Failure Behaviour of Textile Reinforced Composites under Dynamic Loading

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ABSTRACT
Novel textile reinforced composites have outstanding specific mechanical properties and superb energy absorption capabilities, which makes them excellent candidates for the application in structural lightweight components subjected to impact and crash loads. Despite their distinguished properties, textile reinforced polymeric composites have not experienced a broad application yet, mainly due to the lack of reliable material models and realistic failure models, that account for the complex mechanisms involved in the dynamic failure of such materials. In developing appropriate simulation models and failure models for textile reinforced composites under highly dynamic loading, basic experimental investigations are required to understand the complex structural behaviour and failure mechanisms. The performed experiments provide the necessary knowledge basis to develop adapted material models, which take into account the influence of the textile reinforcement structure and serve for the simulation of the impact and crash behaviour with the help of numerical programs.

1. INTRODUCTION

The load-adapted design of advanced lightweight structures made of novel textile reinforced polymers − especially with respect to highly dynamic loading conditions due to crash or impact events − requires a reliable knowledge of the strain rate dependent deformation and failure behaviour of the anisotropic material itself [1]. This article focuses on the experimental investigation of strain rate dependent material properties and the time dependent deformation and failure behaviour of textile reinforced composites. Experimental results of highly dynamic tests on glass fibre reinforced epoxy specimen with fabric and multi-layred knitted fabric reinforcement are presented. The results serve as a basis for the development of material and failure models for the numerical simulation of the structural behaviour and the assessment of spatial states of stress of textile reinforced composites due to highly dynamic loading [2-4].

2. TEST TECHNIQUES FOR HIGHLY DYNAMIC MATERIAL TESTS

Within the experimental work, basic investigations of the material's phenomena of textile reinforced composites under high strain velocities and the determination of the resulting time dependent deformation and fracture characteristics were performed. The strain rate dependent material properties are essential input data for high dynamic structural analyses.

For the determination of the strain rate dependent material properties dependent on different fibre/matrix combinations, reinforcement architectures and fibre orientations, a servo-hydraulic high-speed test unit was used (Fig. 1). The high-speed test unit enables mechanical stiffness and strength tests with velocities up to 20 m/s and maximum forces of 160 kN. This test unit differs from conventional high-speed test stands not only in the increased maximum forces and an additional temperature chamber but also by the adapted grip unit, which enables an abrupt application of the force.

Fig. 1: INSTRON-Servo-hydraulic high-speed test unit at ILK

In addition to high-speed tensile tests, impact tests were also carried out. To apply the desired impact loading on specimen plates, a loading system also known as the split Hopkinson-bar device was used, which enables impact test with velocities up to 10 m/s [5]. The particular device used, enables the impact of a titanium bar with hemispherical tip to a specimen plate, which was supported by a long brass tube(Fig. 2).

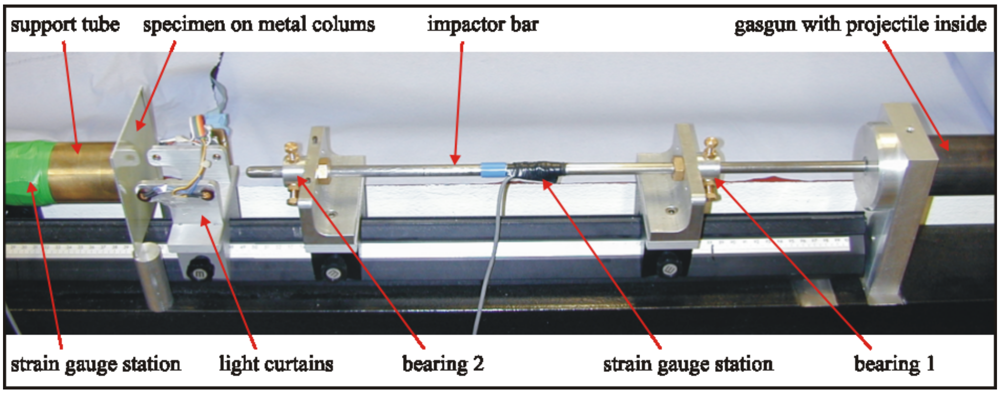

Fig. 2: Components of the Hopkinson device [6]

The projectile, accelerated by high air pressure, collides with the impacter bar of the same shape, size and mass thus enabling the kinetic energy to be transferred entirely to the impacter bar, which theoretically continues to move unstressed. Having cut through the light curtains of the timer, the impacter bar hits the specimen plate, which is leaning against the support tube. The impact causes the plate to bend and push against the support tube, which then starts to move in the direction of impact.

Only two strain gauge stations, each consisting of 4 strain gauges, are used for data acquisition. One station is in the middle of the impacter bar and the other is placed on the support tube 100 mm away from the interface with the specimen. To control the triggering and to check the initial velocity of the impacter two light curtains are installed between the impacter bar tip and the specimen plate. Before impact occurs the impacter bar tip cuts through the two light curtains and the time delay between closing the respective electric circuits is measured. During impact the generated axial strain within the impacter bar and support tube is recorded by the strain gauges and converted into a voltage using an uncompensated Wheatstone bridge. The data was acquired at the frequency of 1 MHz (one data point per µs). The recorded voltage signals were converted into force signals by multiplication with a calibration factor f [N/V]. For the determination of these factors the impacter bar as well as the support tube were statically loaded with a defined force which resulted in a certain difference of the strain gauge voltage [6].

3. HIGH-SPEED TENSILE TESTS

Primarily to the high-speed tests, the specimen geometry had to be adapted to high-speed tensile test conditions in order to get a defined fracture area. Tests on specimens with parallel edges showed multiple fractures, delaminations in the whole specimen and fracture in the grip area. Therefore, adapted specimen geometries were developed and tested [7]. A choice of tested specimens is shown in Fig. 3. It can be seen that specimens with a variable width, as is known from metallic specimens, show fractures in the notched area. Only after several optimisation loops in combination with numerical simulations an optimal specimen geometry could be found, which leads to a defined failure.

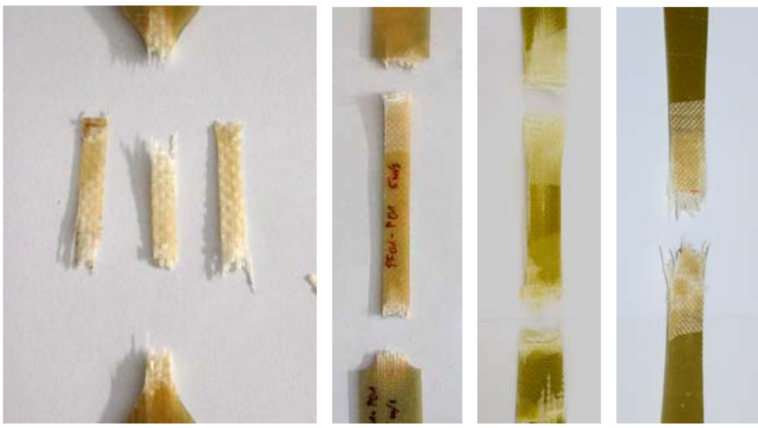

Fig. 3: Fracture types of high-speed test specimen with conventional and optimised geometries

After the manufacturing of the specimens with the help of the RTM process, first high-speed tensile tests were carried out on glass fibre reinforced specimen with a fabric reinforcement structure [7]. The strain rates were varied from 0.0004 1/s (quasi-static test) up to 40 1/s (highly dynamic test). The associated stress-strain diagrams of the single tensile tests are shown in Fig. 4. It can be seen, that the strain at failure and the tensile strength increases with an increasing strain rate. Furthermore, it was observed that the oscillation increase with increasing strain rates and lead to an additional periodic loading of the specimen. Based on subsequent investigations and modal analyses the clamping system was modified and the amplitude of the oscillation could be decreased by 80 %.

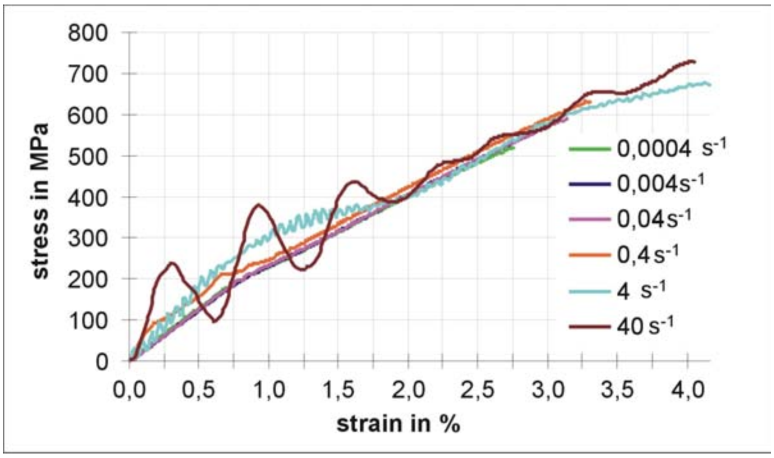

Fig. 4: Strain rate dependent stress-strain diagrams of glass fibre reinforced specimen

Moreover, after a linearisation of the measured stress strain curves in a range from 0 % to 0.9 % strain, a qualitative and quantitative increase of Young's modulus with an increasing strain rate can be observed (Fig. 5).

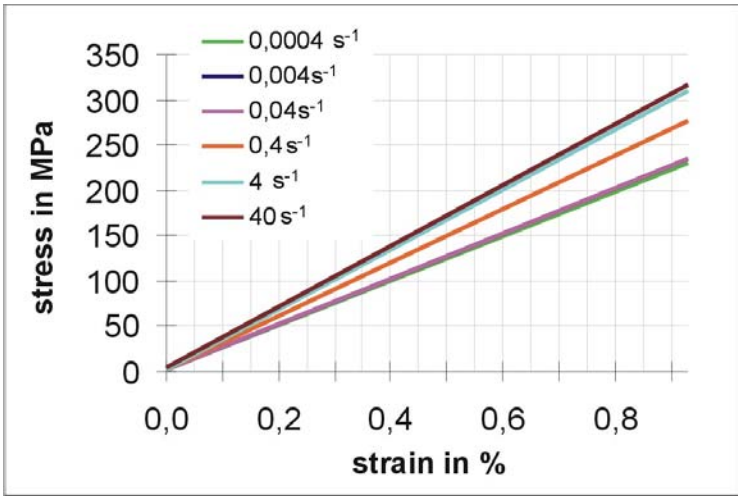

Fig. 5: Strain rate dependent stress-strain diagrams of glass fibre reinforced specimen (linearised)

Additionally, to the determination of the strain rate dependent strengths and elastic moduli the damage progress of the textile reinforced specimen is monitored using a high speed camera system HSFC Pro (PCO Computer Optics GmbH). The camera system enables the exposure of 50 million photos per second. The triggering impulse is coupled to the force signal and the trigger modus has to be adapted to the test speed. The screen sequences of the fracture progression, as for example shown in Fig. 6 for an exposure time of 100 µs, is correlated with the associated stress strain curve in order to gain information for the development of adapted damage models.

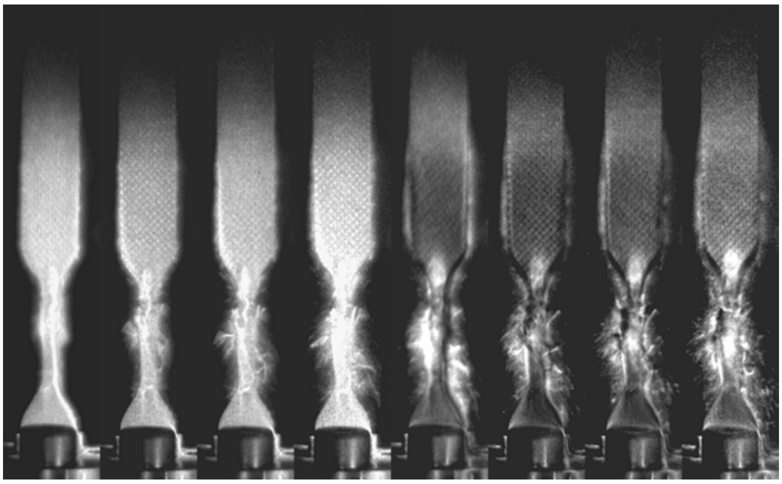

Fig. 6: Screen sequence of the fracture progression of textile reinforced GFRP specimen (exposure time 100 μs)

4. IMPACT TESTS

In numerous impact tests, failure phenomena of multi-layered knitted fabrics (MKF) made by the Institut für Textil- und Bekleidungstechnik (ITB), TU Dresden were investigated under several impact speeds. The MKF specimen with the textile architecture as illustrated in Fig. 7 are based on glass fibres and were infiltrated with an epoxy resin by the resin transfer moulding (RTM) process. Two different lay-ups were analysed: MKF 1 (consists of two layers of MKF type 1, which are arranged symmetrically) and MKF 3 (consists of one layer MKF type 3). The specimen size is 100 mm × 100 mm. The impact load is realised by a cylindrical steel impacter with a diameter of 9.8 mm.

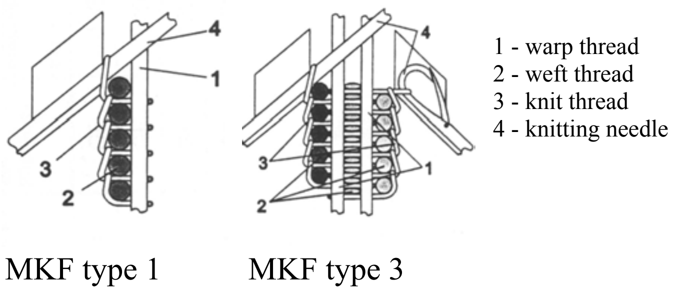

Fig. 7: Basic architecture of multi-layered knitted fabrics (MKF) of ITB [8]

The aim of the analysis consists of an evaluation of the failure behaviour of textile composites under impact loads and the description of their energy absorption capabilities. Dependent on the impact speed, different failure modes (fiber failure, inter-fiber failure and delamination) emerge with variable intensity. For the evaluation of the damage of the tested specimen optic and ultrasonic excited thermography and nonlinear vibrometry analysis were used beside the well established ultrasonic inspection (Fig. 8).

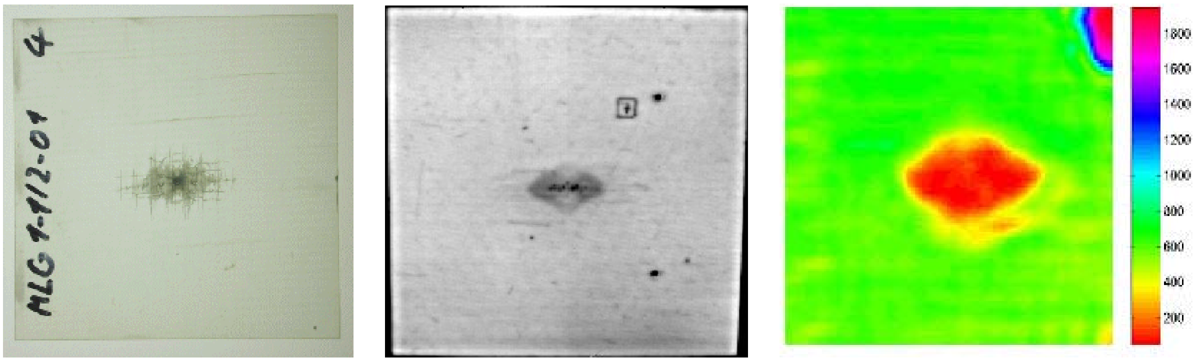

Fig. 8: Multi-layered knitted fabric test specimen after impact and associated optic excited thermography photo and ultrasonic inspection exposure

Dependent on the impacter velocity, different intensities of the fracture modes fibre failure, inter-fibre failure and delamination could be observed. A summary of the non-destructive investigations of the impact specimen is given in Fig. 9. The crack length in x- and y-direction is shown dependent on the impact velocity. The extent of the crack field in y-direction of MKF 1 is, for all impact velocities, bigger than of MKF 3, which is reasoned by an additional reinforcement in y-direction of MKF 3. In the x-direction however, the crack field of MKF 1 is smaller compared to MKF 3, although there is no additional reinforcement.

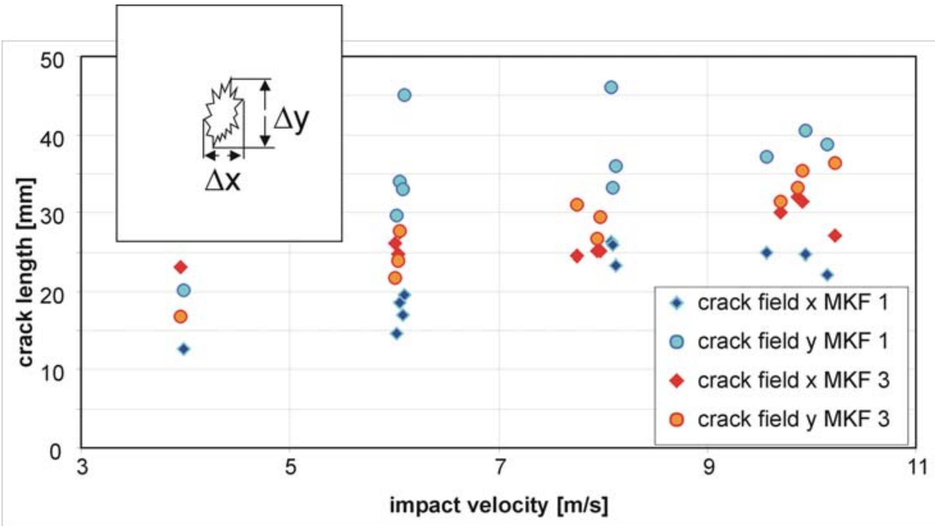

Fig. 9. Fracture extents of different MKF dependent on the impact velocity

5. CONCLUSIONS

For the development of realistic simulation models for textile reinforced lightweight structures under highly dynamic loading, such as crash or impact loads, basic experimental investigations of textile reinforced composites are necessary in order to gain an indepth knowledge about their dynamic material behaviour and failure mechanisms. This paper focuses on the analysis of material phenomena of textile reinforced composites under highly dynamic loading as well as the determination of time dependent deformation and fracture characteristic. For the experimental determination of the strain rate dependent material properties and the energy absorption capability dependent on different fibre/matrix combinations, reinforcement architectures and fibre orientations, a servo-hydraulic high-speed test unit and an impact test stand were adapted. First strain rate dependent material properties and textile specific characteristics due to impact loads were analysed. The increase of stiffness and strength with increasing strain rates was quantified for textile reinforced composites and the fracture extents of composites with multi-layered knitted fabric reinforcement due to impact loads was characterised. This experimental data serve as the basis for the development of simulation models and novel failure criteria for the realistic assessment of three-dimensional states of stress due to highly dynamical loads.

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