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Comparing experimental results to a numerical meso-scale approach for woven fiber reinforced plastics

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ABSTRACT

Meso-mechanical analysis, allowing for the study of local phenomena, is one of the strongest tools for the investigation of woven carbon fiber reinforced plastics (CFRP). A meso-scale representative volume element (RVE) of a twill weave CFRP ply is modeled, which consists of the yarn part, and the surrounding matrix region. The yarns are considered to be elastic and transversely isotropic. To obtain the material properties of the yarn, a hexagonal dense packing (HDP) RVE representing the microstructure inside a tow, is homogenized. Furthermore, isotropic elasto-plastic behavior is assumed for the neat matrix region at the meso-scale. The material model accounts for different yield strengths in tensile and compressive direction as well as pressure dependence. For the verification of the meso-model and their homogenized results, experiments are conducted, which provide strains in a very high local resolution as well as the global response. The numerically and experimentally obtained strain fields as well as the global stress–strain responses are compared.

1. Introduction

Increasing energy costs necessitate efficient lightweight constructions particularly in the fields of mobility and transport. For these applications, tailorable materials like woven fiber reinforced plastics (FRP) are gaining more and more importance. However, the characterization of woven composite structures is difficult. The prediction of the global FRP weave response is only possible if the internal structure is taken into account, and thus different scales need to be considered.

The scale bridging from the meso- to the macro-scale is suitably supported by a numerical meso-mechanical investigation of woven FRP [1,2]. Moreover, such a meso-mechanical investigation allows the study of phenomena caused by the non-uniformity of the woven FRP such as stress and strain localization — even under global uniform loading [3] — as well as damage initiation [4,5] and propagation [6–8], including compressive loading [9–11]. These numerical analyses build a sound basis for the computationally cheaper macro-mechanical approaches, which are used whenever the mechanical response of large parts is of interest. Therefore, scale bridging due to e.g. homogenization procedures must be applied [12].

Several attempts with different numerical and analytical methods have been made throughout the years to estimate the mechanical properties of different types of weaves. For example in [13,14] the mechanical properties of woven composites are analytically determined. The authors idealize the internal structure as a regular mosaic. This simplification leads to an inadequate representation of the crimp regions and the undulations of the consolidated roving. To overcome this problem, in [15] connected beams are used, where the connectors serve to model the stiffness of the crimp region. In [16], a semi-analytical approach accounting for the waviness of the tows and the periodic micro structure in plain weaves is proposed. Here, the homogenization for different fabric geometries to obtain the effective ply level material properties is achieved using averaged eigenstrains. Nonetheless, the model only provides linear elastic material parameters.

A similar numerical approach is presented in [17]. Therein the yarns are modeled by truss elements and the surrounding matrix by hexahedrals. Thereby, the undulation is incorporated and additional structural nonlinearities are taken into account. In [18], finite element analyses are performed on RVEs of plain weaves, which are in agreement with experimental results. Similar FE simulations are conducted in [19] in order to investigate the damage mechanisms of plain weaves using an anisotropic damage formulation for the tows and an isotropic damage evolution for the neat matrix. The proposed method is experimentally verified only for the global response under tensile loading. More recently, in

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[20,21] satin weaves are investigated in order to study the stiffness degradation and damage evolution under different loading conditions.

In any case, for the verification of the small-scale models, experimental data with a local resolution higher than the dimensions of an individual yarn is necessary [3,21]. Digital image correlation (DIC) is an advisable tool for high resolution full field strain measurements at the specimen's surface. In most cases, a second experiment must provide the global data set for the verification of the homogenized response of the meso-model. It is a challenge to achieve the same test conditions for both levels. An alternative technique to experimentally investigate damage initiation and location is to combine acoustic emission with microscopic analysis [22].

In this work, an experimental setup is proposed capable of recording both, local and global kinematic values. The strain distributions obtained for a twill weave FRP plate are compared to strain fields of an idealized meso-scale representative volume element (RVE). The latter is generated by finite element calculations under in-plane loading conditions using periodic boundary conditions with varying fiber orientations at the same deformation state. The elastic properties of the yarn are obtained by a micro-mechanical simulation of an hexagonal dense packing RVE under periodic boundary conditions. In contrast, the neat matrix domain is assumed to be elasto-plastic with different behavior in tensile and compressive direction. Finally, the experimentally obtained global recordings are compared to the homogenized stress–strain response of the meso-scale analysis.

2. Experiments

2.1. Setup

The test setup, including a Zwick Z100 testing machine and an Aramis M4 digital image correlation (DIC) system, is shown in Fig. 1. This setup allows for synchronized recording of force as well as local displacement fields and global displacement values. The load cell signal as well as the global displacement signals of the DIC system are recorded using the control software 'TestXpert II'. Analog online signal transfer — e.g. the strain in longitudinal and transversal direction, measured by the DIC system — from Aramis to the testing machine's software is realized by the integration of a 'HBM Spider 8' measuring amplifier. Time, force, cross head displacement, and nominal strain are generated by Zwick's (internal) sensors. Unfortunately, the kinematic quantities of the cross head displacement are insufficient, since the deformation of the load frame and the gliding of the grippers are added to the pure elongation of the specimen. However, Aramis supports the observation of up to ten points at the specimen's surface in the real-time-sensor (rts) mode, while simultaneously saving images for the later analysis of the whole strain field. Thus, the global kinematic quantities can be captured at the specimen in real time, providing valid global strain values. All displacement values are mapped online to a coordinate system that is parallel to the testing machine's force axis. Coded markers attached to a stiff frame at the static (upper) clamp serve as fixed points to span up the virtual coordinate system within the Aramis software. The arrangement of the specimen, the coded markers, and the measurement points on the specimen's surface within the measuring device are shown in Fig. 2.

While testing, the DIC system acts similarly to an optical extensometer. The sampling rate of the global strain values has to be very high, since in this setup the testing machine is controlled by the global length change. On the other hand, the bandwidth to stream the live images of the two cameras restricts the sampling rate, initially to 60 Hz only. To increase the sampling rate to 120 Hz, only the upper half of the cameras CCD chip is used. Thus, the amount of data that is transferred from the cameras to the computer is halved. Thereby, the height of the image is halved too, whereas the width remains the same. Since the specimens are longer than wider, the cameras are turned by 90° to use the image width to capture the full length of the specimen. In consequence, there is no need to increase the distance between the cameras and the specimen to capture the interesting domain, preserving the accuracy of the DIC setup. Thus, at least four

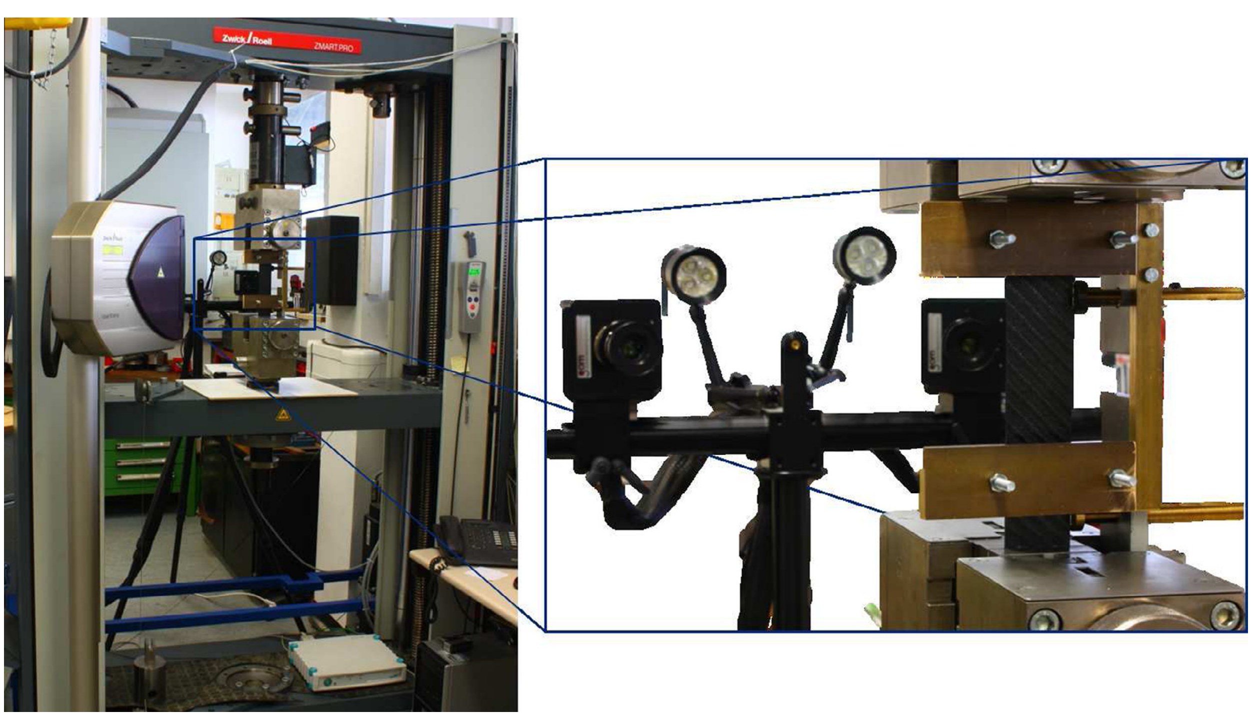

Fig. 1. Experimental setup.