ADVANCES IN IN-SITU MONITORING OF FIBER REINFORCED COMPOSITES

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Keywords: in-situ, full-field, digital image correlation, computed tomography, acoustic emission, electromagnetic emission

Abstract

Failure of fibre reinforced composites is a process that starts on the microscopic scale, that undergoes growth in size until reaching a structurally relevant extent on the macroscopic scale. Due to the complexity of the fibre architecture seen in today's composites the initiation and evolution of such damage is a complex procedure. In mechanical testing this is often solely reflected as extreme value, such as the ultimate stress the composite can withstand. Today many mature methods are established to detect and record the occurrence of damage in a composite material in-situ. As function of the applied load, this allows to follow the hierarchical evolution of damage more closely and may be used to define limit loads for the structure or material under test. Among these numerous methods, digital image correlation, acoustic emission, electromagnetic emission and computed tomography are reviewed more closely herein.

1. Introduction

There is an ongoing discussion regarding the testing methods involved to obtain material properties of fibre reinforced polymers. Present standards to obtain material properties for fibre reinforced composites focus on the signatures of load-displacement curves or stress-strain curves to deduce angle dependent moduli or strength values. However, for some cases such global stress-strain curves have only limited relevance to the determination of the true (or required) material properties [1]. Since microscopic failure precedes the ultimate failure of the test specimen on the macroscopic scale, it is doubtful if maximum values of stress-strain curves are the correct way to derive relevant material properties. The heterogeneity and anisotropy on the mesoscopic scale can often induce extremely different stress and strain states than expected from the macroscopic loading condition. In particular, the individual layers of a laminate are subject to constraining effects of the neighbouring layers and thus exhibit stress states distinctly different to the global average. After initiation of first failure on the microscopic scale a complex interplay of failure mechanisms initiates that involves mechanisms on length-scales spanning from the atomistic scale to the dimensions of the test specimen. The loading conditions, the fibre architecture, fibre volume fraction and the fracture behaviour of the matrix material all contribute to the ability of the material to survive upon further loading until finally ultimate failure occurs on the macroscopic scale. Due to the statistically driven initiation and evolution of microscopic failure, fibre reinforced polymers have the reputation to typically exhibit a large scatter of material properties. Consequently, one way to approach this challenge is to improve the testing methods involved to provide an in-situ detection of failure, i.e. to identify the occurrence of particular failure mechanisms as function of the applied load.

In this context, one obvious possibility is the application of in-situ microscopy. This yields continuous observation, but the imaging process is either restricted to surface observations using optical microscopy or electron microscopy and is limited to the specimen size or resolution as in computed tomography (CT). As an alternative for surface and near surface, digital image correlation (DIC) can add valuable information to spot damaged areas by sudden changes in the strain field. In the same way as the ear complements the eye, the detection of acoustic emission (AE) can act as complementary method to imaging methods in order to detect failure initiation and to track growth of damage in the full volume of the specimen. Also the generation of electromagnetic emission (EME) during crack initiation and crack growth is a non-destructive method useful for online monitoring of failure in fibre reinforced polymers. Furthermore, methods such as thermography, guided wave testing, vibrometry, X-Ray diffraction, electrical resistance measurements and many more have been applied to detect the in-situ occurrence of failure [2]–[11]. Among the multitude of advances that happened within the last decade, just few representative examples are presented in the following to develop a first understanding of the individual capabilities.

2. Digital image correlation (DIC)

The idea of DIC techniques is to yield a quantitative measure of motion, motion velocity and deformation occurring between two subsequently acquired images of an object under load [12]. Shooting images of Speckle-patterns applied on the surface of a test specimen, this can be used to quantitatively measure the strain values in the full field of view. Traditionally this is used to avoid/replace strain gages with quite similar accuracy [13], [14]. However, the availability of high-resolution cameras nowadays also enables further analysis based on the full-field information. It is of high value to compare to numerical computation results, but also to visualize strain concentration effects as exemplarily seen in Fig. 1. Here, the formation of off-axis cracks in a quasi-isotropic laminate is well seen in local, stripe-like strain concentrations following the orientation of the plies close to the surface. The sensitivity of DIC as function of crack size, laminate type and depth position in this context has just recently been assessed by experiments and numerical methods [1], [15].

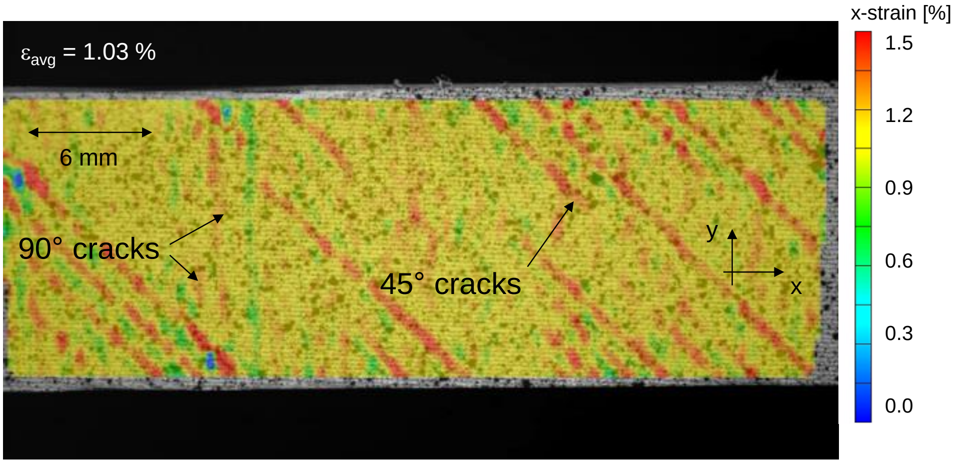

Figure 1. Example for strain concentration effects due to formation of off-axis cracks in quasi-isotropic laminate.

3. Acoustic emission (AE)

AE analysis is about the detection and interpretation of ultrasonic waves caused by rapid internal displacements, such as the formation and propagation of cracks in fibre reinforced materials. During propagation of the emitted acoustic wave, the characteristics of the signal (e.g. frequency content) suffer from attenuation, dispersion and propagation in guiding media. In addition, the characteristics of the signals detected at the surface of the solid are further altered by the detection process using piezoelectric sensors.

AE has been used for a long time to monitor the occurrence of failure in composite materials on the material level as well as on the level of structural components [16], [17].

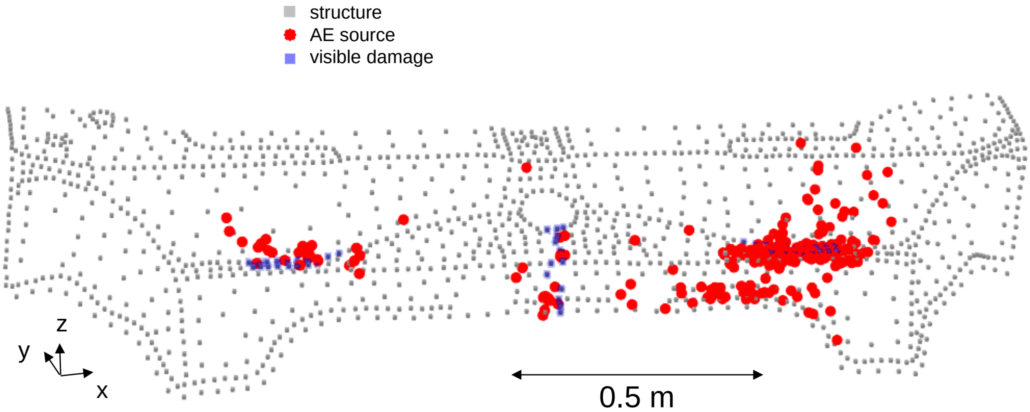

Figure 2. Example for AE source localization in structural composite part.

Primary distinction can be made between solely detecting AE signals as indication of active failure, localizing signals using sensor networks and identifying signals using dedicated data analysis. Especially for source localization and source identification substantial advances have been made to provide reliable tools for use with composite materials. These benefit from the simultaneous development of numerical methods to cover the full chain of AE including source mechanics, wave propagation and signal detection [18]–[20]. Recently proposed methods for source localization procedures use artificial neural networks to deal with the complexity of wave propagation encountered in typical fibre reinforced composites [21]. As seen in the exemplary data from 3-point bending in Fig. 2 these provide very high accuracy for application to 3D-localization in composite structural parts, which are beyond the capabilities of traditional methods. For source identification, a pattern recognition approach has been proposed [22], which follows the principle ideas also outlined by many other research groups [23]–[37]. Using such approaches AE is capable of distinguishing the occurrence of different failure mechanisms such as matrix cracking, interfacial failure or fibre breakage (details provided in [1]).

4. Electromagnetic emission (EME)

EME analysis is a non-destructive measurement technique to monitor crack formation and propagation. Many proposals have been made in literature to describe the actual cause of EME, but so far no general agreement on the source mechanism has been reached. Most descriptions agree that the break of bonds during crack formation causes a generation of electric charges at the surface of the crack, which then undergo a sudden spatial movement (the latter being also the cause of AE). Such moving charges in space and time are known to generate electromagnetic fields which can be detected in the near-field of the source. This results in signals of similar dynamics as AE signals (cf. Fig. 3), but comes with several advantages. First, the EME signals are not influenced by the signal propagation, so they provide a direct observation window on the crack source. Second, they were found to show a distinct radiation pattern [38], which can be used to inversely derive the orientation of the crack surface [1]. Third, the detection systems are ideally flat with frequency and their bandwidth is just limited by the acquisition system, so the full frequency of the source dynamics can be used for interpretation. This can be used to quantify the rise-time of the crack source and the crack velocity [1].

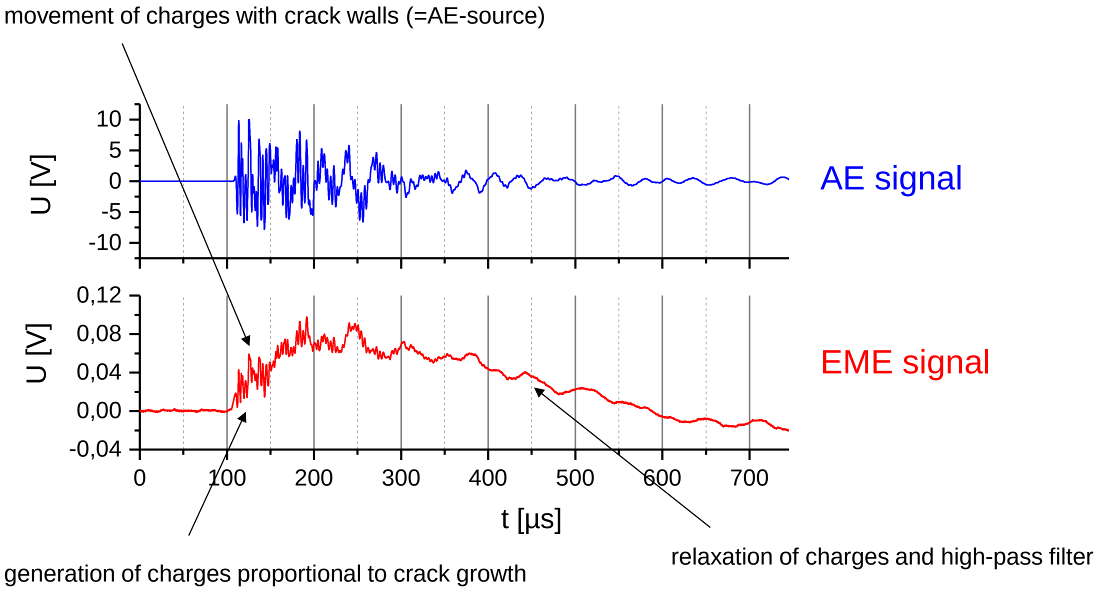

Figure 3. Comparison of AE and EME signal detected during Mode-I testing as described in [1] with signal contributions to EME signal assigned by arrows.

5. In-situ computed tomography (CT)

Complementary to the conventional in-situ imaging methods, several research groups demonstrated the use of X-Ray imaging to obtain information on the damage progress in fibre reinforced materials. The main advantage of X-Rays compared to light is their ability to penetrate the specimen and therefore to obtain volumetric information. The possibility to use computed tomography for visualization of internal damage states has become a standard method already. Some groups have been using synchrotron radiation in combination with in-situ loading stages to carry out volumetric imaging of miniature specimens under mechanical load, investigating the failure of fibre reinforced materials under various load conditions [39]–[45]. Such microscopic imaging of the specimen intuitively allows to track the initiation of damage in the interior and to deduce the interaction between different failure mechanisms at increasing load levels. As seen in Fig. 4 in exemplary images using a commercial X-Ray computed tomography device, the level of detail reached in small specimens is sufficiently high to visualize details of the fracture mode occurring in different load configurations and is even sufficient to spot single fibre filaments (i.e. < 1µm voxel size). This high resolution gives rise to numerous investigations to track the occurrence and accumulation of failure in composite materials under mechanical load in-situ. The term “in-situ” in this context typically refers to load-hold cycles with intermediate scanning. That way damage is first introduced and existing damage states are kept under load.

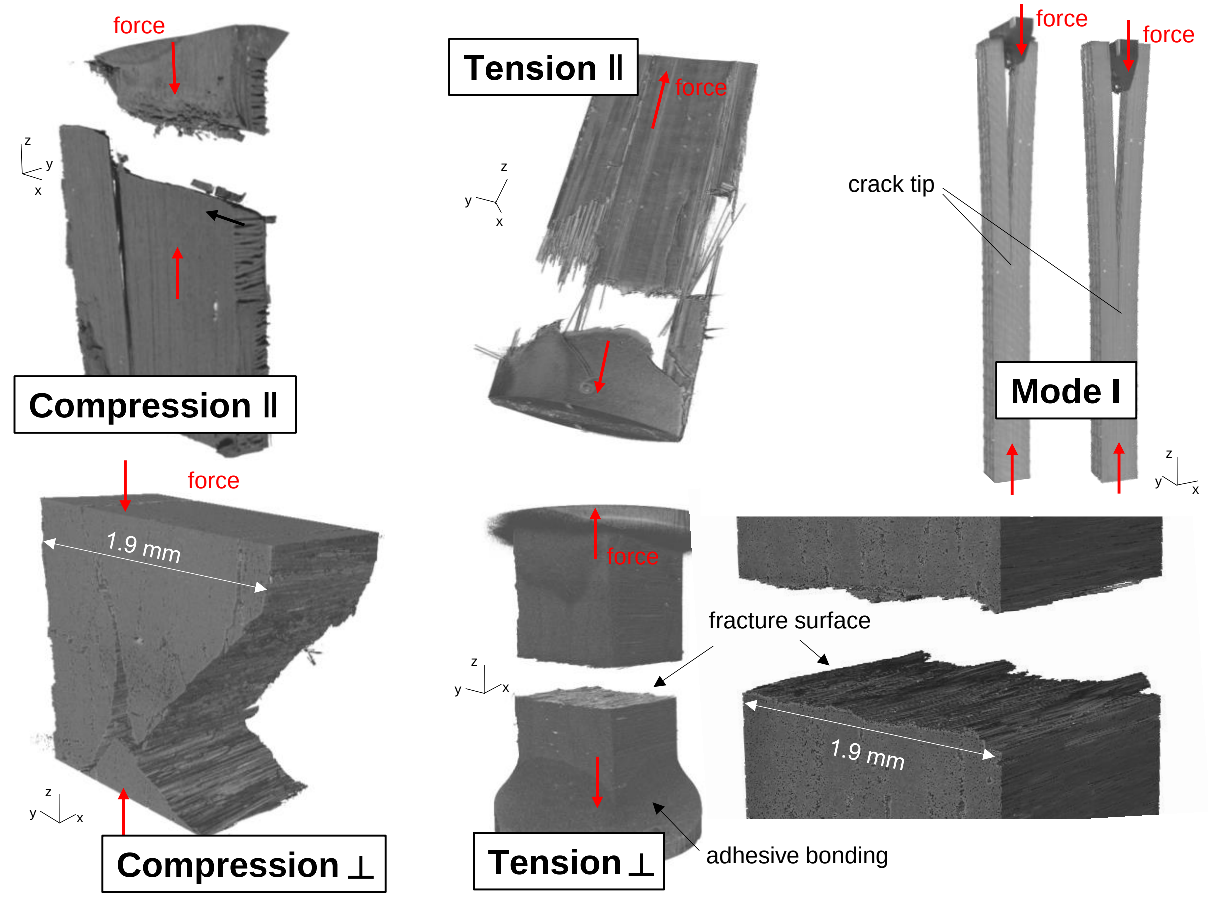

Figure 4. Examples of failure modes acquired in-situ using high-resolution computed tomography imaging.

6. Summary

Using modern in-situ methods it is feasible to accompany regular mechanical testing procedures to improve the reliability of the test results and to increase the understanding on how failure occurs in the material. Clearly, this short review may only provide a first look on this comprehensive topic, so the interested reader is encouraged to take a closer look at the original publications cited throughout the text.

Acknowledgments

Financial support was provided by a number of sources. I gratefully acknowledge the financial support by the Federal Ministry of Education and Research (BMBF) for funding the joint research projects MAI zfp and MAI plast within the leading edge cluster MAI Carbon, the joint research project FORCiM³A funded by the Bavarian Research Foundation, the German Research Foundation (DFG) for funding the research project HO 955/8-1 and HO 955/8-2, the Free state of Bavaria for funding of the project ComBo within the program „BayernFIT“ and the Free state of Bavaria for funding the project CFK-Integral within the program „Neue Materialien für Bayern“.

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