onset force as required by the test standard.

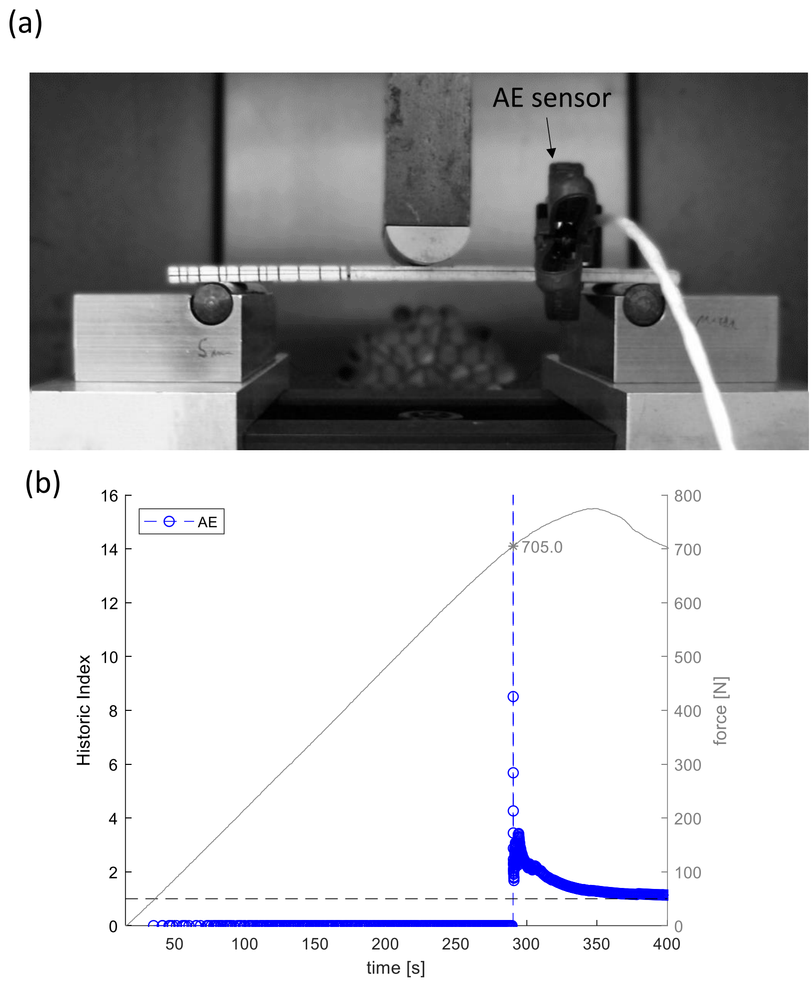


Fig. 7. Example for Mode II fracture toughness with attached AE sensor (c) and corresponding determination of the AE onset (d).

Fatigue testing. Another class of mechanical tests that benefits from the use of AE is fatigue testing. In this context, the geometry and fixtures are not too different from quasi-static testing, so AE instrumentation can be combined with these setups. The larger challenge stems from the generation of AE noise signals during these tests, which can originate from machine noise (e.g., servo-hydraulics), friction at supports and at existing crack faces, as well as mechanical vibration in general [162]. Still there are various successful applications, e.g. in tension-tension fatigue [163, 164] or in flexural setups like in short beam shear to detect first delamination [153]. AE can be used to detect the onset of damage in this setting, but can also be related to modulus/compliance changes and therefore assist in the general interpretation of the test [165]. Likewise, it is also straightforward to assess the residual capacity of the material after fatigue cycling in a quasi-static test [166].

Impact testing. Impact and the resulting damage in FRP composites is often assessed by performing specific mechanical tests after impact. Such tests can be monitored by AE in order to determine, e.g., the extent, the type, or the location of damage. Examples of this are discussed by [167] using AE with four-point bending after impact, and by [168] with Compression After Impact (CAI) on repaired and unrepaired GFRP plates. Direct detection of impact by AE is also performed, e.g., on Charpy-type specimens by [169] or during drop tests [145]. An application of AE developed for debris impact on spacecraft is described by [170]. Depending on the energy of the impact, coupling of conventional piezoceramic AE sensors may be difficult, but AE signals from impact can also be detected by other strain sensing systems, such as Fiber Bragg Gratings (FBG), see, e.g., [171] for details.

Stress rupture / Creep testing. Applying constant load conditions to a polymeric composites also results in formation of damage as function of loading time. Concise information about the onset of such damage as well as its activity may be provided from AE monitoring during such tests. In creep experiments this has been used to compare matrix systems [172], whereas in stress-rupture tests such information is helpful to understand the damage evolution that have caused the final failure [173, 174].

Relevant standards. In the following, we list some established AE test standards related to polymeric composites testing at Lab scale in order to aid in the conduction of own experiments:

- Evaluation criteria (EN 15857 and ISO 18249) Testing of fibre-reinforced polymers - Specific methodology and general evaluation criteria
- Nondestructive testing (ASTM E2533) Standard Guide for Nondestructive Testing of Polymer Matrix Composites used in Aerospace Applications
- Nondestructive testing (MIL-HDBK 732A) Nondestructive Testing Methods of Composite Materials - Acoustic Emission

There are several ASTM standard test methods for mechanical properties of FRP composite materials, parts or elements that note AE as a means for detecting first damage occurring in the test. These are listed below. Typically, the text reads (cite) "*Record the method used to determine the initial failure (visual, acoustic emission, etc.)*". However, no details on how to apply AE, and no criteria for evaluating the AE data for assessing the occurrence of the initial failure are provided. Transferability to the corresponding EN or ISO standards is typically given in the case the mechanical testing procedures are deemed equivalent as well.

- Tension ASTM D3039/D3039M Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials
- Tension ASTM D5766/D5677M Standard Test Method for Open-Hole Tensile Strength of Polymer Matrix Composite Laminates
- Indentation ASTM D6264/D6264M Standard Test Method for Measuring the Damage Resistance of a Fiber-Reinforced Polymer-Matrix Composite to a Concentrated Quasi-Static Indentation Force
- Compression ASTM D6484/D6484M Standard Test Method for Open-Hole Compressive Strength of Polymer Matrix Composite Laminates
- Compression ASTM D6742/D6742M Standard Practice for Filled-Hole Tension and Compression Testing of Polymer Matrix Composite Laminates
- Impact ASTM D7136/D7136M Standard Test Method for Measuring the Damage Resistance of a Fiber-Reinforced Polymer Matrix Composite to a Drop-Weight Impact Event
- Flexure ASTM D7249/D7249MStandard Test Method for Facesheet Properties of Sandwich Constructions by Long Beam Flexure
- Pull-through resistance ASTM D7332/D7332M Standard Test Method for Measuring the Fastener Pull-Through Resistance of a Fiber-Reinforced Polymer Matrix Composite
- Compression ASTM D8066/D8066M Standard Practice Unnotched Compression Testing of Polymer Matrix Composite Laminates
- Tension ASTM D8131/D8131M Standard Practice for Tensile Properties of Tapered and Stepped Joints of Polymer Matrix Composite Laminates

6.3 Component testing

With more and more structures fabricated from polymeric composites, there is a driving need to qualify and re-qualify such structures in industry. Performing mechanical testing of such components in the usual way, applying AE instrumentation on the component aids in the understanding of the damage processes inside. This section deals with geometries significantly larger in size than the typical lab-scale tests of the previous section. We present some established fields for component testing, as well as some other fields that have seen less attention.

Pressure vessels and pipes. As safety critical structures, composite overwrapped pressure vessels (COPV) as well as pure composite vessels have seen lots of attention in using AE for their inspection. Meanwhile, established testing standards cover the qualification as well as re-qualification of pressure vessels in the field. Early on, researchers have started to monitor the pressurization of composite vessels with AE. Information from AE was used to correlate with the residual strength of COPVs [175, 176], proof pressure [86, 177] and to predict the burst pressure [70, 178, 179]. In development of new pressure vessels, AE was used to study damage based on the matrix rigidity, fiber type and orientation patterns [180–183]. In addition, AE was used to develop acceptance tests based on AE data [47, 184]. Other than AE monitoring during quasi-static pressurization, the method has also be used to analyze stress rupture behavior of COPVs [185] and creep effects [73].

Fig. 8-a presents an instrumentation for a 2.5m long composite pressure vessel. Based on the attenuation level faced in polymeric composites, a suitable number of AE sensors is required to cover the entire vessel. For the 30 channels used for this setting, AE sources were localized as seen in Fig.8-b. Preferential AE source positions are found in the lower dome as well as in the upper 2/3 of the cylindrical part. The densification of AE source locations in the lower dome coincides with the later failure region as presented in [70]. Such unequal distribution of AE sources in narrow regions allows identifying weak spots in a composite structure as a result from design or manufacturing. For quality control purpose, the AE data acquired during proof testing may be used to increase safe operation or to re-qualify pressure vessels. AE applied to FRP pipes and pipelines is discussed by [186] and [187] and there is a standard practice for AE examination [188].

Structural components. Based on the early experience from pressure vessels, polymeric composites soon started to find their place in other applications. From the testing perspective, those components were identified as mostly relevant that carry significant structural loads. Most of the time this implies, that these components are also safety relevant. A recent ASTM standard practice deals with AE for determining a damage-based design stress for glass-fiber reinforced plastics (GFRP) vessels or structures [78]. The procedure uses the so-called Historic index for assessing the damage obtained from standard four-point flexure and in-plane shear tests.

Due to the broad range of application fields, AE has been applied in many fields and testing cases. In the automotive industry, the method has been used to design components for racing cars as well as commodity cars [189–191]. The use of FRP composites (mainly FRP thermoplastics, but also FRP thermosets and sandwich parts) for components in automotive applications (structural and non-structural) is increasing, due to demand for lightweight structural car parts. AE for damage detection is hence also explored in this sector [192, 193], and there is potential for implementing AE in quality control and process monitoring.

In aircraft industry AE has been used to aid in testing of structural components as well [141, 194–197]. Fatigue loading of a CFRP panel after impact and identification of damage mechanisms by AE is discussed by [198].

Another strong application field of composite materials is the wind energy branch, making use of AE in testing campaigns of segments or full scale wind turbine blades [199–201].

Furthermore, structural components are finding their way into civil engineering applications, particularly due to their high strength properties. One prominent example are composite cables [202].

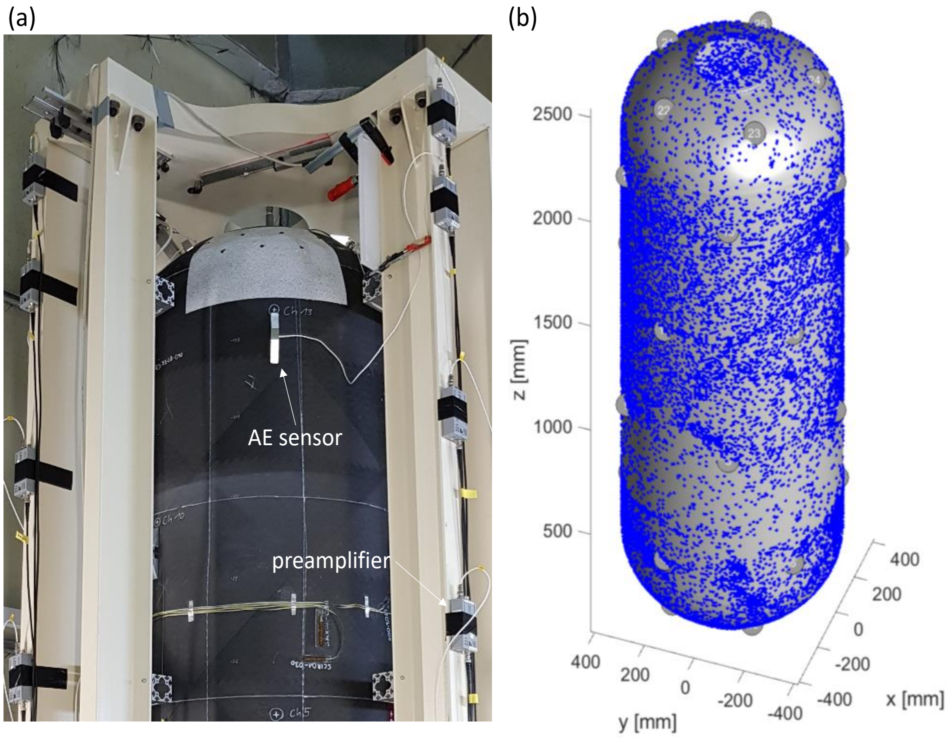


Fig. 8. Typical instrumentation setting for composite pressure vessel (a) and exemplary AE source location result shown as density plot (b).

Storage containers. Another field of composite use is storage tanks and containers in the chemical industry. Typically, these structures are not excessively loaded by mechanical forces other than gravity and the (low) internal pressure of the stored liquid. Polymeric composites are chosen for this application due to their chemical stability and corrosion resistance. Accordingly, the formation of cracks in these scenarios is related mostly to the aspect of leakage and potential local over-stressing, which would require removal from service.

A general description of AE use for integrity monitoring of storage containers was given early on [103]. For oil containers, the occurrence of first fiber failure was detected by AE [203], and critical sections like feedthrough, ports and manholes can be specifically inspected to ensure safe operation [204].

A special case is the monitoring of underground storage tanks. A recent review identified ultrasonic guided waves and AE, and specifically a fusion of signals from both methods, as the most promising approach [205]. Advanced signal analysis (Support Vector Machine) is discussed for a water storage tank by [206].

Relevant standards. Meanwhile, a reasonable list of standards for testing of specific components is available. Based on the sub-sections above, these are listed accordingly below.

Pressure vessels and pipes; storage vessels:

- Composite gas cylinders (ISO DTS 19016) Gas cylinders -- Cylinders and tubes of composite construction -- Modal acoustic emission (MAE) testing for periodic inspection and testing.
- Large glass fiber reinforced tanks in the chemical processing industry (ASTM E1067) Standard Practice for Acoustic Emission Examination of Fiberglass Reinforced Plastic Resin (FRP) Tanks/Vessels (*based on earlier CARP Guideline)*
- Composite pressure vessels (ASTM E2191) Standard Test Method for Examination of Gas-Filled Filament-Wound Composite Pressure Vessels Using Acoustic Emission
- Composite wrapped pressure vessels (ASTM E2981) Standard Guide for Nondestructive Testing of the Composite Overwraps in Filament Wound Pressure Vessels Used in Aerospace Applications.
- Composite hydrogen tanks (ASME STP-PT-021) Nondestructive Testing and Evaluation Methods for Composite Hydrogen Tanks.
- Metal liners in filament wound pressure vessels (ASTM E2982) Standard Guide for Nondestructive Testing of Thin-Walled Metallic Liners in Filament-Wound Pressure Vessels Used in Aerospace Applications.
- Pressurized containers of fiberglass with balsa cores (ASTM E1888) Standard Test Method for Acoustic Emission Testing of Pressurized Containers Made of Fiberglass Reinforced Plastic with Balsa Wood Cores (*based on earlier CARP Guideline*).
- Composite pipelines (ASTM E1118) Standard Practice for Acoustic Emission Examination of Reinforced Thermosetting Resin Pipe (RTRP) (*based on earlier CARP Guideline*).
- Filament-wound pressure vessels (ASTM E 1736) Standard Practice for Acousto-Ultrasonic Assessment of Filament-Wound Pressure Vessels.
- Fiber Reinforced Plastic Vessels (ASME BPVC, Article 11) Acoustic Emission Examination of Fiber Reinforced Plastic Vessels.
- Hoop wrapped FRP cylinders (GRI-92/0564) Integrity Assessment of Aluminum Alloy Lined FRP Hoop-Wrapped Cylinders (*GRI = US Gas Research Institute*).
- Space Systems -Composite Overwrapped Pressure Vessels (COPVs) (AIAA S-081A-2006) or (ANSI/AIAA S-081B-2018) (*AIAA = American Institute of Aeronautics and Astronautics*) *However, AE is only noted as one example of NDT to be used among others, without further details.*
- Fuel containers (Pamphlet C-6.4) Methods for External Visual Inspection of Natural Gas Vehicle (NGV) and Hydrogen Gas Vehicle (HGV) Fuel Containers and

Their Installations, Compressed Gas Association (*cited in ASTM E2533, Section 7 on AE*).

Structural components:

- Bucket truck booms (ASTM F914/F914M) Standard Test Method for Acoustic Emission for Aerial Personnel Devices Without Supplemental Load Handling Attachments.
- Bucket truck booms (ASTM F1430/F1430M-18) Standard Test Method for Acoustic Emission Testing of Insulated and Non-Insulated Aerial Personnel Devices with Supplemental Load Handling Attachments.
- Booms (AS 4748) Acoustic emission testing of fibreglass-insulated booms on elevating work platform.
- Amusement ride and device components (ASTM F 1193) Standard Practice for Quality, Manufacture, and Construction of Amusement Rides and Devices.
- Fan blades (ASTM E2076) Standard Test Method for Examination of Fiberglass Reinforced Plastic Fan Blades Using Acoustic Emission.
- Aerospace composite panels (ASTM E2661) Standard Practice for Acoustic Emission Examination of Plate-like and Flat Panel Composite Structures Used in Aerospace Structures.
- Digger Derricks (ASTM F 1797) Standard Test Method for Acoustic Emission Testing of Insulated and Non-Insulated Digger Derricks
- Small parts (ASTM E1932) Standard Guide for Acoustic Emission Examination of Small Parts.

6.4 Quality control

Monitoring with AE during proof loading of production items can be used to determine if the fabrication process was performed in the right way. Thus, errors in fabrication or defects outside specifications can be detected or the process can be improved based on the feedback from the AE data. Although AE is frequently used in industry for this purpose, only scant literature is available, since such procedures are typically carried out as confidential contract work inside industry.

Among the documented applications, one finds using the AE from proof testing (e.g. leaf springs [191] and others [105]), monitoring of proof cycles of COPVs [207], comparison of material charges from quality inspection with AE of tensile samples [208] and finding fabrication errors from tension test of simultaneously cured samples [209].

Relevant standards. No particular standard has been established yet that has a sole focus on the use of AE for quality control purposes. However, all testing standards quoted in the other sections may be used for a quality control step, given they are feasible for assessing the material or product quality and are reliable enough for the given task.

6.5 Process monitoring

Because the composite material is typically being fabricated at the same time as the composite structure, quality control of the production process is extremely important. In addition to other monitoring concepts, such as cure sensors, vacuum sensors, temperature sensors or imaging systems, the development of a characteristic "damage" state can also help to understand if the current process is within the anticipated process window.

Curing. For many industrial polymer composites, a thermoset formulation is used. Accordingly, the curing of the thermoset can be considered as one of the most critical steps in the value chain, as after that, modifications to the geometry, fiber orientation and architecture is only possible via destructive processes. As consequence of the temperature change during cooling after curing, the thermal expansion may induce a characteristic growth of microscopic damage, which can be used as fingerprint of a successful curing reaction [210], but also to develop an appropriate cool-down profile [211].

Machining. Machining of composite materials naturally induces damage close to the machining edge or hole. While the machining operation is a strong AE source itself, its characteristic continuous AE can also be used to monitor the quality of composite machining such as drilling [212–214], water-jet cutting [215] or laser-cutting [216]. In principle, AE monitoring of machining processes may provide an approach for controlling and optimizing the process, as discussed in Section 6.6 below.

Fastener application and crimping. The design and integration of load introduction elements is another critical part of the production process. In case of hybrid materials (e.g. fiber-metal-laminates) the joining process is already included in the curing or consolidation step of the matrix polymer. In case of fasteners (e.g. bolts, screws, rivets, …) as load introduction elements, this is a subsequent step in the processing chain. Similar to metallic structures, fasteners are inserted in a composite with significant loads, requiring plastic deformation of the metallic fastener for self-tightening. Due to the load acting, there is a certain amount of microscopic damage generated by this step, which can be used as characteristic fingerprint for this operation. Naturally, an excessive amount of damage indicates a preferential damage spot at the load introduction point, thus indicating that this sample is not qualified for service and, potentially, adjustment of the process is required. Among others, the crimping process of electrical insulators was monitored with AE [217–219].

6.6 Process control

Monitoring production steps with AE, in principle, provides a basis for implementing a process control system. There are a few research publications exploring this. In [220] the potential of AE monitoring for the identification of the drill location in drilling of FRP-metal stacks is investigated. The authors conclude that AE monitoring and real-time analysis, in principle, allows for adjusting the drilling parameters for the specific material stack. However, this has not been validated experimentally. In [221] the application of AE for control of a pyrolysis process in manufacturing of carbon-carbon composites is discussed and presents proof-of-concept data. It seems likely that AE process control will be further developed and increasingly used in FRP composites manufacturing, processing and machining. Another area in this context is additive manufacturing, specifically 3D-printing of FRP composites. Current literature on that does not generally note AE process control yet, but AE is among the NDT-techniques that have been applied for post-process control and monitoring of additive manufacturing in a recent publication [222].

6.7 Condition Monitoring (CM) and Structural Health Monitoring (SHM)

Condition Monitoring. Condition Monitoring (CM) with AE is discussed by [223]. In terms of composite materials, examples shown are concrete bridges [224] and FRP storage and pressure vessels, the latter essentially the AE monitoring developed by [73]. FRP sandwich bridge decks are increasingly used in civil engineering, especially in the United States, and [225] developed an AE monitoring system for these structures. Condition monitoring with AE may also be useful for civil engineering structures that have been repaired or refitted with FRP, as discussed by [226].

Structural Health Monitoring. As a specific case of condition monitoring, structural health monitoring during the service life of a composite part has received noticeable attention as well. As with most of the SHM techniques, the maturity level of AE is not yet established in its full extent. Therefore, reports on industrial SHM applications for composites mostly focus on the exploitation of the method for this purpose. With the many different possibilities, researchers have looked closely into potential application scenarios for permanent monitoring of small and large structures. Among the various scenarios, offshore wind parks seem to be a challenging, but worthwhile application [116, 199]. Some applications were reported in patents, e.g. for SHM of helicopter rotor components [227]. Comprehensive reviews on SHM applications were presented in [72, 228], covering many of the different tracks for AE application in the SHM context.

Another traditional track that has seen decent interest is the secondary use of other SHM sensing systems for the recording of AE, such as fiber Bragg gratings [229] and acousto-ultrasonic combinations [230].

A primary challenge stems from the integration of AE systems into composite structures. This has a long history (e.g., KC-135 military aircraft in the 1980ies [231]) and is still challenging today. Long-term SHM of FRP composite structures either with AE or guided waves may benefit from the integration of the complete monitoring system into the structure. This requires the development of integration techniques for sensors (see, e.g., [232, 233]) and of the data acquisition modules. The integration of piezoelectric sensors into FRP composites has recently been reviewed by [234]. As discussed by [235], simulation tools may become more and more useful for developing SHM with acoustic methods. There is scant literature on embedding signal processing units into FRP composite structures, one example is discussed by [236], but the majority of sensors embedded in FRP composite part or structures to date uses external signal processing units.

Relevant standards. So far, only one standard was proposed that has a general focus on the use of AE technology for SHM.

- Structural Health Monitoring (ASTM E2983) Standard Guide for Application of Acoustic Emission for Structural Health Monitoring

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