applied sciences

MDPI

Review

Structural Health and Condition Monitoring with Acoustic Emission and Guided Ultrasonic Waves: What about Long-Term Durability of Sensors, Sensor Coupling and Measurement Chain?

Andreas J. Brunner †

Empa, Swiss Federal Laboratories for Materials Science and Technology, CH-8600 Dübendorf, Switzerland; andreas.brunner@empa.ch
† Retired Scientist.

Abstract: Acoustic Emission (AE) and Guided Ultrasonic Waves (GUWs) are non-destructive testing (NDT) methods in several industrial sectors for, e.g., proof testing and periodic inspection of pressure vessels, storage tanks, pipes or pipelines and leak or corrosion detection. In materials research, AE and GUW are useful for characterizing damage accumulation and microscopic damage mechanisms. AE and GUW also show potential for long-term Structural Health and Condition Monitoring (SHM and CM). With increasing computational power, even online monitoring of industrial manufacturing processes has become feasible. Combined with Artificial Intelligence (AI) for analysis this may soon allow for efficient, automated online process control. AI also plays a role in predictive maintenance and cost optimization. Long-term SHM, CM and process control require sensor integration together with data acquisition equipment and possibly data analysis. This raises the question of the long-term durability of all components of the measurement system. So far, only scant quantitative data are available. This paper presents and discusses selected aspects of the long-term durability of sensor behavior, sensor coupling and measurement hardware and software. The aim is to identify research and development needs for reliable, cost-effective, long-term SHM and CM with AE and GUW under combined mechanical and environmental service loads.

Keywords: Acoustic Emission; Guided Ultrasonic Waves; Structural Health Monitoring; Condition Monitoring; process monitoring and control; long-term durability; sensor coupling; measurement hardware and software; equipment maintenance

Citation: Brunner, A.J. Structural Health and Condition Monitoring with Acoustic Emission and Guided Ultrasonic Waves: What about Long-Term Durability of Sensors, Sensor Coupling and Measurement Chain?. *Appl. Sci.* **2021**, *11*, 11648. https://doi.org/10.3390/app112411648

Academic Editor: Kanji Ono

Received: 15 November 2021
Accepted: 6 December 2021
Published: 8 December 2021

1. Introduction

The physical phenomena of Acoustic Emission (AE) and Ultrasonics (UT), the latter providing the basis for the Non-Destructive Test (NDT) method of Guided Ultrasonic Waves (GUW), have been observed and investigated since the early 1930s (see [1–3]). However, it took until the late 1960s for the implementation of AE and GUW as technically applicable NDT methods. These developments and selected industrial applications are described in, e.g., the NDT Handbooks on AE [4] and on UT [5] published by the American Society for Nondestructive Testing. AE and GUW [6] are complementary methods in the following sense: AE is passively monitoring and recording elastic waves (generated by material or test object specific mechanisms) that then propagate to the surface of the test objects, whereas GUWs, the same as UT, are elastic waves actively excited at a given location and time (often by a suitable UT-transducer) and then recorded after propagation in the test object by another UT transducer. Most commercial AE equipment can perform both AE and GUW. AE systems currently have a function for sending a "short" voltage pulse (duration of µs or less) to the AE sensors in some systems adaptable or provided by a suitably amplified function generator signal. The transducers convert the pulse into a transient displacement of the piezoelectric sensing element, thus exciting a propagating elastic wave in the test object to which the exciting transducer is coupled.

Initially, AE analysis included the simple counting of recorded single, transient AE signals called "hits" as a function of time or applied loads or stresses ([4] p. 34). In the 1960s, the extraction of a set of AE signal parameters from the analogue voltage signals generated by the AE sensors became a "standard" analysis approach [7]. In the last three decades, digital technology has played an important role in the further development of AE and GUW data recording and analysis. A first step, in the early 1990s, was the design of digital electronic equipment for data acquisition. This provided a suitable means for recording transient AE signals with sampling rates in the megahertz range (now up to 40 MHz) and increasingly higher resolution of signal magnitude (from initially 12 bit up to 18 bit). High-resolution records of transient AE waves also rendered identification of the different wave modes in so-called "modal AE" feasible [8]. Recently, modal AE data were complemented by Finite Element Models (FEM) and Fast Fourier Transform (FFT) for mode identification [9]. Digital technology development also continues to provide increasing computational power. As a next step, in the last decade, this enabled use of sophisticated approaches for the discrimination and identification of the physical source mechanisms of the AE signals. One successful approach combined unsupervised or supervised pattern recognition for signal classification with multi-physics simulation of model signal sources with signal initiation and signal propagation in the test object, also including the effects from the transfer function of the measurement chain [10,11]. Another approach combined imaging with complementary NDT, such as in situ X-ray micro-tomography, with the AE signal classification from pattern recognition for identification of the source mechanisms. This combination yielded quantitative correlations between defect or damage size and the AE signal magnitude [12]. In situ X-ray radiography of fracture tests with contrast agent also yielded estimates of delamination increments per average AE signal amplitude [13].

Currently under way, the next step in digitalization of NDT with AE and GUW relates to what has been labelled "Industry 4.0" [14], still driven by increasing computational power on one hand but, on the other hand, also by major software developments. The latter, among others, comprises the use of artificial intelligence (AI) algorithms, such as machine learning or deep learning, various neural networks, support vector machine, random forest, etc. [15–17]. Increasing computational power allows for virtually real-time handling of so-called "big" data (see, e.g., [18,19]). This enables continuous Structural Health Monitoring (SHM) of large-scale civil engineering structures, e.g., bridges and high-rise buildings, or of supply infrastructure, e.g., pipelines, as well as Condition Monitoring (CM) of complex production facilities, e.g., power plants [20–22] or chemical production plants [23–25]. Digital tools also allow for data fusion from different types of monitoring systems and sensors and provide data almost in real time [26,27]. All these developments make continuous process monitoring with AE and GUW, possibly in combination with other NDT, feasible and show high potential for real-time process control in the future [28–30].

Most applications of AE or GUW developed and standardized so far deal with either proof testing or periodic inspection that require mounting transducers on the test objects for durations between one and a few hours, e.g., for small LPG vessels inspected according to [31] up to a few days maximum, e.g., for large tanks or storage vessels [32]. Long-term continuous or intermittent SHM of structures or components and in-line process monitoring or process control, hence, pose challenging problems for transducer coupling and mounting. The same holds for the long-term durability of the transducers themselves as well as for the signal transmission and data acquisition systems if subject to complex service load spectra or exposed to rather severe operating environments. The successful implementation and use of AE and GUW for long-term SHM and process monitoring or process control, hence, not only requires respective solutions for coupling and mounting transducers or sensors but also suitable monitoring of the long-term performance of the entire measurement chain (transducers, signal transmission, data acquisition and analysis) as well as secure long-term data storage. Service providers of SHM and similar long-term monitoring likely have gained some experience in these issues, but only scant information is publicly available at best. Hence, there is a need for understanding long-term behavior and durability of all components of the AE and GUW measurement systems and considering that in the design of the SHM or CM system. In any case, long-term SHM and CM require suitable equipment performance monitoring as well as defined maintenance and repair strategies before system design and implementation.

2. Materials and Methods

The discussion of long-term durability issues for SHM and CM with AE and GUW, hence, focusses on (1) the couplant materials and sensor mounting devices or methods, (2) transducers or sensors, (3) the electronic equipment for signal transmission, data acquisition, analysis and storage and (4) the software for their operation. Transducers or sensors for AE and GUW can be classified by the physical principles producing the signals. A major class of AE and GUW transducers uses the piezoelectric and inverse piezoelectric effect, respectively [33]. These transducers consist of piezoelectric elements with specific size and shapes, with electrodes providing electric contact, and usually packaged in some type of casing. Piezoelectric material is often lead-zirconate-titanate (PZT) [34,35], except for applications at elevated temperatures, i.e., near or above the so-called Curie temperature of PZT [36,37]. Due to environmental and health concerns, however, PZT may mandatorily have to be replaced by lead-free alternatives soon [38]. The shapes of the piezoelectric elements and transducers, respectively, comprise, e.g., disks [39] or wafers [40,41]; thin, planar piezoelectric fiber composites, e.g., so-called Active Fiber Composites (AFC) [42,43] or Macro Fiber Composites (MFC) [44,45]; various piezoelectric composites made with piezoelectric powders or particles [35]; piezoceramic thin films [46]; or piezoelectric polymers often also in the form of thin films. The latter are mainly used in high-frequency UT devices, e.g., for medical ultrasound [47,48]. Transducers for air-coupled ultrasound, i.e., contact-less signal excitation and/or recording, are also made from piezoelectric materials [49–51]. Micromachined transducers for UT were reviewed by, e.g., [52] and micro-electro-mechanical-systems (MEMS) Acoustic Emission (AE) sensors by, e.g., [53]. These consist of thin film piezoelectric components and may offer advantages in terms of small size and power efficiency, which are both important for the integration of such devices. A second class of AE and GUW sensors uses optical fibers, either made of glass [54] or polymers [55–57], typically with Fiber Bragg Gratings (FBG) for sensing [58,59]. Recently, there were further materials developments for improving fiber optics performance [60]. Complex, multifunctional optical fibers can also be manufactured [61]. Optical fibers sensors for GUW require a separate excitation mechanism or device for generating the elastic waves propagating in the test objects. Advantages of fiber optics sensors include the following (cite): "*Fiber-optic ultrasonic sensors have several merits, such as broadband response, high sensitivity, disturbance resistance, and good reusability...*" [62] and "*An important advantage of FOS* [Fiber Optical Sensor] *over conventional piezoelectric sensors is their high temperature resistance. Temperature resistant FBGs for AE sensing have been of interest to the industry for a variety of applications*" [59]. Fiber optics sensors, different from PZT-tranducers or other piezo-transducers, are not sensitive to electromagnetic interference, and this is useful for applications in environments with strong or oscillating electromagnetic fields. Even switching on neon lights or machines or equipment drawing high currents has been observed to create noise signals in PZT-transducers during AE measurements. However, there are also disadvantages of fiber optics (cite), "*Their durability during handling and cost are two important disadvantages. Moreover, cladding modes that are observed during or after the fabrication process, adversely influence successful damage detection. These modes permit light to oscillate into the cladding from the fibre core, particularly in single-mode fibres where the light is strongly attenuated into the cladding...*". Further disadvantages include the size and mass of fiber optics measurement equipment, often mounted on heavy optical tables for vibration damping and stability. These constitute a major drawback for integration of fiber optics systems. However, downsizing this measurement equipment seems feasible to some extent.

A third class of transducers is contact-less. Air-coupled, contactless UT has been noted above [49–51]. Other contactless methods comprise, e.g., laser-based systems, such as laser interferometry [43], or vibrometers [63]. One disadvantage of contactless laser methods is that they often require a sufficient and fairly uniform surface reflectivity of the test object. This may sometimes be difficult to achieve in field testing, and in many cases a thin layer of paint has to be applied even under laboratory conditions. However, there are also advantages, as stated in [63] (cite): "*Laser vibrometry used for fatigue crack detection has many advantages if compared with contact techniques. This approach not only eliminates frequency shifting due to additional mass of Transducers and avoids problems associated with local stiffening due to transducer surface-bonding but also eliminates possible measurement-related to nonlinear sources*". Lasers are also capable of exciting elastic waves in materials [64]; hence, they can act as both emitter and sensor for GUW. A comparison between different SHM systems for composite structures has recently been published by [65], and the latest developments of NDT and SHM, for aerospace composites, are discussed in [66].

Depending on the type of transducer or sensor as well as test object and its service environment, the mounting device and couplant have to be appropriately chosen. Piezofiber composites such as AFC or MFC and piezopolymer films often are flexible to some extent and easily conform to curved surfaces without the need for a so-called waveguide [67]. AFC have been adhesively bonded on pipe surfaces with diameters of 60 mm [68] and 50 mm [69] without any waveguide. The flexibility of AFC and MFC is somewhat higher in the direction transverse to the fiber direction; hence, fibers were oriented along the pipe length in these applications on comparatively small diameter pipes. Another application of waveguides is in AE or GUW monitoring at high temperatures [70]. Waveguides are often made from metals (steel or Aluminum) and, hence, are fairly robust and durable. A disadvantage may be that they introduce two additional contact interfaces (one more than for direct coupling of sensors) yielding higher signal attenuation due to reflections. However, more importantly, waveguides act as a wave propagation filter by limiting or changing the types of waves that can propagate through them. The exact type of this AE wave signal filtering depends on the material, the shape and the size of the waveguide [65,71]. For high-temperature applications, special sensor design with fiber optics [72] or development of piezo-materials with higher Curie temperature T_C [36,37] provide alternatives that yield lesser effects on the recorded signals than waveguides.

3. Long-Term Durability of Sensor Coupling and Mounting and of the Measurement Equipment

As noted in the Introduction, this review focusses on long-term durability of selected components of the AE and GUW measurement equipment used for long-term monitoring. The different sections each deal with one specific aspect: the first deals with sensor couplants and sensor mounting devices; the second deals with the durability of the sensors under service conditions and different environments; the third deals with the electronic signal transmission and data recording; and the fourth deals with the related software. However, not all aspects are discussed at the same depth, reflecting the different levels of experience of the author, especially where there is scant literature available.

3.1. Long-Term Sensor Coupling

3.1.1. Surfaces to Which AE and GUW Transducers Are Coupled

The coupling material or "couplant" shall provide the "acoustic" contact, i.e., allow the transmission of elastic waves with frequencies in the relevant range of AE signals or GUW from the test object to the sensor. Many transducers for AE or GUW have a ceramic contact plate; hence, one partner in the coupling often is a ceramic material. Some special transducers have a full metal (steel) case, e.g., those developed for use in so-called ATEX condition, i.e., potentially explosive environments [73,74]. AFC and

MFC are packaged between polyimide polymer films (trade name Kapton®). The main contact surface materials on the transducers' side, hence, are essentially ceramics, metals or polymers.

Contact surfaces of test objects consist of a wider range of materials, e.g., metals, polymers, concrete, rock and sometimes coatings or combinations of different materials. The contact surfaces can be planar, uniaxially or biaxially curved and, for any overall shape, show varying degrees of corrugation or roughness on the smaller scales. The general aspects of contact surface preparation are noted, e.g., in [75] (cite): "*The contacting surfaces should be cleaned and mechanically prepared. This will enhance the detection of the desired acoustic waves by assuring reliable coupling of the acoustic energy from the structure to the sensor. Preparation of these surfaces must be compatible with the construction materials used in both the sensor and the structure. Possible losses in acoustic energy transmission caused by coatings such as paint, encapsulants, loose-mill scale, weld spatter, and oxides as well as losses due to surface curvature at the contact area must be considered*". These recommendations are fairly general, and one may ask, e.g., how "compatible surfaces" are defined. Surface curvature is noted, but surface roughness or corrugation on smaller scales are not. Usually, the couplant is expected to fill the small scale "valleys" on rough or corrugated surfaces, while the waveguides provide adaptation to the overall shape (e.g., uniaxial or biaxial curvature) of the test object.

As mentioned above, AFC and MFC can conform directly to biaxially curved surfaces of the test object to some extent [68,69]. In this case, the contact surface of the pipe was cleaned with acetone and slightly abraded with emery paper, and the AFC bonded with a thermoset epoxy adhesive. Other transducers with stiff casing essentially require the use of a waveguide providing a sufficiently flat and sufficiently large contact area on the side of the transducer and a suitably shaped contact surface on the side of the test object. In addition to adapting the sensor contact to the curvature and size of the surface on the test object, waveguides may also be required for tests objects operated, e.g., at elevated temperatures exceeding the operating temperature range of the transducers, or more generally in harsh or hostile conditions not suitable for transducer monitoring operations. In these cases, waveguide designs often are comparatively thin metallic rods with suitable contact surfaces at either end. Their length is determined by the requirement to place the sensor into an environment compatible with the operating limits of the transducers.

With respect to the mounting device or mounting method, ref. [75] again notes several important points: "*Mounting fixtures must be constructed so that they do not create extraneous Acoustic Emission or mask valid Acoustic Emission generated in the structure being monitored*" and further, "*The mount must not contain any loose parts of particles*". The movement of transducers relative to the test object is a potential source of noise signals, and an important caveat, hence, is as follows: "*Permanent mounting may require special techniques to prevent sensor movement caused by environmental changes*". The most important aspect for the selection of the mounting device or method is, however, stated as follows: "*Detection of surface waves may be suppressed if the sensor is enclosed by a welded-on fixture or located at the bottom of a threaded hole. The mounting fixture should always be designed so that it does not block out a significant amount of acoustic energy from any direction of interest*". A suitably designed sensor mount device, on the other hand, may also prevent a sensor that has lost contact with the surface of the test object from falling off or, on the other hand, can be damaged by impact from falling objects, e.g., tools, hail, bird strikes, etc., especially in field testing.

Examples of special contact conditions sometimes requiring specific couplant media and/or sensor mounts are AE sensors coupled to biological tissue [76]; to electric power devices, mainly applied for detection of partial electric breakdown [77], in corrosive environments [78], in nuclear or ion radiation areas [79]; to snow or ice [80,81]; and possibly to certain art and archaeological objects where couplants and sensors may not leave any mark and surface preparation of the test object is not possible. Some of the conditions noted here may not only require special couplant materials but may also affect the short-term or long-term performance of the transducers themselves.

3.1.2. Couplants and Bonding Agents

The ASTM standard guide for mounting piezoelectric Acoustic Emission sensors [75] provides general recommendations for the couplants used in compression mounts or for bonding agents for permanent bonding of the sensors (cite): "*The type of couplant or bonding agent should be selected with appropriate consideration for the effects of the environment (for example, temperature, pressure, composition of gas, or liquid environment) on the couplant and the constraints of the application. It should be chemically compatible with the structure and not be a possible cause of corrosion. In some cases, it may be a requirement that the couplant be completely removable from the surface after examination*".

For fiber-reinforced polymer composite parts, in particular components or structures that are adhesively bonded for aerospace or other applications, silicone contaminations on the surface are not allowed [82]. Therefore, silicone or silicone-containing couplants shall not be used in these cases. On the other hand, a silicone-free vacuum grease used as sensor couplant on CFRP at the authors' laboratory still left visible stains on the surface that could not be removed. The question of whether these might also have an effect on the quality of adhesive bonds, however, is not answered.

The AE standard [75] provides further details on the choice of couplants (cite): "*Testing has shown that in most cases, when working at frequencies below 500 kHz, most couplants will suffice. However, due to potential loss of high frequency (HF) spectra when working above 500 kHz, a low viscosity couplant or rigid bond, relative to sensor motion response, is recommended. Additionally, when spectral response above 500 kHz is needed, it is recommended that FFT be performed to verify adequacy of HF response*" and "*The thickness of the couplant may alter the effective sensitivity of the sensor. The thinnest practical layer of continuous couplant is usually the best. Care should be taken that there are no entrapped voids in the couplant. Unevenness, such as a taper from one side of the sensor to the other, can also reduce sensitivity or produce an unwanted directionality in the sensor response*". The thickness of the couplant layer has to exceed the level of surface roughness or corrugation of the test object, and this provides a lower bound. Furthermore, a question can be asked with respect to the extent the couplant has to be "void-free" and how this could be quantitatively assessed, whatever the required limits are. It is not known to which extent specific couplants really penetrate to the "bottom" of rough or corrugated surfaces from macroscales to nanoscales and, thus, provide a sufficiently homogeneous contact layer. Surface preparation, type of couplant, its viscosity and wetting behavior on the material of the test object, the procedure for applying it and possibly further treatment, ambient environmental and variable service conditions may all play a role.

There are additional recommendations for the choice of couplants and their application in [83], a Standard Practice on Acoustic Emission Monitoring During Resistance Spot-Welding, e.g., (cite) "*For sustained monitoring, such as on-line AE examination or control of each nugget, the sensor should be permanently mounted using an epoxy adhesive or a similar material. A preamplifier is usually positioned near the sensor*". This is one example explicitly suggesting permanent adhesive bonding for coupling sensors for sustained, i.e., longer, monitoring. In cases where such a permanent bonding of the AE sensors is used, a general recommendation in [75] states the following (cite) "*When bonding agent are used, the possibility of damaging either the sensor or the surface of the structure during sensor removal must be considered*".

There are further recommendations for special test conditions or environments, e.g., (cite) "*In some applications, it may be impractical to use a couplant because of the nature of the environment (for example, very high temperatures or extreme cleanliness requirements). In these situations, a dry contact may be used, provided sufficient mechanical force is applied to hold the sensor against the structure*". Cleanliness requirements may limit choice or use of couplants, e.g., in semiconductor industry or the biomedical and pharmaceutical industry. There is also a comment on a type of bonding agent that apparently has been proven unsuitable, even though no reason or explanation is given, namely (cite), "*The use of double-sided adhesive tape as a bonding agent is not recommended*".

One example of AE monitoring with sensors that did not require a couplant is discussed by [84]. The test object was a highway bridge made from reinforced concrete and monitoring was performed under service conditions for two weeks each in 2012 and 2014. The conical Proctor–Glaser type sensors [85,86] were screw threads mounted in adhesively bonded aluminum plates and directly placed in contact with the concrete surface. The effective contact area between sensor and test object surface was fairly small in this case, and this is one explanation provided for why the lack of a coupling agent apparently did not play a role. The plates stayed in place for more than two years, and the sensors were removed between the two monitoring sessions. The exact type of bonding agent used for the aluminum plate mount is not given in the thesis, but it was an epoxy-based adhesive.

3.1.3. Examples of Long-Term Coupling for AE Monitoring

Infrastructure, in particular bridges or bridge components such as bridge decks, cables or connections, is one example where AE monitoring has been investigated with respect to long-term performance. However, the effective monitoring periods in most applications presented by, e.g., [87–90], were on the order of hours or days and not months or years.

A few publications present long-term AE measurements and their analysis. The first is from a 10-year rock monitoring operation in the Gran Sasso mountain in Italy [91] with the aim to observe whether AE activity also exists in non-volcanic areas with seismic activity. Analysis showed that, for an AE sensor (type Brüel and Kjær model 8312) mounted on the end of stainless-steel rod fixed by cement in a rock-drill hole, about 90% of all signals recorded (after an 82 dB amplifier) in the frequency range between 100 kHz and 1 MHz were noise from electromagnetic sources. A second sensor, with the metal case coupled electrically but not acoustically to the first, provided a simple approach for noise discrimination. The second sensor only recorded the electromagnetically induced signal, and the other recorded all signals. Unfortunately, the paper does not discuss the long-term performance of the AE sensors, of its coupling and of the measurement setup.

A second example is a four-month monitoring operation of a bridge across the Yellow river in China based on modal analysis from accelerometer data [92]. There were fifteen accelerometers installed on each of the two separate bridge lanes. Again, no information on long-term accelerometer and data recording system performance or problems encountered in the course of the test was provided. The authors, however, note the following (cite): "*The influence of temperature, moisture, wind, traffic load, etc., need to be simulated in the finite element model and verified in the measured data*".

A third example is a two-year AE monitoring operation of two parallel steel-arch highway bridges [93]. An AE monitoring system (type Sensor Highway IITM System) with sixteen channels and AE sensors (type R15I-LP-AST) was installed on each of the two bridge arches. Sensor positions were set as far apart as possible, and their couplings were tested by lead pencil breaks (Hsu–Nielsen sources). Sensors mounted ten feet apart proved sufficient for monitoring the relevant parts, while still providing source location. Remote AE system operation was via a 3G modem. The AE equipment was powered by a solar panel (520 W), with four 110 Ah batteries. Due to problems believed to be caused with respect to the solar panel from ice, snow, de-icing salts and other road debris, as well as vandalism, installing an alternative power source is recommended in the conclusions of the report. For data transmission, the authors explicitly stated (cite) the following: "*A land-based internet connection is recommended to insure that the monitoring system is always accessible for a remote login and/or data upload. Wireless connection are less reliable that land-based internet connections and often suffer communication interruptions. Furthermore, wireless modem antennas are susceptible to factors such as vandalism, damage during bridge maintenance and equipment failure*".

Two sets of data were collected under service conditions: the first from November 2012 to October 2013 (from one bridge only), and the second from November 2013 to October 2014 (from both bridges). Separate fracture test specimens acoustically coupled to the bridge structure provided a data base to discriminate AE noise signals from fractures occurring in the bridge. This discrimination required a combination of several criteria. For analysis, analyzing bridge AE limited amounts of data for easy of handling is recommended. Therefore, the continuous data were broken down into one day segments for detecting fracture events. The AE bridge data never exceeded the combined criteria defined from the separate fracture tests, indicating that no fractures had occurred in the bridge structures during monitoring. Of course, this holds for the given sensitivity level of the AE system as installed. There is a system troubleshooting timeline table in Appendix D of the document [93]. This shows system power problems (low battery power) and modem problems as main troubles.

A fourth example, for a reinforced concrete bridge, is an in situ monitoring operation of a reinforced concrete slab on a sixty-year-old bridge with a combination of AE, UT, strain gauges and thermocouples [94,95]. The aim was to detect fatigue damage initiation under normal service loads, which, of course, had increased since the design and construction of the bridge. The monitoring system with strain gauges and thermocouples was installed in 2016 and operated at least until 2019 (publication date). The AE system installed in November 2018 had 32 channels, of which 24 were connected with 150 kHz resonant sensors (type PK15l) with an integrated preamplifier of 26 bB gain; the threshold was set at 30 dB. Remote monitoring was performed with a 4G signal transmission system. Finite element simulations helped to select sensor positions near the highest loads of the concrete slab. Traffic noise was shown to be eliminated by a front-end filter set to let pass AE hits between 40 and 1000 counts and the waveforms with counts between 5 and 10,000 and an amplitude between 40 and 1000 dB. A time filter was also defined, namely Peak Definition Time (PDT) 200 µs, Hit Definition Time (HDT) 800 µs and Hit Lockout Time (HLT) 1000 ms. The monitoring duration was 18 months. The Ph.D. thesis published recently provides detailed analysis and results [95]. The main conclusion is that there was no indication of fatigue problems in the concrete as well as in steel rebars.

A fifth example is from an acoustic monitoring operation of a North Sea well with hydrophones (frequency range from 10 kHz to 100 kHz and 200,000 samples per second). There were two consecutive campaigns: one of four months in the summer of 2011 [96] and the second for seven months from Fall of 2011 to Spring 2012, both in a harsh environment. The measurement system was designed for an acquisition duration of about ten months. Again, no problems with sensor performance or data acquisition were explicitly noted.

The cited examples clearly illustrate that for long-term AE monitoring experiments reported in the literature, there is scant explicit, detailed and quantitative information on long-term performance at best. Lack of published specific details on technical problems with the sensors or the measurement chain, however, does not constitute proof that no problems occurred or were not observed.

An example of long-term sensor bonding from the authors' laboratory is an MFC element adhesively bonded on the landing wheel gear of a real glider plane [97]. This device was mounted with a standard Araldite® adhesive and used with a wireless electromechanical impedance (EMI) measurement setup that fitted into the wheel bay of the plane. Even though no measurements were taken during flight ever, laboratory investigations on identical replicas of the landing wheel gear showed that fine, hardly visible cracks induced by mechanical loading could be identified by changes in the 20–25 kHz range of the EMI-spectrum (recorded in 200 Hz steps). MFC was mounted in 2010 and is still bonded to the gear after a total of 240 flight hours and 120 takeoffs and landings until the spring of 2021 (the glider plane is kept at an airfield and flying in Switzerland). Repeating the EMI-measurements after more than ten years, however, is still pending.

There are a few examples of long-term infrastructure monitoring over a period of almost 25 years now. An Empa publication in 2019 summarized bridge monitoring experience up to 23 years [98], but the measurement systems are still in place and operational. The sensor system used in the three cases reported in the paper consisted of fiber optics with FBG and linear variable differential transducers (LVDT) for measuring loads or strains in selected load-bearing components made from CFRP or their anchorage. The stability and reliability of the measurement system is essential, and this required a major effort with long-term reference experiments in the laboratory. The fiber optics FBG system proved suitable for integration into CFRP structures and components, and the data indicate sufficient long-term performance without maintenance or repair. Even though fiber optics in this case was not for measuring AE or GUW, developing similar fiber optics systems for SHM of infrastructure monitoring with AE or GUW looks promising.

3.2. Durability of Sensors or Transducers under Service Loads and Environmental Exposure

Ambient temperature and its variation are likely the most important environmental in-service exposures affecting transducer performance—if packaged into a suitable case—and durability of coupling agents. Transducers may reach service lives of thirty and more years as shown, e.g., by sensors in the authors' laboratory manufactured in the early 1990s. Of course, using sensors in a service environment that is sufficiently stable and moderate, e.g., laboratory with controlled climate is advantageous. Piezoelectric materials such as PZT for signal detection do have an upper operating temperature limit. This is caused by the fact that the piezo-effect disappears due to a phase transition above the Curie temperature (Tc). In practice, the maximum operating temperature has to be set sufficiently below Tc. In a student project at Empa, an MFC element was repeatedly bonded and debonded to a GFRP beam with a thermoplastic adhesive applied by a heat gun. The thermoplastic adhesive was briefly heated to a temperature between about 110 °C and 120 °C for application on the GFRP. Consecutive measurements, in this case with EMI, indicated a decrease in MFC sensitivity with increasing numbers of bonding–debonding cycles, even though the temperature was below Tc [99]. This is likely due to thermally induced depolarization of the PZT. An investigation of thermomechanical loading effects on MFC in [100] established a theoretical fatigue model that fitted experimental data of the degradation of the piezoelectric coupling coefficients fairly well. This model further allowed for predictions of stiffness and strength degradation of the MFC under thermomechanical loads. Whether higher-temperature cure of thermoset adhesives (e.g., epoxies) might induce analogous changes in sensitivity of coupled PZT-transducers is not known. If the thermoset bonding is applied only once and not repeatedly, the effect of the cure on sensitivity is expected to be limited, otherwise room-temperature cure adhesives can be used [101]. In principle, transducers showing thermal depolarization effects for whatever reason during us could possibly be re-polarized by applying a suitable poling voltage at elevated temperature for a defined duration [102]. For AFC, the poling voltages varied between about 2.5 and 3 kV per mm distance between the interdigitated electrodes and re-poling would likely require similar voltages. AFC electrode distance varied between 0.7 and 1.3 mm, and poling temperature varied between 40 °C and 80 °C (clearly below Tc of the PZT fibers and below Tg of the epoxy matrix of the AFC). Such a procedure has never been applied to commercial transducers to the best knowledge of the author. Depending on their design, voltages significantly exceeding 4 kV might have to be applied, and this could induce electric breakdown (as it did in several AFC elements for poling voltages above about 3 kV/mm). For trials on commercial transducers, information on which combination of temperature, time and poling voltage is appropriate for re-poling would have to be obtained from the manufacturer.

For AE and GUW measurements at "high" temperatures, the following approaches have been attemped: (1) design and optimize piezoelectric materials with higher Tc for sensors operating at higher temperatures (see, e.g., [36,37,103]); (2) use of waveguides between the surface of the test object and the sensor (these, however, do affect the signals that are transmitted; see, e.g., [67]); and (3) use of alternative physical principles for sensor and measurement. The latter comprise, e.g., fiber optics either integrated or surface bonded [104]; special AE sensors made with optical fibers [72]; or contactless methods, e.g., laser interferometry [43], vibrometry [63] or air-coupled ultrasound for GUW [50,51,105]; and electric methods, e.g., electrical conductivity for CFRP [106,107] or dielectric methods [108].

Long-term monitoring operations of salt rock with AE have been performed in Germany since 1995, and partial results have been published in, e.g., [109]. A total of twenty-four sensors were installed in boreholes between three and twenty meters deep. Five sensors were pressed pneumatically against the borehole walls and the remaining nineteen by springs against the borehole faces. Even though they were not noted in the publication, there were failures in the measurement chain [110]. These occurred in the preamplifiers due to leakage of saltwater into the casing. Therefore, in corrosive media or environments, as far as possible, use of corrosion-resistant materials is recommended, and the long-term sealing of the entire measurement system, including plugs and electric contacts, is essential. For checks performed with automatic sensor tests, the result combines sensor and mounting device performance, including the quality or degree of the coupling to the test object.

3.3. Durability of Electronic Data Acquisition Equipment for AE and GUW

Signal transmission to data acquisition and power supply for the electronics are also dependent on the choice of transducer or sensor and, hence, on the test object and its environment. For long-term operation and durability of electronic measurement equipment, the reliability of the electronic components and modules is essential for providing sufficient technical availability. There are standard procedures [111,112] for the verification of AE equipment operating characteristics; they recommend periodic verification. Certain procedures for AE testing of safety-relevant infrastructure explicitly require this verification at least once per year as well as in case of malfunction of the system.

For electronic components and systems, ref. [113] discusses basic reliability issues. However, no electronic equipment operates without some maintenance and repair for several decades. NASA's deep space network is probably the electronic signal recording and analysis system with the longest operating duration known to date. It was set up in 1958 [114] and is still in operation today. However, as discussed in [115], there has been virtually continuous maintenance work and several upgrades have been implemented, the latter mainly for adapting the system to new communication technology for satellites launched more recently. To some extent, the deep space network system requirements differ from those for equipment transmitting and recording AE or GUW signals (except for space applications), since the sensor or, more generally, the measurement and wireless signal transmission systems on most satellites cannot be changed, repaired or upgraded anymore. Of course, depending on the object to be monitored by AE or GUW, the effort to change sensors and signal transmission devices can be quite substantial and may only be feasible at certain times, e.g., during shutdown from service. Nevertheless, if properly planed and prepared, repair and upgrade installations are feasible in these cases.

Data files from AE and GUW for long-term SHM or CM tend to be "large" (of course, due to development of evermore computationally powerful data processing and storage technology, this term is not quantified here). This may not only pose respective problems for data storage and processing but also for signal transmission, the latter especially for wireless modules. Currently, for AE systems with twenty or more channels operating at sampling rates of 10 MHz or more (AE equipment currently provides up to 40 MHz sampling at 18 bit amplitude resolution) with signal rates of 1000 or higher per second and channel require signal transmission rates clearly above 1 GBit/second. This exceeds the transmission rates provided by the latest commercial wireless technologies, e.g., 5G as discussed in [116]. Potential solutions are interim storage of data at the sensor node with signal transmission in periods of lower activity, signal preprocessing and respective data reduction at the node before transmission or reduction in wave signals to selected signal parameters instead of transmission of full waveforms. Interim storage on the wireless node with delayed signal transmission as a solution of course inhibits real-time signal processing and analysis.

Maintenance and repair of hardware benefit from standardized and modular design with standard components [113]. This also implies respective supply chain considerations. Standard components available from several manufacturers, maybe even from companies with production facilities "nearby," are one key issue. The supply and delivery problems of electronic parts and components experienced during and in the aftermath of the worldwide COVID pandemic in 2020 and 2021 nicely illustrate this point. For application-specific parts or components, a "local" manufacturer is preferable, possibly even at somewhat higher costs. The service lifetime of electronic components, modules and systems can be extended, if components are not operated at the limit of their specified rating. This means that the design shall consider a certain amount of so-called "derating" with respect to electric and thermal loads. This may further require, e.g., specific cooling of the equipment in operation. Protection against electrostatic discharge, on the component and module level, is also recommended. Effects of ambient humidity or humidity variation during service operation may also play a role. These can be considered in the design phase by utilizing, e.g., the choice of the packaging rating of the components.

If commercial AE and GUW equipment instead of in-house developed instrumentation are installed, there may be the question of how long the commercial manufacturer will provide equipment support and related services such as calibration, repair or extension and upgrades. Another aspect is long-term data storage, including both raw data and analysis results. Of course, all data storage shall have a backup. Whether cloud services are an acceptable option may be questionable. If AE or GUW monitoring effectively yields data at rates of 1 GBit/second or more, the data storage necessary becomes impressive. Again, data storage demands for the deep space network provide a nice example [117] for comparison.

3.4. Issues of Long-Term Use of Software

Specific software development for data acquisition, storage and processing instead of using or adapting commercial codes has the advantage of offering full control and flexibility and, hence, independence from software suppliers and their support and updates. Another issue in the long term may be data format and software compatibility if upgrades or new software versions change these. Compatibility with older data formats or data acquired with previous software versions cannot be taken for granted in all cases. However, cost for own developments may be considerable, especially for ensuring proper operation of the software by extensive validation tests and quality control measures.

For software development in general also applicable to software for AE or GUW data acquisition, data processing and analysis systems, ref. [113] again provides some guidelines. Planning and organizing the software development with a view to high reliability with quality assurance and validation, as well as writing modular and well documented code, are basic recommendations. Potential problems caused, e.g., by inexperienced users and resulting operating errors or even misuse shall also be considered. Users may need a certain level of software support that has to be readily provided when required.

Depending on the type of computer operating system used, commercial suppliers will stop development and support for "older" system operating software at some point in time. The question then is whether a system still operating well will be replaced. With any change or upgrade with implementation of new software for improved performance or elimination of identified bugs or problems, there is a risk to installing new software bugs. Often, older operating systems do not offer the level of "security" that will protect the system against interference from outside. If signal transmission and data storage rely on commercial communication and data storage systems, such as internet and cloud services, installation of upgrades or changing to new operating systems can hardly be avoided. Data processing and analysis software continuously developed or periodically upgraded by the AE or GUW monitoring service provider can and shall be updated, if necessary. Information from one service provider indicates that software and hardware upgrades are implemented fairly frequently, often on a yearly or biannual basis. In this case, software and hardware development is performed in house but using standard components as far as possible.

4. Discussion

The information presented from the literature suggests the following aspects that deserve attention when planning and implementing AE or GUW for long term SHM or CM: (1) performance of the couplant material and of the mounting device; (2) assuring sufficiently constant sensor sensitivity; (3) hardware and software development; (4) signal transmission and data storage; and (5) maintenance and repair concepts. In addition to planning and respective design of the components and software, for all these aspects, periodic performance checks are essential. These comprise sensor performance and coupling, typically with automatic sensor test routines at defined time intervals, and periodic equipment performance characterization. These, e.g., apply standard procedures or equivalent tests implemented by the equipment manufacturers. Data backups are also essential. Procedures for specifically checking on proper operation of AE or GUW signal transmission and software performance are not available in standards. Operator experience is, even though a "human factor", probably the best current approach for this. Of course, double checking by another operator ("four eyes instead of two") may also help in detecting malfunction of any component of the measurement chain.

The scant information available in literature seems to suggest bonding with thermoset epoxy-based adhesives as the first approach for coupling sensors for long-term monitoring. Epoxies, as other polymers, may age and degrade, particularly at elevated temperatures or under hygro-thermal changes of the environment. For special applications or service conditions, it might be useful to contact strain gauge manufacturers or suppliers for recommendations on specific surface preparation and choice of the adhesive. For the latter, adhesives manufacturers may also provide useful information. Note that complete removal of the adhesive after the test without any damage to the test object and its surface may be an important requirement. However, for typical long-term monitoring tests, e.g., on infrastructure, this likely is less important. If adhesive bonding is used, the question can be asked whether an additional sensor mount device is still necessary. Without mount device, potential interference with signal propagation is automatically eliminated. There are also cases where a couplant may not be necessary or suitable, as noted above, but then a mounting device is necessary.

Magnetic sensor holders are used in many AE applications that involve test objects made of magnetic materials. Again, service temperature may limit the use of magnet holders. For example, Neodymium-Iron-Boron (NdFeB) magnets start to demagnetize at temperatures around +80 °C. Adding Dysprosium (Dy) and Terbium (Tb) improves temperature stability to at least +200 °C but is likely to also increase cost. NdFeB-magnets further are sensitive to corrosion. These effects may be reduced by adding cobalt or by coating the magnets with a suitable surface protection layer [118]. In the literature, there is no information on long-term performance of magnet holders to the best knowledge of the author. Sensor mounts may simultaneously have to hold the transducer and protect it against the environment, accidental damage caused by other equipment or service operations or against interference by non-authorized personnel or vandalism.

As noted above, for PZT-based transducers, the operating temperature range is limited by the Curie-temperature of the piezo-material, typically to about +100 °C or less. Recent developments of special AE sensors extend the limits to higher temperatures up to +150 °C [119] or +180 °C [120]. However, the maximum and minimum operating temperatures are not the only criterion. PZT is a piezoelectric and pyroelectric material [121]. The latter property may be useful for, e.g., energy harvesting from temperature fluctuations [122] but produces noise signals in AE measurements where temperature changes or fluctuates sufficiently. Depending on the circumstances, these noise signals may occur much more frequently than the "real" AE signals from the test object. An analogous situation was the observation of large amounts of electromagnetic noise signals discussed in [91]. Noise signals constitute a potential problem for data processing (large amounts of signals) as well as for analysis (requiring criteria for defining noise signals). Possibly, AI algorithms can soon eliminate noise signals with an acceptable probability of detection.

The last part of the discussion now focusses on practical experience that is not available in literature yet. A working group of the German Committee on AE (a member of the German Society for Nondestructive Testing, DGZfP) dealing with long-term performance of AE for SHM and CM has drafted a questionnaire that was sent to all members of the committee. So far, there were five questionnaires returned, both from AE service providers and research institutes. The responses received so far (end of October 2021) are briefly summarized and compared with the information and recommendations detailed above.

The first response deals with process monitoring applications in various industrial sectors. The sensors for structure-borne sound are usually coupled with a M5 screw (tightened to 6 Nm with a torque wrench), and, for very rough surfaces, a tin washer may be used for coupling. Sensor tests are implemented in the system and service technicians check the measurement equipment once per year. If the signal amplitude in a specific frequency window falls below a defined limit by, e.g., 10% of the reference value, the sensor has to be checked. Often, the problem was not the sensor itself but a connection. Equipment development is continuous using commercial parts and components. Modules of the equipment are changed or upgraded about every two years. Hardware components that are exchanged are mostly motherboards, RAM and hard-disks. Due to failures of magnetic hard-disks, the use of SSD is recommended for data storage. Sensors are exchanged after five to seven years or sometimes earlier depending on use. Equipment malfunction is often found to be due to erroneous operation by the client.

The second response deals with a three-year monitoring operation of a steam pipeline segment in a power plant. Due to the high operating temperature (above 500 °C), six high temperature sensors (type D9215) were coupled with a ceramic based adhesive (type Thermoguss 2000) and protected with a casing made from austenitic steel. Sensor tests during service were not possible. Data acquisition was operated with a front-end filter in order to limit the amount of noise signals recorded. Observation after demounting the pipe segment indicated that sensors were still coupled, but cracks had appeared in a few of the couplant adhesive. After removing the austenitic bands that held the sensors, four of the six sensors easily detached from the test object. The total amount of data recorded was about 220 GB. The data acquisition unit worked well, but data storage hardware failed a few times, resulting in loss of data. These data storage failures were attributed to ambient vibrations from power plant operation. The PC and monitor screen also had to be changed once. Data analysis is still in progress, however.

The third response deals with concrete elements that were monitored for alkali–silicic acid reactions at elevated temperature (40–60 °C) and humidity (98–100% relative humidity). Monitoring duration was between six and twelve months (AE sensors type VS-150K). Results are presented and discussed in [123]. Automatic sensor tests were initially performed every five minutes and every twelve hours later. Due to chemical reactions, the wave propagation properties of the concrete changed, and this was reflected in the measurements. Different couplants were tested and several proved suitable, including kneadable putty-type pads, hot-melt adhesives (temperature control for the application is noted to be important) and silicone. The humid, alkaline test environment is highly corrosive; hence, waterproof sensors, cables and connections are essential.

The fourth response describes several periodic inspection tests on a range of test objects. The effective monitoring duration was up to a few hours each time. For these applications, sensors were standard 150 kHz with integrated preamplifier and, under the test conditions (in any case indoor, one test object even in a clean room), these sensors achieved service lifetimes of between eight and eleven years.

The fifth response deals with a process reactor continuously monitored for about one and a half years. The aim was to detect crack initiation and propagation during service. The sensor mount with an adhesive (type Duraseal 1531) that also served as couplant used magnet holders. Due to the surface temperature of the reactor of about 120 °C, the holding force of the magnet holders was reduced, confirming the effect discussed for the NdFeB magnets above. Sensor tests (AE sensor type ISR15CA-HAT) were performed once per month with Hsu–Nielsen sources. Data transmission was via internet and TeamViewer software. A reduction in sensor sensitivity was observed (not quantified in the response) and attributed to elevated operating temperatures. Two sensors accidentally removed by someone else had to be replaced and additional sensors were mounted to compensate for a loss in sensitivity. No software updates were installed, and no components changed during monitoring.

These examples show different types of problems, from sensor and connection to equipment failure. Both the service environment and possibly misuse or erroneous operation are causes of problems or failure. Sensor coupling and mounting have to be adapted to the test object and the service conditions, and periodic sensor tests are essential. In harsh service environments, signal transmission and data storage may be more easily prone to failure than the AE data acquisition system itself.

5. Conclusions

What are the conclusions from the information presented and discussed regarding the long-term behavior of the sensors for AE and GUW, the sensor coupling agents, the measurement electronics and related software? The first is that there is scant quantitative, published information available on these topics. For the piezoelectric transducers, the conclusions are as follows: Sensor performance requires proper mounting providing sufficient protection against external mechanical impact, shocks or misuse. Nevertheless, sensors for long-term SHM or CM may have to be replaced from time to time even for test durations of less than two years. Therefore, periodic checks of sensor performance, ideally yielding a frequency-dependent sensitivity curve, are essential. The frequency of the checks, e.g., daily, weekly or monthly, depends on the application, on the service loads and on the ambient conditions. Therefore, maintenance and repair concepts for easy and quick sensor or sensor mount replacements are essential. Redundancy in the sensor array may be useful, especially when access to the test object and the sensors is limited to specific time periods due to operating conditions (e.g., certain parts of power plants) or would require a major effort (e.g., accessibility of the test object location). The cost for such redundancy in sensor setup and in respective data processing and analysis, however, can be significant and has to be carefully assessed when planning the monitoring.

For long-term sensor mounting and coupling for SHM or CM, the available information likely points to adhesive bonding, preferably with thermoset epoxy-based adhesives, as a promising solution, at least for sufficiently low operating temperatures. An alternative includes mechanical fasteners, e.g., screws applying the contact pressure with suitable mounting devices, independent of whether a coupling agent is used or not. On test objects made from magnetic materials, magnetic sensor mounts will work if service temperatures are sufficiently low. No information on the long-term behavior of magnetic holders is publicly available. With respect to long-term adhesive bonding, it is likely that strain gauge manufacturers or suppliers may provide recommendations on the choice of the adhesive and the appropriate surface preparation for both, sensor contact plate and test object. Long-term operations of adhesively bonded strain gauges, e.g., on ropeway cable cars, are often subject to rather severe ambient conditions (large temperature and humidity variation).

The main conclusions on electronic measurement hardware and software are as follows: Considering durability as well as the necessary reliability for long-term performance is recommended for specifying the components and parts. This has to be complemented by planning maintenance, repair and later upgrades of hardware and software. Modular design and extensive documentation are, hence, essential. A required reliability or service lifetime for hardware can be achieved by "derating" electronic components and the implementation of redundancy or stabilizing operating conditions. Use of "standard" parts available from several manufacturers or suppliers is one approach for dealing with supply chain problems. For software, ref. [113] clearly states (cite) the following: "*Defects are thus generally caused by human errors (software developer or user).*" Hence, human errors have to be avoided in development and in application. This requires careful planning, organization and documentation of software development and extensive quality assurance shall validate that the code performs correctly. Even though this may seem costly, having full control of software design may yield higher reliability and, hence, less troubleshooting and maintenance cost.

With respect to long-term SHM and CM, research providing quantitative performance measures, reliability or service life estimates for all components of the measurement chain seems highly desirable. Such data are essential for any planning and design of SHM and CM systems. Establishing performance data from sensors, sensor couplants and sensor mounting devices has priority, since the other components of the measurement chain typically can be replaced more easily (except in special cases, including spacecraft or dangerous operating environment with, e.g., risk of exposure to radiation). The service environment likely has a more significant effect on sensor and coupling performance than on other components of the measurement system, if these are either suitably protected or placed in appropriate locations. The variety of environmental factors and their combinations make quantitative assessment of long-term durability and of service lifetime challenging and time consuming. Acceleration of environmental tests is limited as soon as the accelerating factor (e.g., temperature and media exposure) induces additional damage mechanisms. Developing models for combining and extrapolating experimental data to the expected service lifetimes would be beneficial. There clearly is much to perform.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Acknowledgments: Contributions to this review by the following people are gratefully acknowledged: first and most important, Richard A. Nordstrom for introducing me to AE and its application on FRP composites and Kanji Ono (UCLA) for sharing literature and for discussions. Then, Rolf Brönnimann (Empa) for discussions of long-term coupling and reliability aspects of fiber optics for SHM, Christian Dürager (imitec GmbH) for implementing the MFC-based EMI system in his glider plane, Gosia Felux (formerly at ETH Zürich) for providing details on her bridge monitoring with AE, M. Pfister (formerly at ETH Zürich) for the thermoplastic adhesive student project, Alex Stutz (Empa) for information on strain-gauge mounting and their application in ropeway cable-cars, and, finally Empa's Mechanical Systems Engineering Laboratory and its employees for supporting my AE research and SHM development activities for many years. Several members of the German NDT Society's committees on AE and GUW supplied information on their long-term monitoring tests: Sören Barteldes (QASS GmbH, Wetter (Ruhr), Germany), Anne Jüngert (MPA Stuttgart), Manuel Löhr (GMA Werkstoffprüfung GmbH, Düsseldorf, Germany), Gerd Manthei (TH Mittelhessen), Stephan Pirskawetz (BAM Berlin) and Peter Weinzettl (TPA-KKS GmbH, Vienna, Austria); their contributions were essential for assessing the current state of knowledge.

Conflicts of Interest: The author declares no conflict of interest.

References

1. Kishinouye, F. An Experiment on the Progression of Fracture (A Preliminary Report). *J. Acoust. Em.* **1990**, *9*, 177–180. (In English)
2. Förster, F.; Scheil, E. Akustische Untersuchung der Bildung von Martensitnadeln. *Z. Metallkde.* **1936**, *28*, 245–247. (In German)
3. Sokolov, S.Y. On the problem of the propagation of ultrasonic oscillations in various bodies. *Elek. Nachr. Tech.* **1929**, *6*, 454–460.
4. Miller, R.K.; Hill, E.v.K.; Moore, P.O. *Nondestructive Testing Handbook Volume 6, Acoustic Emission Testing (AE)*, 3rd ed.; American Society for Nondestructive Testing (ASNT): Columbus, OH, USA, 2005; pp. 1–446.
5. Workman, G.L.; Kishoni, D.; Moore, P.O. *Nondestructive Testing Handbook Volume 7, Ultrasonic Testing (UT)*, 3rd ed.; American Society for Nondestructive Testing (ASNT): Columbus, OH, USA, 2007; pp. 1–600.
6. Ling, E.H.; Abdul Rahim, R.H. A review on ultrasonic guided wave technology. *Aust. J. Mech. Eng.* **2020**, *18*, 32–44. [CrossRef]
7. Beattie, A.G. Acoustic Emission, Principles and Instrumentation. *J. Acoust. Em.* **1983**, *2*, 85–128.
8. Gorman, M.R. Progress in Detecting Transverse Matrix Cracking using Modal Acoustic Emission. In *Review of Progress in Quantitative Nondestructive Evaluation*; Thompson, D.O., Chimenti, D.E., Eds.; Plenum Press: New York, NY, USA, 1998; Volume 17, pp. 557–564.
9. Le Gall, T.; Monnier, T.; Fusco, C.; Godin, N.; Hebaz, S.E. Towards Quantitative Acoustic Emission by Finite Element Modelling: Contribution of Modal Analysis and Identification of Pertinent Descriptors. *Appl. Sci.* **2018**, *8*, 2557. [CrossRef]

10. Sause, M.G.R.; Horn, S. Simulation of Acoustic Emission in Planar Carbon Fiber Reinforced Plastic Specimens. *J. Nondestruct. Eval.* **2010**, *29*, 123–142. [CrossRef]
11. Sause, M.G.R.; Richler, S. Finite Element Modelling of Cracks as Acoustic Emission Sources. *J. Nondestruct. Eval.* **2015**, *34*, 4. [CrossRef]
12. Baensch, F.; Zauner, M.; Sanabria, S.J.; Pinzer, B.R.; Sause, M.G.R.; Brunner, A.J.; Stampanoni, M.; Niemz, P. Damage Evolution in Wood—Synchrotron based microtomography (SRμCT) as complementary evidence for interpreting acoustic emission behavior. *Holzforschung* **2015**, *68*, 1015–1025. [CrossRef]
13. Brunner, A.J. Correlation between acoustic emission signals and delaminations in carbon fiber-reinforced polymer-matrix composites: A new look at mode I fracture test data. *J. Acoust. Emiss.* **2016**, *33*, S41–S49.
14. Lu, Y. Industry 4.0: A survey on technologies, applications and open research issues. *J. Ind. Inf. Integr.* **2017**, *6*, 1–10. [CrossRef]
15. AlShorman, O.; Irfan, M.; Saad, N.; Zhen, D.; Haider, N.; Glowacz, A.; AlShorman, A. A Review of Artificial Intelligence Methods for Condition Monitoring and Fault Diagnosis of Rolling Element Bearings for Induction Motor. *Shock Vibr.* **2020**, *2020*, 8843759. [CrossRef]
16. Górriz, J.M.; Ramírez, J.; Ortíz, A.; Martínez-Murcia, F.J.; Segovia, F.; Suckling, J.; Leming, M.; Zhang, Y.D.; Álvarez-Sánchez, J.R.; Bologna, G.; et al. Artificial intelligence within the interplay between natural and artificial computation: Advances in data science, trends and applications. *Neurocomputing* **2020**, *410*, 237–270. [CrossRef]
17. Pandiyan, V.; Shevchik, S.; Wasmer, K.; Castagne, S.; Tjahjowidodod, T. Modelling and monitoring of abrasive finishing processes using artificial intelligence techniques: A review. *J. Manuf. Process.* **2020**, *57*, 114–135. [CrossRef]
18. Tantalaki, N.; Souravlas, S.; Roumeliotis, M. A review on big data real-time stream processing and its scheduling techniques. *Int. J. Parallel Emerg. Distrib. Syst.* **2020**, *35*, 571–601. [CrossRef]
19. Dubuc, T.; Stahl, F.; Roesch, E.B. Mapping the Big Data Landscape: Technologies, Platforms and Paradigms for Real-Time Analytics of Data Streams. *IEEE Access* **2021**, *9*, 15321–15374. [CrossRef]
20. Rodgers, J.M.; Morgan, B.C.; Tilley, R.M. Acoustic emission monitoring for inspection of seam-welded hot reheat piping in fossil power plants. In *Nondestructive Evaluation of Utilities and Pipelines, Proceedings of the SPIE 2947, Nondestructive Evaluation Techniques for Aging Infrastructure and Manufacturing, Scottsdale, AZ, USA, 3–5 December 1996*; Prager, M., Tilley, R., Eds.; SPIE: Bellingham, WA, USA, 1996; pp. 126–135. [CrossRef]
21. Morgan, B.C.; Tilley, R. Inspection of power plant headers utilizing acoustic emission monitoring. *NDT E Int.* **1999**, *32*, 167–175. [CrossRef]
22. Ayo-Imoru, R.M.; Cilliers, A.C. A survey of the state of condition-based maintenance (CBM) in the nuclear power industry. *Ann. Nucl. Energy* **2018**, *112*, 177–188. [CrossRef]
23. Fowler, T.J. Chemical-Industry Applications of Acoustic Emission. *Mater. Eval.* **1992**, *50*, 875–882.
24. Boyd, J.W.R.; Varley, J. The uses of passive measurement of acoustic emissions from chemical engineering processes. *Chem. Eng. Sci.* **2001**, *56*, 1749–1767. [CrossRef]
25. Kirillov, K.I.; Kraevskii, V.N. Evaluation of the residual service life of chemical technological equipment at the Odessa port plant. *Mater. Sci.* **2011**, *46*, 561–567. [CrossRef]
26. Bernardo, J.T. Cognitive and Functional Frameworks for Hard/Soft Fusion for the Condition Monitoring of Aircraft. In Proceedings of the 18th International Conference on Information Fusion, Washington, DC, USA, 6–9 July 2015; IEEE: Piscataway, NJ, USA, 2015; pp. 287–294.
27. Kralovec, C.; Schagerl, M. Review of Structural Health Monitoring Methods Regarding a Multi-Sensor Approach for Damage Assessment of Metal and Composite Structures. *Sensors* **2020**, *20*, 826. [CrossRef]
28. Margot, R.D.Y. Strategische Signalerfassung mit piezoelektrischen Sensoren für die Prozessüberwachung in der Zerspanung. Ph.D. Thesis, ETHZ, Zürich, Switzerland, 2005. No. 16138 (In German).
29. Shevchik, S.; Masinelli, G.; Kenel, C.; Leinenbach, C.; Wasmer, K. Deep Learning for In Situ and Real-Time Quality Monitoring in Additive Manufacturing Using Acoustic Emission. *IEEE Trans. Ind. Inf.* **2019**, *15*, 5194–5203. [CrossRef]
30. Wasmer, K.; Le-Quan, T.; Shevchik, S.; Violakis, G. Piezo acoustic versus opto-acoustic sensors in laser processing. In *22. Kolloquium Schallemission und 3. Anwenderseminar Zustandsüberwachung mit geführten Wellen, Karlsruhe Germany, 27–28 March 2019*; Deutsche Gesellschaft für Zerstörungsfreie Prüfung (DGZfP): Berlin, Germany, 2019; Volume 20, pp. 1–8.
31. EN 12819. LPG Equipment and Accessories—Inspection and Requalification of LPG Tanks Greater Than 13 m^3. 2009. Available online: https://standards.iteh.ai/catalog/standards/cen/ba842fdb-4284-4b0b-810a-0f90b87a767c/en-12819-2019 (accessed on 14 November 2021).
32. ASTM D1067/D1067-M. Standard Practice for Acoustic Emission Examination of Fiberglass Reinforced Plastic Resin (FRP) Tanks/Vessels. *Am. Soc. Test. Mater. Int.* **2018**. [CrossRef]
33. Jiao, P.C.; Egbe, K.-J.I.; Xie, Y.W.; Matin Nazar, A.; Alavi, A.H. Piezoelectric Sensing Techniques in Structural Health Monitoring: A State-of-the-Art Review. *Sensors* **2020**, *20*, 3730. [CrossRef]
34. Uchino, K. The Development of Piezoelectric Materials and the New Perspective. In *Advanced Piezoelectric Materials*, 2nd ed.; Uchino, K., Ed.; Elsevier Woodhead Publishing: Cambridge, UK, 2017; pp. 1–92. [CrossRef]
35. Chen, J.Y.; Qiu, Q.W.; Han, Y.L.; Lau, D. Piezoelectric materials for sustainable building structures: Fundamentals and applications. *Renew. Sustain. Energy Rev.* **2019**, *101*, 14–25. [CrossRef]

36. Zu, H.; Wu, H.; Wang, Q.-M. High-Temperature Piezoelectric Crystals for Acoustic Wave Sensor Applications. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **2016**, *63*, 486–505. [CrossRef]
37. Tittmann, B.; Batista, C.F.G.; Trivedi, Y.P.; Lissenden III, C.J.; Reinhardt, B.T. State-of-the-Art and Practical Guide to Ultrasonic Transducers for Harsh Environments Including Temperatures above 2120 °F (1000 °C) and Neutron Flux above 1013 n/cm^2. *Sensors* **2019**, *19*, 4755. [CrossRef] [PubMed]
38. Koruza, J.; Bell, A.J.; Frömling, T.; Webber, K.G.; Wang, K.; Rödel, J. Requirements for the transfer of lead-free piezoceramics into application. *J. Materiomics* **2018**, *4*, 13–26. [CrossRef]
39. Tuloup, C.; Harizi, W.; Aboura, Z.; Meyer, Y. Structural health monitoring of polymer-matrix composite using embedded piezoelectric ceramic transducers during several four-points bending tests. *Smart Mater. Struct.* **2020**, *29*, 125011. [CrossRef]
40. Lin, B.; Giurgiutiu, V. Review of in situ fabrication methods of piezoelectric wafer active sensor for sensing and actuation applications. In Proceedings of the SPIE 5765, Smart Structures and Materials 2005: Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems, SPIE Smart Structures and Materials + Nondestructive Evaluation and Health Monitoring, San Diego, CA, USA, 7–10 March 2005; SPIE: Bellingham, WA, USA, 2005; pp. 1033–1044. [CrossRef]
41. Bachmann, F. Integration of Monolithic Piezoelectric Damping Devices into Adaptive Composite Structures. Ph.D. Thesis, ETHZ, Zürich, Switzerland, 2013. No. 20747. [CrossRef]
42. Bent, A.A.; Hagood, N.W. Piezoelectric fiber composite with interdigitated electrodes. *J. Intell. Mater. Syst. Struct.* **1997**, *8*, 903–919. [CrossRef]
43. Birchmeier, M.; Gsell, D.; Juon, M.; Brunner, A.J.; Paradies, R.; Dual, J. Active fiber composites for the generation of Lamb waves. *Ultrasonics* **2009**, *49*, 73–82. [CrossRef]
44. Gómez Muñoz, C.Q.; García Marquez, F.P.; Hernandez Crespo, B.; Makaya, K. Structural health monitoring for delamination detection and location in wind turbine blades employing guided waves. *Wind Energy* **2019**, *22*, 698–711. [CrossRef]
45. Di Rito, G.P.; Chiarelli, M.R.; Luciano, B. Dynamic Modelling and Experimental Characterization of a Self-Powered Structural Health-Monitoring System with MFC Piezoelectric Patches. *Sensors* **2020**, *20*, 950. [CrossRef] [PubMed]
46. Khan, A.; Abbas, Z.; Kim, H.S.; Oh, I.-K. Piezoelectric thin films: An integrated review of transducers and energy harvesting. *Smart Mater. Struct.* **2016**, *25*, 053002. [CrossRef]
47. Shung, K.K.; Cannata, J.M.; Zhou, Q.F. Piezoelectric materials for high frequency medical imaging applications: A review. *J. Electroceram.* **2007**, *19*, 139–145. [CrossRef]
48. Tuloup, C.; Harizi, W.; Aboura, Z.; Meyer, Y. Integration of piezoelectric transducers (PZT and PVDF) within polymer-matrix composites for structural health monitoring applications: New success and challenges. *Int. J. Smart Nano Mater.* **2020**, *11*, 343–369. [CrossRef]
49. Di Scalea, F.L.; Robinson, J.; Tuzzeo, D.; Bonomo, M. Guided wave ultrasonics for NDE of aging aircraft components. In Proceedings of the SPIE 4704, Nondestructive Evaluation and Health Monitoring of Aerospace Materials and Civil Infrastructures, San Diego, CA, USA, 17–21 June 2002; Gyekenysei, A., Shepard, S.M., Huston, D.R., Emin Aktan, A., Shull, P.J., Eds.; SPIE: Bellingham, WA, USA, 2002; pp. 123–132. [CrossRef]
50. Neuenschwander, J.; Furrer, R.; Roemmeler, A. Application of air-coupled ultrasonics for the characterization of polymer and polymer-matrix composite samples. *Polym. Test.* **2016**, *56*, 379–386. [CrossRef]
51. Fang, Y.M.; Lin, L.J.; Feng, H.L.; Lu, Z.X.; Emms, G.W. Review of the use of air-coupled ultrasonic technologies for nondestructive testing of wood and wood products. *Comput. Electron. Agric.* **2017**, *137*, 79–87. [CrossRef]
52. Jung, J.T.; Lee, W.J.; Kang, W.J.; Shin, E.J.; Ryu, J.H.; Choi, H.S. Review of piezoelectric micromachined ultrasonic transducers and their applications. *J. Micromech. Microeng.* **2017**, *27*, 113001. [CrossRef]
53. Ozevin, D. MEMS Acoustic Emission Sensors. *Appl. Sci.* **2020**, *10*, 8966. [CrossRef]
54. Wang, X.S.; Nie, Q.H.; Xu, T.F.; Liu, L.R. A review of the fabrication of optic fiber. In Proceedings of the Optical Design and Fabrication (ICO20). ICO20:Optical Devices and Instruments, Changchun, China, 21–26 August 2005; Breckinridge, J., Wang, Y.T., Eds.; SPIE: Bellingham, WA, USA, 2006; p. 60341D. [CrossRef]
55. Yang, H.Z.; Qiao, X.G.; Luo, D.; Lim, K.S.; Chong, W.Y.; Harun, S.W. A review of recent developed and applications of plastic fiber optic displacement sensors. *Measurement* **2014**, *48*, 333–345. [CrossRef]
56. Talataisong, W.; Ismaeel, R.; Beresna, M.; Brambilla, G. Suspended-Core Microstructured Polymer Optical Fibers and Potential Applications in Sensing. *Sensors* **2019**, *19*, 3449. [CrossRef]
57. Yamada, Y. Textile-integrated polymer optical fibers for healthcare and medical applications. *Biomed. Phys. Eng. Express* **2020**, *6*, 062001. [CrossRef]
58. Xiong, W.; Cai, C.S. Development of Fiber Optic Acoustic Emission Sensors for Applications in Civil Infrastructures. *Adv. Struct. Eng.* **2012**, *15*, 1471–1486. [CrossRef]
59. Willberry, J.O.; Papaelias, M.; Franklyn Fernando, G. Structural Health Monitoring Using Fibre Optic Acoustic Emission Sensors. *Sensors* **2020**, *20*, 6369. [CrossRef]
60. Zhang, L.; Tang, Y.; Tong, L. Micro-/Nanofiber Optics: Merging Photonics and Material Science on Nanoscale for Advanced Sensing Technology. *iScience* **2020**, *23*, 100810. [CrossRef] [PubMed]
61. Xiong, Y.F.; Xu, F. Multifunctional integration on optical fiber tips: Challenges and opportunities. *Adv. Photonics* **2020**, *2*, 064001. [CrossRef]

62. Qiao, X.G.; Shao, Z.H.; Bao, W.J.; Rong, Q.Z. Fiber-optic ultrasonic sensors and applications. *Acta Phys. Sin.* **2017**, *66*, 074205. [CrossRef]
63. Staszewski, W.J.; bin Jenal, R.; Klepka, A.; Szwedo, M.; Uhl, T. A Review of Laser Doppler Vibrometry for Structural Health Monitoring Applications. *Key Eng. Mater.* **2012**, *518*, 1–15. [CrossRef]
64. Hess, P.; Lomosonov, A.M.; Mayer, A.P. Laser-based linear and nonlinear guided elastic waves at surfaces (2D) and wedges (1D). *Ultrasonics* **2014**, *54*, 39–55. [CrossRef] [PubMed]
65. Güemes, A.; Fernandez-Lopez, A.; Pozo, A.R.; Sierra-Pérez, J. Structural Health Monitoring for Advanced Composite Structures: A Review. *J. Compos. Sci.* **2020**, *4*, 13. [CrossRef]
66. Giurgiutiu, V. *Stress, Vibration, and Wave Analysis in Aerospace Composites—SHM and NDE Applications*, 1st ed; Elsevier Academic Press: Cambridge, MA, USA, 2022; pp. 1–1032.
67. Zelenyak, A.M.; Hamstad, M.; Sause, M.G.R. Finite Element Modeling of Acoustic Emission Signal Propagation with Various Shaped Waveguides. In Proceedings of the 31st Conference of the European Working Group on Acoustic Emission (EWGAE), Dresden, Germany, 3–5 September 2014; Paper We.1.A.4. Deutsche Gesellschaft für Zerstörungsfreie Prüfung (DGZfP): Berlin, Germany, 2014; pp. 1–8.
68. Brunner, A.J.; Barbezat, M. Acoustic Emission Monitoring of Leaks in Pipes for Transport of Liquid and Gaseous Media: A Model Experiment. *Adv. Mater. Res.* **2006**, *13–14*, 351–356. [CrossRef]
69. Brunner, A.J.; Barbezat, M. Acoustic Emission Leak Testing of Pipes for Pressurized Gas Using Active Fiber Composite Elements as Sensors. *J. Acoust. Em.* **2007**, *25*, 42–50.
70. Rastegaev, I.A.; Merson, D.L.; Danyuk, A.V.; Afanas'ev, M.A.; Krushtalev, A.K. Universal Waveguide for the Acoustic-Emission Evaluation of High-Temperature Industrial Objects. *Russ. J. Nondestr. Test.* **2018**, *54*, 164–173. [CrossRef]
71. Grazion, S.V.; Mukomela, M.V.; Erofeev, M.N.; Spiryagin, V.V.; Amelin, S.S. Experimental Estimation of the Waveguide Effect on the Acoustic Emission Signal Parameters in Monitoring Facilities with a Long Surface Radius of Curvature. *J. Mach. Manuf. Reliab.* **2020**, *49*, 971–979. [CrossRef]
72. Takayama, Y.; Cho, H.; Matsuo, T. Detection of Acoustic Emission (AE) from Zinc Embrittlement Cracking During Welding Using Optical Fiber AE Monitoring System. *J. Nondestruct. Eval.* **2012**, *31*, 208–214. [CrossRef]
73. Vallen Systeme GmbH, ATEX Products. Available online: https://www.vallen.de/products/atex-products/ (accessed on 14 November 2021).
74. Physical Acoustics Corporation. Intrinsically Safe Sensors. Available online: https://www.physicalacoustics.com/intrinsically-safe-sensors/ (accessed on 14 November 2021).
75. ASTM E650/E650-M. Standard Guide for Mounting Piezoelectric Acoustic Emission Sensors. *Am. Soc. Test. Mater. Int.* **2017**. [CrossRef]
76. Ziegler, B.; Dudzik, K. An Overview of Different Possibilities to Master the Challenge of Coupling an AE-Sensor to an Object of Interest Partly Using Examples of Previous Investigations. *J. KONES Powertrain Trans.* **2019**, *26*, 207–214. [CrossRef]
77. Li, J.; Shi, W.; Zhang, P.P.; Wang, P.; Wang, J.W.; Yan, S.S.; Si, W.S. Study on the Effect of Coupling Materials on the Ultrasonic Signals Detection of Partial Discharge. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *440*, 032120. [CrossRef]
78. Calabrese, L.; Proverbio, E. A Review on the Applications of Acoustic Emission Technique in the Study of Stress Corrosion Cracking. *Corros. Mater. Degrad.* **2021**, *2*, 1–30. [CrossRef]
79. Denett, C.A.; Choens, R.C.; Taylor, C.A.; Heckman, N.M.; Ingraham, M.D.; Robinson, D.; Boyce, B.L.; Short, M.P.; Hattar, K. Listening to Radiation Damage In Situ: Passive and Active Acoustic Techniques. *JOM* **2020**, *72*, 197–209. [CrossRef]
80. Girard, L.; Beutel, J.; Gruber, S.; Hunziker, J.; Lim, R.; Weber, R. A custom acoustic emission monitoring system for harsh environments: Application to freezing-induced damage in alpine rock walls. *Geosci. Instrum. Methods Data Syst.* **2012**, *1*, 155–167. [CrossRef]
81. Reiweger, J.; Mayer, K.; Steiner, K.; Dual, J.; Schweizer, J. Measuring and localizing acoustic emission events in snow prior to fracture. *Cold Reg. Sci. Technol.* **2015**, *110*, 160–169. [CrossRef]
82. Ledesma, R.I.; Palmieri, F.L.; Lin, Y.; Belcher, M.A.; Ferriell, D.R.; Thomas, S.K.; Connell, J.W. Picosecond laser surface treatment and analysis of thermoplastic composites for structural adhesive bonding. *Composites Part B* **2020**, *191*, 107939. [CrossRef]
83. ASTM E751. Standard Practice for Acoustic Emission Monitoring During Resistance Spot-Welding. *Am. Soc. Test. Mater. Int.* **2017**. [CrossRef]
84. Felux, M.W. Acoustic Emission Monitoring on Bridges under Regular Operating Conditions. Ph.D. Thesis, ETHZ, Zürich, Switzerland, 2016. No. 23502.
85. Proctor, T.M. An improved piezoelectric acoustic emission transducer. *J. Acoust. Soc. Am.* **1982**, *71*, 1163–1168. [CrossRef]
86. Mhamdi, L.; Schumacher, T.; Linzer, L. Development of seismology-based acoustic emission methods for civil infrastructure applications. *AIP Conf. Proc.* **2013**, *1511*, 1363–1370. [CrossRef]
87. Tan, A.C.C.; Kaphle, M.R.; Thambiratnam, D. Structural health monitoring of bridges using acoustic emission technology. In Proceedings of the 8th International Conference on Reliability, Maintainability and Safety (ICRMS 2009), Chengdu, China, 20–24 July 2009; IEEE: Piscataway, NJ, USA, 2009; pp. 839–843. [CrossRef]
88. Nair, A.; Cai, C.S. Acoustic emission monitoring of bridges: Review and case studies. *Eng. Struct.* **2010**, *32*, 1704–1714. [CrossRef]
89. De Santis, S.; Tomor, A.K. Laboratory and field studies on the use of acoustic emission for masonry bridges. *NDT E Int.* **2013**, *55*, 64–74. [CrossRef]

90. Anay, R.; Lane, A.; Jáuregui, D.V.; Weldon, B.D.; Soltangharaei, V.; Ziehl, P. On-Site Acoustic-Emission Monitoring for a Prestressed Concrete BT-54 AASHTO Girder Bridge. *J. Perform. Constr. Facil.* **2020**, *34*, 04020034. [CrossRef]
91. Diodati, P.; Piazza, S. Simple discrimination method between False Acoustic Emission and Acoustic Emission revealed by piezoelectric sensors, in Gran Sasso mountain measurements (L). *J. Acoust. Soc. Am.* **2004**, *116*, 45–48. [CrossRef]
92. Wang, L.; Li, B.B.; Hou, J.L.; Ou, J.P. Modal analysis of Dongying Yellow River Bridge for long term monitoring. In Proceedings of the Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems, San Diego, CA, USA, 7–10 March 2011; Tomizuka, M., Ed.; SPIE: Bellingham, WA, USA, 2011; p. 79811Z. [CrossRef]
93. Tillman, A.S.; Schultz, A.E.; Campos, J.E. *Protocols and Criteria for Acoustic Emission Monitoring of Fracture-Critica l Steel Bridges*; Report MN/RC 2015-36; Minnesota Department of Transportation: Twin Cities, MN, USA, 2015; pp. 1–164.
94. Bayane, I.; Brühwiler, E. Acoustic emission and ultrasonic testing for fatigue damage detection in a RC bridge deck slab. In Proceedings of the Fifth Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures SMAR2019, Potsdam, Germany, 27–29 August 2019; Deutsche Gesellschaft für Zerstörungsfreie Prüfung DGZfP: Berlin, Germany, 2019; pp. 1–8.
95. Bayane, I. Fatigue Examination of Reinforced-Concrete Bridge Slabs Using Acoustic Emission and Strain Monitoring Data. Ph.D. Thesis, EPFL, Lausanne, Switzerland, 2021. No. 8587.
96. Wiggins, S.M.; Leifer, I.; Linke, P.; Hildebrand, J.A. Long-term acoustic monitoring at North Sea well site 22/4b. *Mar. Pet. Geol.* **2015**, *68*, 776–788. [CrossRef]
97. Brunner, A.J. From materials and components to structural health monitoring systems and smart structures: Examples from research on advanced composites. In Proceedings of the International Conference on Advanced Technology in Experimental Mechanics, atem'11, Kobe, Japan, 19–21 September 2011; Paper No. OS08F014; The Japan Society of Mechanical Engineers JSME: Tokyo, Japan, 2011; pp. 1–8.
98. Anderegg, P.; Broennimann, R.; Meier, U. Long-Term-Monitoring of CFRP-cables over almost a quarter of a century. In Proceedings of the Fifth Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures SMAR2019, Potsdam, Germany, 27–29 August 2019; Deutsche Gesellschaft für Zerstörungsfreie Prüfung (DGZfP): Berlin, Germany; pp. 1–8.
99. Brunner, A.J.; Birchmeier, M.; Melnykowycz, M.; Barbezat, M. Piezoelectric Active Fiber Composites as Sensor Elements for Structural Health Monitoring and Adaptive Material Systems. In Proceedings of the 6th International Symposium on Advanced Composite Technologies (COMP-07), Corfu, Greece, 16–18 May 2007; Paper No.037. pp. 1–8.
100. Pandey, A.; Arockiarajan, A. An experimental and theoretical fatigue study on macro fiber composite (MFC) under thermo-mechanical loadings. *Eur. J. Mech. A/Solids* **2017**, *66*, 26–44. [CrossRef]
101. Li, B.M.; Wang, X.L.; Bai, M.D.; Shen, Y. Improvement of curing reaction activity of one-component room temperature-curable epoxy adhesive by the addition of functionalized graphene oxide. *Int. J. Adhes. Adhes.* **2020**, *98*, 102537. [CrossRef]
102. Kornmann, X.; Huber, C.; Barbezat, M.; Brunner, A.J. Active Fibre Composites: Sensors and Actuators for Smart Composite Structures. In Proceedings of the 11th European Conference on Composite Materials (ECCM-11), Rhodos, Greece, 31 May–3 June 2004; Paper B074. Galiotis, C., Ed.; European Society for Composite Materials: Rhodes, Greece, 2014; pp. 1–9.
103. Noma, H.; Ushijima, E.; Ooishi, Y.; Akiyama, M.; Miyoshi, N.; Kishi, K.; Tabaru, T.; Oshima, I.; Kakami, A.; Kamaohara, T. Development of High-Temperature Acoustic Emission Sensor using Aluminum Nitride Thin Film. *Adv. Mats. Res.* **2006**, *13–14*, 111–116. [CrossRef]
104. Pappas, G.; Botsis, J. Intralaminar fracture of unidirectional carbon/epoxy composite: Experimental results and numerical analysis. *Int. J. Solids Struct.* **2016**, *85–86*, 114–124. [CrossRef]
105. Castaigns, M.; Hosten, B. Ultrasonic guided waves for health monitoring of high-pressure composite tanks. *NDT E Int.* **2008**, *41*, 648–655. [CrossRef]
106. Todoroki, A.; Tanaka, Y. Delamination identification of cross-ply graphite/epoxy composite beams using electric resistance change method. *Compos. Sci. Technol.* **2002**, *62*, 629–639. [CrossRef]
107. Yamane, T.; Todoroki, A. Doublet analysis of changes in electric potential induced by delamination cracks in carbon-fiber-reinforced polymer laminates. *Compos. Struct.* **2017**, *176*, 217–224. [CrossRef]
108. Giurgiutiu, V. SHM of Fatigue Degradation and Other In-Service Damage of Aerospace Composites. In *Structural Health Monitoring of Aerospace Composites*, 1st ed.; Giurgiutiu, V., Ed.; Elsevier: Amsterdam, The Netherlands, 2015; pp. 395–434. [CrossRef]
109. Manthei, G.; Eisenblätter, J.; Spies, T.; Eilers, G. Source Parameters of Acoustic Emission Events in Salt Rock. *J. Acoust. Em.* **2001**, *19*, 100–108.
110. Manthei, G.; TH Mittelhessen, Giessen, Hessen, Germany. Personal communication, 2021.
111. EN 13477-2. Non-Destructive Testing—Acoustic Emission—Equipment Characterisation—Part 2: Verification of Operating Characteristic. Available online: https://standards.iteh.ai/catalog/standards/cen/8aa59426-a5a2-4a4f-bfce-8281fcfffe13/en-13477-2-2010 (accessed on 14 November 2021).
112. ASTM E750. Standard Practice for Characterizing Acoustic Emission Instrumentation. *Am. Soc. Test. Mater. Int.* **2020**. [CrossRef]
113. Birolini, A. *Reliability Engineering—Theory and Practice*, 8th ed.; Springer Nature: Berlin, Germany, 2017; Volume I–XVII, pp. 1–651. [CrossRef]
114. Yuen, J.H.; Resch, G.M.; Stelzried, C.T. Telecommunications Technology Development for the Deep Space Network. *Acta Astronaut.* **1991**, *25*, 51–60. [CrossRef]

115. Geldzahler, B.J.; Rush, J.J.; Deutsch, L.J.; Statman, J.L. Engineering the Next Generation Deep Space Network. In Proceedings of the IEEE/MTT-S, International Microwave Symposium, Honolulu, HI, USA, 3–8 June 2007; IEEE: Piscataway, NJ, USA, 2007; pp. 931–934. [CrossRef]
116. Brunner, A.J.; Kühnicke, H.; Oemus, M.; Schubert, L.; Trattnig, H. Drahtlose Übertragung von Schallemissionssignalen bei Strukturüberwachung: Anforderungen. In *22. Kolloquium Schallemission und 3. Anwenderseminar Zustandsüberwachung mit geführten Wellen, Karlsruhe Germany, 27–28 March 2019*; Deutsche Gesellschaft für Zerstörungsfreie Prüfung (DGZfP): Berlin, Germany, 2019; Volume 14, pp. 1–8. (In German)
117. Jasper, L.E.Z.; Xaypraseuth, P. Data Production of Past and Future NASA Missions. In Proceedings of the 2017 IEEE Aerospace Conference, Big Sky, MT, USA, 3–11 March 2017; IEEE: Piscataway, NJ, USA, 2017; pp. 1–11. [CrossRef]
118. Liu, Z.W.; He, J.Y.; Ramanujan, R.V. Significant progress of grain boundary diffusion process for cost effective rare earth permanent magnets: A review. *Mater. Des.* **2021**, *209*, 110004. [CrossRef]
119. Physical Acoustics Corporation. High Temperature Sensors. Available online: https://www.physicalacoustics.com/high-temperature/ (accessed on 14 November 2021).
120. Vallen GmbH, High/Low Temperature Sensors. Available online: https://www.vallen.de/sensors/standard-frequency-sensors-100-400-khz/vs160-ns/ (accessed on 14 November 2021).
121. Jain, A.; Prashanth, K.J.; Sharma, A.K.; Jain, A.; Rashmi, P.N. Dielectric and Piezoelectric Properties of PVDF/PZT Composites: A Review. *Polym. Eng. Sci.* **2015**, *55*, 1589–1616. [CrossRef]
122. Bowen, C.R.; Taylor, J.; Le Boulbar, E.; Zabek, D.; Chauhan, A.; Vaish, R. Pyroelectric materials and devices for energy harvesting applications. *Energy Environ. Sci.* **2014**, *7*, 3836–3856. [CrossRef]
123. Wallau, W.; Pirskawetz, S.; Voland, K.; Meng, B. Continuous expansion measurement in accelerated concrete prism testing for verifying ASR-expansion models. *Mater. Struct.* **2018**, *51*, 79. [CrossRef]