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Special Issue

AE and Related NDT for Damage Evaluation of Civil Structures

Identification of damage mechanisms in fiber-reinforced polymer-matrix composites with Acoustic Emission and the challenge of assessing structural integrity and service-life

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HIGHLIGHTS

- Identification of microscopic damage mechanisms from acoustic emission signals.
- Fiber-reinforced polymer-matrix specimens with single dominant damage mechanism.
- Single dominant damage mechanisms active in limited volume or at selected time/load.
- Extrapolating from microscopic damage mechanisms to structural integrity.

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ABSTRACT

Acoustic emission (AE) analysis for identifying microscopic damage mechanisms in fiber-reinforced polymer (FRP) composites has a long history. Recently, combining unsupervised pattern recognition with Finite Element Modelling (FEM) of signal generation, propagation, and sensor transfer function yielded source mechanism identifications of located sources for laboratory-scale FRP composite specimens. Designing FRP specimens yielding one specific damage mechanism that dominates the damage behavior, at least for selected stages of the damage development, allows for validating the pattern recognition-simulation approach for identifying the damage mechanisms. The challenge of using identified source mechanisms of located AE signals for structural integrity assessment is also discussed.

1. Introduction

Continuous fiber-reinforced polymer-matrix (FRP) composites are anisotropic or orthotropic materials with at least two distinct constituents, namely fibers (e.g., carbon, glass, aramide, basalt, or combinations of different fiber types) and the matrix polymer (thermosets, e.g., epoxy, or thermoplastics, e.g., polyamide or polyphenylene sulfide) into which the fibers are embedded. In many applications, the polymer-matrix contains fillers and additives to reduce cost or to improve properties and durability. Fibers can be arranged in many different ways, e.g., unidirectionally, multidirectionally, as woven rovings or as three-dimensional reinforcement. This yields a morphology of the FRP composites in which several types of damage mechanisms, covering different length scales from the nanometer-scale up can be activated by quasi-static or cyclic mechanical, thermal or thermo-mechanical loads [1–3]. Matrix cracks can cover a wide range of scales, from sub-micrometer to several millimeters, and of course may continue growing under service loads. Coalescence of matrix cracks can lead to larger areas of separation in the matrix polymers, such as delaminations between fiber plies. Fiber-matrix debonding along the fiber-matrix interface may occur over distances from a few micrometers to several tens of micrometers or more. Fiber breaks combined with fiber-matrix debonding may lead to fiber pull-out [4] and hence to friction between fiber and matrix. Friction may also occur between crack surfaces in the matrix polymer or in delaminations, especially under cyclic fatigue loads [5].

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Beside the service loads, there are unintentional loading events such as foreign object impact that can cause damage in FRP composites. Depending on the impact energy, there may be no or barely visible indications on the surface of the FRP composite, while in the interior, significant damage, often in the form of delaminations, sometimes in multiple layers, is caused [6]. Manufacturing and processing of FRP composites can yield porosity or induce residual internal stresses in the matrix-polymer that can play a role in damage initiation and evolution [7]. Such manufacturing and processing defects may act as sites for damage initiation or contribute to the growth of defects induced by loads during service. Specific environments also contribute to damage accumulation, e.g., by moisture uptake leading to matrix softening or swelling, or by temperature variation producing cycles of thermal contraction and expansion and hence thermo-mechanical fatigue [2]. While the stochastic occurrence of each single distributed, microscopic damage event may not significantly affect the performance and behavior of FRP structures or elements, growth and coalescence of localized, small defects with time result in measurable stiffness degradation and finally significant damage compromising their structural integrity.

Applications of FRP composites comprise transportation, specifically aerospace [8] and automotive [9], or sporting goods, but they are also increasingly used in infrastructure, e.g., for design of lightweight civil engineering elements [10], or for strengthening of concrete structures [11].

In order to characterize the complex damage initiation and propagation behavior in FRP composite materials and FRP structures, Acoustic Emission (AE) [12,13] can be applied to, e.g., analyzing damage accumulation in FRP laminates [14], or in-service monitoring of civil engineering structures made of concrete or concrete reinforced with FRP [15]. For load-bearing FRP structures, quantitative structural integrity assessment, or service-life estimates are essential. Since AE, besides for characterization of microscopic damage mechanisms in many materials [5,13,14] can also be applied for structural health monitoring [15,16], there is potential for developing AE-based, multi-scale damage models for FRP composite structures. Two specific aspects of this are discussed in more detail here, namely, first how current approaches for identifying microscopic damage mechanisms in FRP composites can be validated, and second, whether identification of these microscopic mechanisms producing damage and their location in large-scale FRP structures can provide quantitative information on structural integrity.

2. Identification of Acoustic Emission (AE) signal source mechanisms in FRP composites

The identification of the microscopic damage mechanisms that occur in FRP materials, components, or structures generating AE signals during load tests or in-service monitoring has been a long-term goal since the early days of AE measurements [17–20]. Already in the early days of AE analysis it was noted that AE signals recorded at the surface of test objects contained information about the underlying source mechanism(s) of the elastic waves. The relation between the source mechanism and the recorded AE signal, however, is affected by the wave excitation and propagation in the material [21], and the transfer function of the sensor as well as that of the data recording system [17]. In AE monitoring of FRP composites, first attempts at identifying the microscopic source mechanisms of the signals focused on AE signal parameter analysis, e.g., AE signal amplitudes. Formation of microcracks in the matrix, larger cracks or delaminations, and fiber breaks in laboratory-scale test specimens were assigned different AE signal amplitude ranges [18]. This approach, however, neglected the signal attenuation effects during propagation in FRP composites [21], and hence, signal amplitudes or other AE signal magnitude parameters do not provide a clear separation between different mechanisms. This holds especially in case of large-scale (several meters or more in size) FRP composite structures, where the signal propagation effects are likely to dominate. For comparing identical, laboratory-scale test coupons (not more than a few 100 mm in size), the amplitude approach yields a tentative classification of signal source mechanisms, at least in a statistical sense, i.e., with a large probability that an AE signal with a given amplitude would be caused by the respective mechanism [19]. Using recorded AE waveforms and power spectra (intensity versus frequency) obtained by Fast Fourier Transform was the next step in AE signal analysis development. It was noted that different microscopic mechanisms yielded clearly different low and high frequency contributions, where “low” and “high” was roughly distinguished by a frequency around 350 kHz [20]. This approach again, is limited to small, laboratory-scale, and essentially identical specimens. Since in structural applications FRP composite elements are frequently relatively thin, i.e., plate- or shell-like, the AE waves likely propagate as so-called Lamb-waves with at least two different modes (called symmetrical and anti-symmetrical of zero order), but may also include higher order modes with different amplitudes and wave speeds [21]. Some of these Lamb wave modes are highly dispersive and the frequency content of the AE signals hence can change significantly during propagation. In FRP composites, signal attenuation is also frequency dependent and the analysis and interpretation of power frequency spectra of the AE signals has to take into account these effects.

The most successful approach to date for identification of the microscopic damage mechanisms from recorded AE signals is using unsupervised pattern recognition combined with Finite Element Modelling (FEM) simulating model damage sources embedded in the FRP composites and the AE signals generated by them [22]. These simulations include signal propagation effects in the material as well as the transfer function of the AE sensor and the data acquisition system. Hence, AE signal source location information is required for comparing the simulations with the pattern recognition results. One example of this methodology applied to mode I delamination propagation in FRP composites is discussed by Sause et al. [14] in detail. Sufficiently accurate AE signal source location in FRP composite elements, however, may prove difficult for two reasons: First, the material is often anisotropic or orthotropic and, second, frequently shows relatively high signal attenuation. In typical thin plate- or shell-like FRP elements, dispersion of the AE signals, essentially Lamb wave modes, during propagation further affects the measured waveforms [21]. Recent progress in AE signal source location seems to indicate that the achievable location accuracy allows for structural health monitoring with AE [23]. Combining these experimental and simulation methods, in principle, resolves the AE analysis problems already discussed in [17]. It can be noted that, even though this has not been tried on large-scale FRP structures, e.g., with sizes of several meters to several tens of meters or more, there is potential to develop this methodology for application on larger-scales than those used so far. Of course, the required detailed modelling may consume extensive computational power, but there is no indication that progress in computer technology is reaching significant limits soon.

An alternative for assigning damage mechanism to AE signal clusters form pattern recognition that has been explored for small-scale specimens (a few centimeters at most) is the use of in situ non-destructive test methods simultaneous with the AE monitoring of the load tests. In situ projection X-ray radiography using a contrast agent and recorded with a video frequency of 25 Hz of quasi-static delamination tests under mode I tensile opening indicated periodic variation in the propagation speed of the