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Application of Real-Time Photoelastic Analysis to Single Fibre Fragmentation Tests

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Abstract. One of our main research areas is the trans-scale modelling of damage in composite materials, which consist of a polymer matrix and carbon or glass fibres in different material combinations and geometrical arrangements. From the local stress redistribution in the fibre-matrix interphase and in the surrounding matrix material information on the parameters of microscopic damage models for composite materials can be obtained. Owing to the difficult interface characterisation based on the properties of the single material components, a photoelastic analysis of single fibre fragmentation tests is performed. In addition to the qualitative visual interpretation in polarized light, an enhanced quantitative analysis in combination with digital photoelasticity using a four image phase shifting method will be applied [1]. As the sequential capturing of images might cause incorrect results, these four pictures are grabbed simultaneously. This allows for continuous testing. Additionally, errors due to the relaxation behaviour of the matrix material can be avoided. To this, a modular optical system consisting of a variable long distance microscope and a beam dividing module proposed by [2] was developed. It allows for the simultaneous projection of four different filtered images of one microscopic scene to the four quadrants of a CCD chip. This special equipment gives the possibility to apply quantitative photoelasticity to tensile tests performed on standard testing machines. This paper explains the measurement hardware and discusses the main problems and realised solutions from picture capturing through image processing to real-time photoelastic analysis at the present state of development. Exemplary results for the qualitative analysis of selected material combinations and different manufacturing processes are shown.

Introduction

On the one hand, modern fibre reinforced composites are more and more used in high technology applications which require a very high reliability and efficiency. On the other, the knowledge of these materials is still based on the experimental investigation of their macroscopic material behaviour. However, the effective properties result from the complex material structure at lower scales. The analysis of the characteristics on the meso and micro scale could therefore provide the understanding and prediction of the effective material behaviour on higher scales. An important role plays the understanding and the knowledge of the interface properties and behaviour between fibre and matrix under load.

The interaction between fibre and matrix can be studied by means of single fibre composites [3]. In this context the optical observation of the damage evolution was established as a special investigation method [4]. From a number of possible experiments the single fibre fragmentation test (SFFT) is often chosen to perform optical observations and measurements during the application of a tensile load to the specimen [5]. In addition to the acquisition of global load-displacement curves, the SFFT allows the qualitative optical investigation of the damage evolution and the quantitative measurement of the local stress distribution in the matrix material. Assuming a gradual destruction

of the embedded fibre all stages of the micromechanical damage process can be studied. This includes adhesion of the intact fibre matrix interface, friction in the destroyed interface and stress redistribution in the vicinity of the opening break gap.
This paper describes the preparation of specimen, the experimental setup and presents the first orientating tests which will be the basis for systematic experimental investigations in future work.

Preparation of specimen for optically analysed SFFT

The SFFT specimen consists of a thermoset matrix (HT2, R&G Faserverbundwerkstoffe GmbH Waldenbuch) and an embedded commercial glass fibre with a diameter of 20 micrometer or carbon fibre with a diameter of 7 micrometer. Due to necessary cross section dimensions for SFFT a dogbone shaped specimen with a measuring length of 20 millimetres, a quadratic cross section of 4 square millimetres and a shoulder radius of 15 millimetres is chosen.
The special configuration of the SFFT specimen and the requirements to enable an optical observation necessitate a precise and reproducible manufacturing process. The specimen are produced by filling degassed uncured epoxy resin into special silicon moulds, which were fabricated out of steel forms with the shape of the specimen (fig. 1). Notches cut into the silicon moulds define the location of the fibre in the middle of the specimen cross section. Single fibres are manually extracted from commercial yarns and fixed at the notches. The preparation of the silicon moulds enables multiple fibre orientations. At first, specimens with a longitudinal fibre orientation (fig. 2) have been produced. After filling the moulds with epoxy resin the later measurement area is covered by a glass plate to guarantee a high surface quality and a uniform cross section shape. The specimen is cured inside an air pressure vessel and post-cured according to the resin specifications.

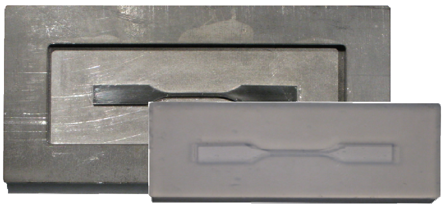

Fig. 1: Steel form and silicon mould for specimen production

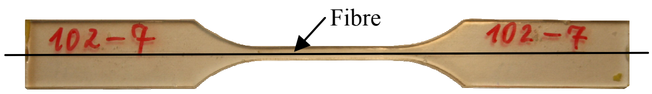

Fig. 2: Specimen with longitudinal embedded carbon

Test setup for microscopically analysed SFFT

The experiments are performed on the commercial tensile testing machine “Instron 5566” with a 5kN load cell. To allow a minimal working distance for the optical observation, special specimen grips were developed and used. The microscopic investigations on the whole measurement area of the produced specimen require a translation of the optical measurement system relative to the loaded specimen. During the translation over the large measuring length features to keep the fibre in focus and to control the exposure of the image sensor are needed. To ensure an adequate frame rate at optimal image quality an automated video controlled translation unit was developed and installed. This system ensures continuous image capturing for every segment of the measuring length while every single image is focused and its brightness is adapted to obtain optimal contrast for later interpretation. The unit is controlled by a software application based on the video signal of the measurement hardware. All captured images are saved with timestamp, coordinates, force and displacement. This additional information will be of interest for the investigation and visualization of the damage evolution.
Parallel to this equipment a second camera is used to capture images with a low frame rate for a local strain measurement. The captured images of a pattern which is applied to one lateral surface of the specimen are later analysed by using the commercial image correlation software ARAMIS from GOM mbH Braunschweig. We use the whole-field strain results for the stress-strain curve of our tensile tests.

Qualitative interpretation of the damage evolution

The qualitative analysis of the SFFT provides knowledge on the local damage evolution for a selected combination of fibre and matrix. Photoelasticity shows a higher activity in matrix regions with higher stress often resulting from inhomogeneous or defect composite components. For instance, local defects of the fibre initiate a stress rearrangement near the break gap which results in higher local photoelastic activity. The intensity and dimension of these effects can give information on the local interfacial shear strength of the fibre matrix interface. Furthermore, global information like the number of fibre breaks or the average fragment length at a certain global strain or stress state can be used to characterize the selected composite material.
FEIH et al. [6] and KIM and NAIRN [7] investigated the qualitative characteristics of the SFFT by photoelasticity. Both described a typical shape of the photoelastic effect near the fibre breaks. They suppose that a fibre break has to occur in conjunction with local interfacial damage. On further investigation they found two regions of different intensity of the photoelastic effect and deduced that this is caused by different processes in the interface. Near the gap this effect is initiated through friction inside the damaged interface. The photoelastic active region far from the gap is supposed to result from stress redistributions through the intact fibre matrix interface.

Application of the realized measurement system to selected composite materials

At the time of composing this paper orientating experiments were performed to evaluate the measurement process. The first specimen were produced from epoxy resin HT2 with the stress fringe value 16.32 N/(mm·fringe) and an embedded glass or carbon fibre. In addition to the evaluation of the measurement system these experiments are performed to obtain knowledge on the influence of different manufacturing parameters on the strength of the selected composite. Different specimen types were produced, which differ in the embedded fibre, the application of air pressure during the curing process and the usage of a post curing procedure. During these first experiments the optical measurement system was still under construction. Therefore only a qualitative analysis of the resulting images was performed with a simple long distance microscope with comparable specifications (fig. 4). A manually configured set of filter plates enables the capturing of photoelastic images.
As expected, the non post-cured specimen displayed a weak interface bonding, which appeared as non-intensive photoelastic effects along the whole length of the measurement range. At the same time only some rare fibre breaks occurred until the failure of the specimen at high global strain.
Figure 3 shows a non-post-cured specimen with a tensile load applied at a constant displacement rate v=0.04mm/min. The image was captured at a tensile stress of 33.75 MPa and a global strain of 2.75 %. Referring to [7] the brighter regions are suspected to represent high shear strain at an intact interface region while the darker areas are related to friction at a failed interface.

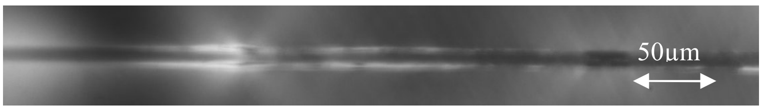

Fig. 3: Photoelastic effects showing the debonding along the whole length of a glass fibre

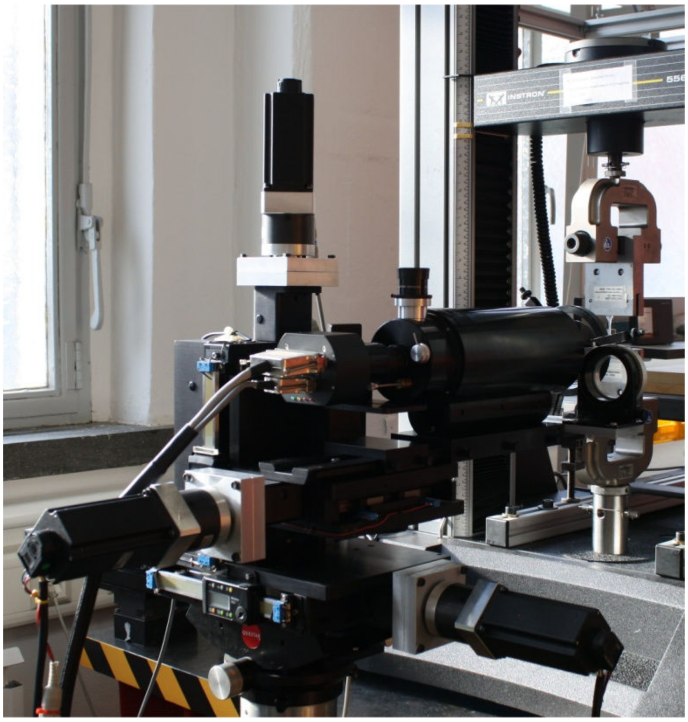

Fig. 4: First experiments with tensile testing machine and a long distance microscope with polarizers

The post-cured specimen showed a contrary behaviour. The effects described by [6] and [7] could be reproduced. Intensive photoelastic effects occured in the vicinity of a fibre break gap. An increasing number of fibre breaks and saturation at higher global strain were observed. The average fragment length at damage saturation was approximately 0.5 millimetre. Figure 5 shows the photoelastic effect near the gap of the broken carbon fibre embedded in post-cured epoxy. One can see the typical shape of the photoelastic effect described by [7].

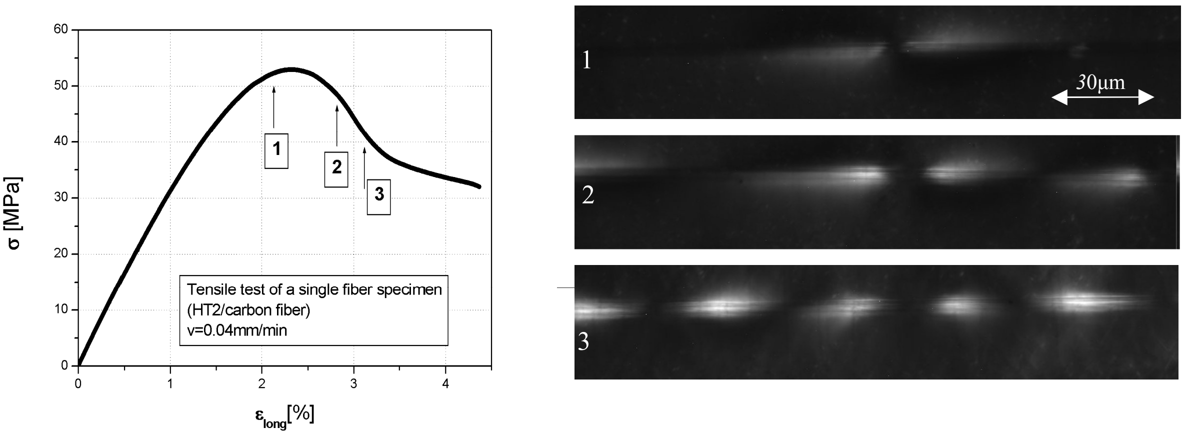

Fig. 5: Photoelastic effects in linear polarized light as a result of breaks at a carbon fibre

Optical measurement system for simultaneous capturing of four phase shifted images of one microscopic scene

The observation of photoelastic effects requires a special arrangement of optical filter plates which filter the light shining through the specimen. A simple set of polarizers allows a qualitative interpretation of the photoelastic effects. For a quantitative analysis it is necessary to take at least four phase shifted images to extract the isochromatic and isoclinic parameters. The application to a dynamic scene (like the SFFT) is only useful if a set of phase shifted images can be captured simultaneously. PATTERSON and WANG [1] first published the simultaneous capturing of four phase shifted images. Their phase stepping automated polariscope was used to quantify the shear stress in the matrix near by the free ends of fibres and near by crack tips of the matrix [8, 9].On this basis an own compact measurement system was built. It consists of a single-wavelength light source with polarizer, and quarterwaveplate and a beam splitter module with filter brackets. The beam splitter module realises the acquisition of four images of the same scene to the four quadrants of the image sensor. In every optical path there are two filter plates attached. In combination with the set of polarizer and quarterwaveplate at the light source side these polarizer and quarterwaveplates are configured analogous to [1] to produce the four differently phase shifted images (table1).

Table 1: Configuration of filter plates for phase shifting [1]

Image number	Orientation of quarter wave plate	Orientation of polarizer
1	π/4	π/4
2	0	0
3	0	-π/4
4	π/2	π/2

To be able to observe microscopic scenes, a modular long distance microscope objective is added to the described optical system. At working distances from 15 to 1430 millimetres in combination with a four mega pixel image sensor this long distance microscope offers resolutions from 1.25 to 325 micrometer per pixel. As a result of using the beam splitter a maximum effective resolution of 2.5 micrometer per pixel is possible. Long distance microscope and beam splitting module were developed by Thalheim Spezial Optik (Fig. 6).

Fig. 6: Modular image acquisition system: Light emitting unit (left), specimen, long distance microscope and beam splitter (centre), video output for an academic example of disc under diametral compression (right)

This modular system can be applied in transmission or reflection photoelastic arrangements. However, the dimension of the long distance microscope and the light source modules inhibits the usage in reflection arrangement for higher resolutions due to the necessary lower working distance.
Due to the complexity of the optical system the four phase shifted images are not absolutely geometrical congruent. Therefore, the captured images have to be corrected by image processing techniques. Based on images of a calibration object with a regular grid edge detection is performed. The detected crossings of the edges are used as reference points on which segments of the images are stretched or compressed to obtain four congruent images.
The aim of the quantitative analysis is the determination of the three-dimensional principal stress field inside the matrix material surrounding the embedded fibre which provides important information for the formulation of phenomenological damage models. This goal cannot be reached directly by photoelasticity. As the thickness of the specimen typically has to be much greater than the diameter of the embedded fibre to ensure a sufficient intensity of the photoelastic effects, the captured information can only represent integral information of the difference between the two principal stresses over the whole thickness of the specimen. This value is represented by the isochromatic value δ, which can be calculated for the used filter configuration analogous to [1] as

$$\delta = \tan^{-1}\left(\frac{i_2 - i_3}{\sin 2\theta (i_2 + i_3 - 2i_4)}\right) \tag{1}$$

with the intensity i_n of the four images and the isoclinic value θ as

$$\theta = \frac{1}{2}\tan^{-1}\left(\frac{i_2 - i_3}{i_2 + i_3 - 2i_1}\right). \tag{2}$$

In the case of the single fibre fragmentation test a theoretical idealization of the stress distribution around the fibre to a rotational symmetric model allows the determination of the searched principal shear stress field [10].

Summary

Single fibre specimens were manufactured with glass and carbon fibres. With these specimens first experiments were performed on a commercial testing machine using a long distance microscope. Damage evolution visualized in polarized light was investigated. A special polariscope, which permits the simultaneous capturing of four phase shifted images, was presented. Quantitative experiments will be performed in the next time and presented at the BSSM Conference 2010.

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