ANALYSIS OF THE FAILURE BEHAVIOUR OF 3D-TEXTILE REINFORCED COMPOSITES UNDER CRASH AND IMPACT LOADS

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SUMMARY: The load-adapted design of textile reinforced composites requires an assured knowledge in strain rate dependent deformation and failure behaviour especially for highly dynamic loaded structures. Basic investigations on materials phenomena of textile reinforced composites at high loading velocities and the determination of the resulting time dependent deformation and fracture characteristic are in the centre of the work. A servo hydraulic high speed tension and penetration unit (SHU) and an impact and crash test unit (ICU) are used for the determination of the materials characteristics dependent on the textile architecture, the combination of fibre and matrix and the direction of the reinforcement. Hereby, strain rate dependent and textile specific characteristics of textile reinforced GFRP-composites were determined. The failure phenomena of composites concerning the impact velocity are investigated in accompanying impact tests, which serve for the verification of numerical impact simulations. Furthermore, the experimentally determined characteristics form the basis for the acquirement of adapted failure models for the realistic assessment of 3D-loading states due to highly dynamic loads.

KEYWORDS: crash, impact, 3D-textile reinforced composites, strain rate dependence, failure analysis

INTRODUCTION

New composite materials with three-dimensional (3D-) textile reinforcement have high specific mechanical properties as well as an adjustable energy absorption capacity. Therefore, 3D-textile reinforced composites are predestined for the application in lightweight structures relevant for impact and crash. In spite of the advantageous property combination the young material group has not yet found a broad application maturity. This is to be led back in the absence of models for the description of the complex strain rate dependent material and failure behaviour what complicates a reliable dimensioning of textile-reinforced composite components for highly dynamic applications.

For the development of suitable calculation models, basic experimental investigations are necessary on textile-reinforced composites to gain established knowledge about their deformation behaviour and failure mechanisms under highly dynamic load [1]. Basic loading tests with different strain rates on multi-layered flat bed weft knitted fabric-reinforced composites with epoxy matrix are necessary for the development of adapted material and failure models for a realistic description of the material behaviour and assessment of three-dimensional loading states [2]. These models are subsequently used to calculate impact and crash behaviour with extended numerical program systems.

TEST TECHNIQUES FOR HIGHLY DYNAMIC LOADINGS

Within the scope of the experimental works, basic investigations of material phenomena of multi-layered flat bed weft knitted fabric-reinforced glass fibre composites are performed under high loading velocities to analyse the resultant strain rate dependent deformation and facture characteristics. Strain rate dependent material characteristic functions are necessary as input parameters for following calculation of the highly dynamic structural behaviour.

A high speed testing complex is used for ascertainment of the functions of the materials characteristics concerning the textile bonding, the combination of fibre and matrix material and the direction of the fibre reinforcement. This testing complex consists of a servo hydraulic high speed tension and penetration unit (SHU) and an impact and crash test unit (ICU). The SHU (Fig. 1) permits the characterisation of materials and components with high deformation velocities up to 20 m/s at a maximum force of 160 kN.

The advantage of the unit are the high maximum force, the possibility of extension by a clamping field for larger components and a temperature chamber. Furthermore an impulse-like and bounce-free load initiation into the specimen is ensured by a special upper clamping device, matched for highly dynamic tests, so that the load initiation take place after reaching the final test speed.

Fig. 1: Servo hydraulic high speed tension and penetration unit (SHU)

The determination of strain rate dependent materials properties of composites and here especially of glass fibre multi-layered flat bed weft knitted fabrics makes special challenges on the measurement technique. Because of the high testing velocities the strain measurement technique with contact to the specimen reaches its limits.

Beside the machines-sided integrated measuring technology to detect the elongation, the strength and the active acceleration, also a Laser-Doppler-Extensometer for local strain measurement and a high-speed camera for the improved validation of the fracture characteristics are applied to analyse the failure behaviour.

Within the scope of extensive calibration tests the exact tuning of the machine-sided control and regulation parameters took place in view of the recording of the fracture process. The adjustment and the synchronisation of the high speed camera system and the Laser-Doppler Extensometer enables beside the recording of the deformation, the begin of failure and the arising fracture series.

The Laser-Doppler Extensometer used for highly dynamic tensile tests works on the principle of laser optical speed measurement according to the Difference-Doppler-Method on two observation points fixed in the space (Fig. 2). The elongation at velocities up to 30 m/s can be recorded by integration of the LDE into the servo hydraulic high speed probe unit.

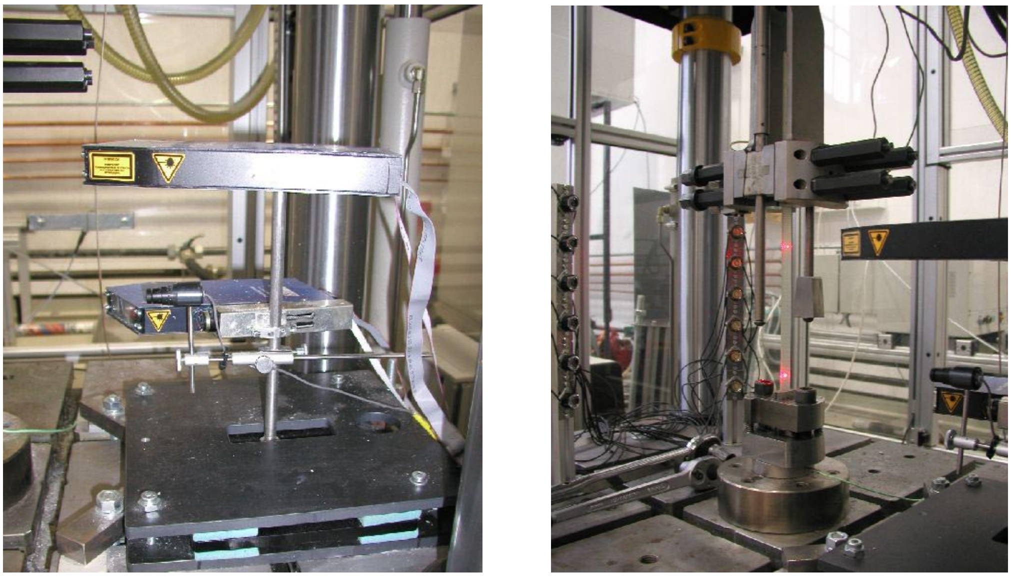

Fig 2: Laser-Doppler-Extensometer (left) und laser scanning of the surface of multi-layered flat bed weft knitted fabric reinforced high speed tension specimen

The tests were recorded with a high speed camera system for the analysis of the failure behaviour. This system (HSFC-PRO of PCO AG) has four digital high speed cameras in parallel position, which are coupled with one objective by beam splitter cubes. By this set-up, recording without distortions and displacements between the cameras is guaranteed. The incidence of light into one camera is a quarter of the incidence of light, which hits the objective. The camera system enables a maximum frame rate of 50 millions frames per second, which a very bright illumination of the probe object. The process of fracture and the area of the crack initiation can be displayed by these recordings (Fig. 3), which is important to detect additional breaks and cracks especially in the clamping areas, caused by oscillations after the first fracture.

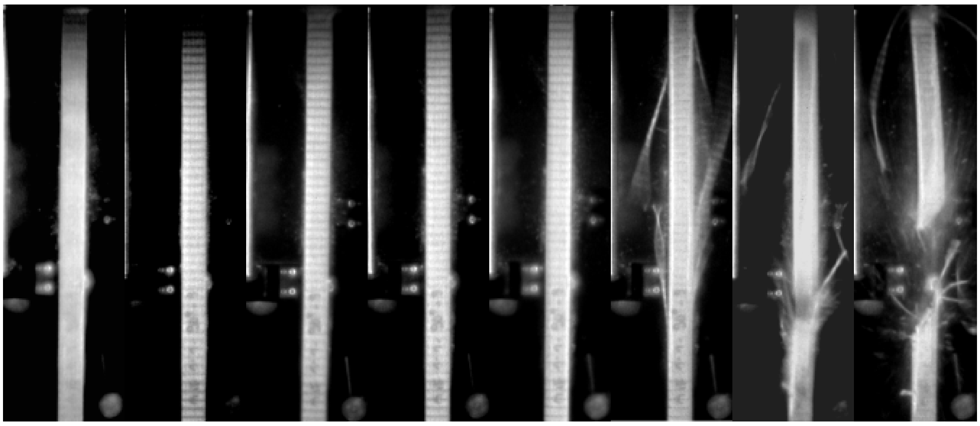

Fig. 3: High speed records of a highly dynamic tensile test

HIGHLY DYNAMIC TENSILE TESTS

In numerous tests, the deformation and failure phenomena of composites with multi-layered flat bed weft knitted fabrics (MKF) were investigated under several impact loading velocities. The MKF specimen with the textile architecture as illustrated in Fig. 4 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).

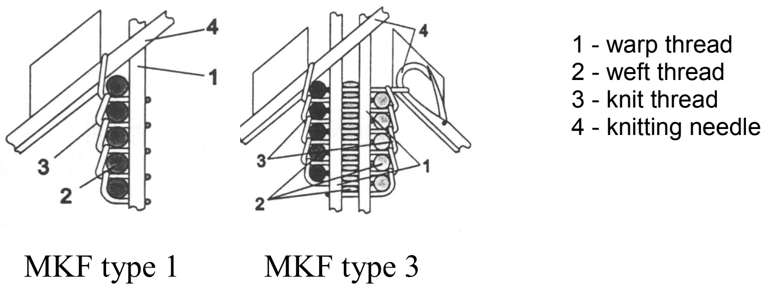

Fig. 4: Basic architecture of multi-layered flat bed weft knitted fabrics (MKF) [6]

The specimen were stressed with increasing loading velocities and strain rates. The same specimen geometry and length between the clamping jaws were used to ensure the comparability of the results in every test.

The increase of the loading velocity causes rising oscillations. These oscillations result from the stimulation of the eigen-oscillation-forms of the hole probe unit by increasing impulse-like loads. The probe unit oscillate with a characteristic eigen-frequency and the matching eigen oscillation form by impulse-like load initiation into the specimen. This oscillation frequency is nearly independent of the test speed, but the oscillations more and more effect the force signal with an increasing strain rate. Furthermore, the oscillation amplitude grows proportional to the increment of the test speed (Fig. 5) [7].

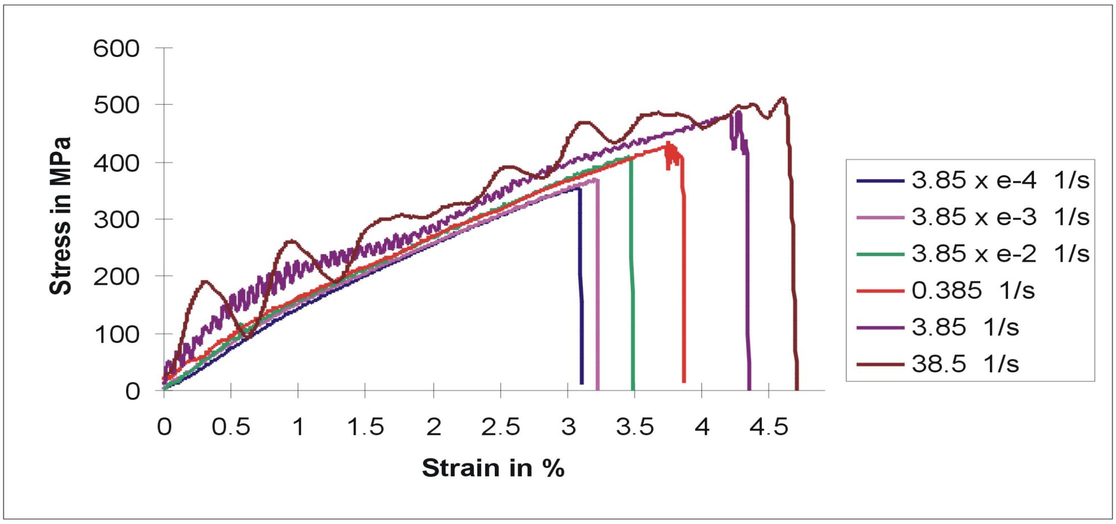

Fig. 5: Influence of the testing velocity on the oscillations of the force signal

The influence of the strain rate to the failure behaviour was investigated by tensile tests with loading velocities of 0.1 mm/s up to 10 m/s. Considering the materials behaviour under quasi-static loads up to impulse-like highly dynamic loads the influence of the strain rate concerning the raising of the strength was observed. The strain rate dependent tensile strengths of the investigated multi-layered flat bed weft knitted fabrics are displayed in Figure 6 within a logarithmic chart.

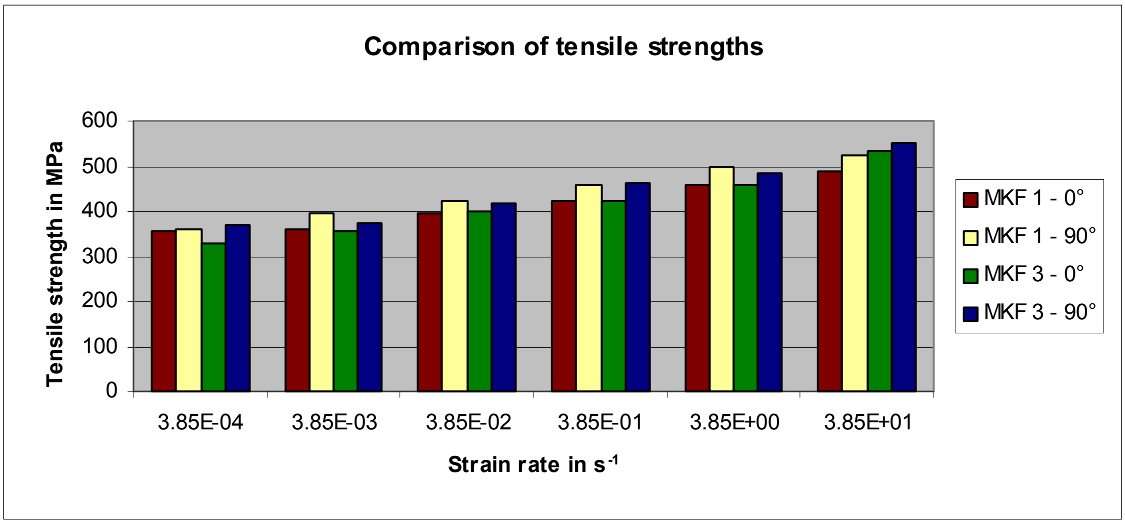

Fig. 6: Strain rate dependent tensile strengths of textile reinforced composites

Figure 7 shows the increase of the strain at failure with growing strain rates. The increase of the tensile strengths and the strains at failure under raising loading speeds points to the strain rate dependence of the energy absorption capacity of multi-layered knitted fabrics.

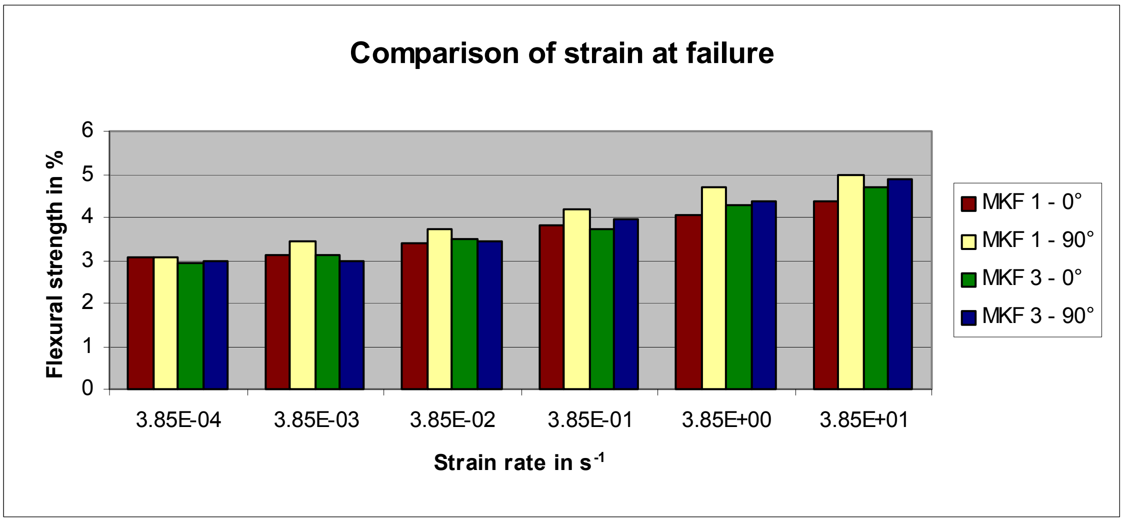

Fig. 7: Strain rate dependent strains at failure of textile reinforced composites

The gradient of the stress-strain-curve also increases with rising strain rates (Fig. 8). This effect is explicable by the growing influence of the matrix viscoelasticity on the resulting stresses. The resulting stress under assumption of a viscoelastic materials behaviour does not depend only on the Young's modulus and the strain, as it is at linear-elastic behaviour. The Kelvin-Voigt-Model as a simple viscoelastic material model describes the dependence of the stress to the Young's modulus and the strain as well as the viscosity and the strain rate.

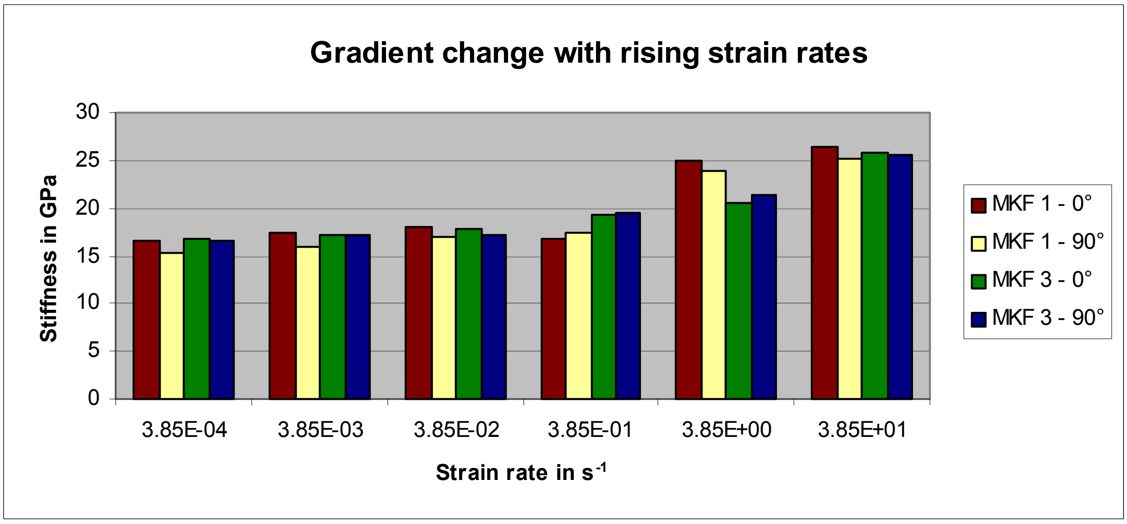

Fig. 8: Change of the gradient of the stress-strain-curves with a increase of the strain rate

Parallel to the high speed tension tests impact tests were performed in cooperation with the Department of Engineering Science of the University of Oxford. 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. Furthermore the impact tests serve for the verification of material and damage models as well as the results of numerical impact simulations [8]. Dependent on the impact speed, different failure modes (fibre failure, inter-fibre 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. 9).

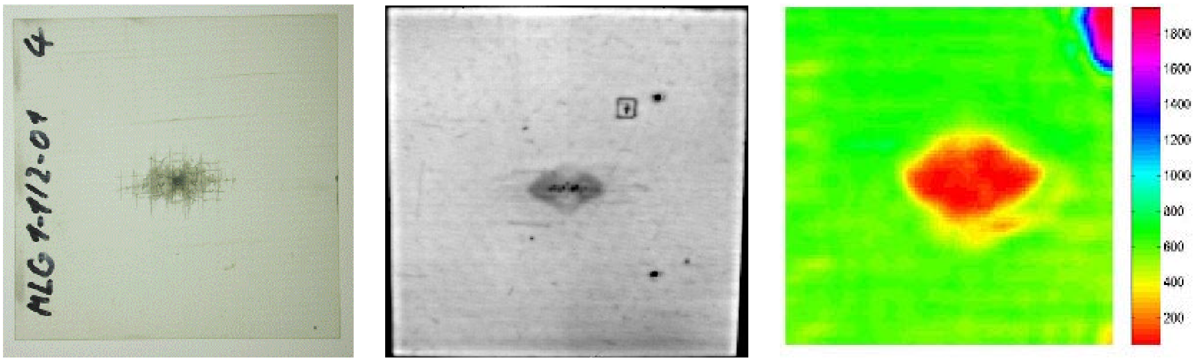

Fig. 9: Multi-layered flat bed weft knitted fabric test specimen after impact and associated optic excited thermography photo and ultrasonic inspection exposure

Dependent on the impactor 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. 10. The damage field extensions in x- and y-direction are shown dependent on the impact velocity. The extent of the damage 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.

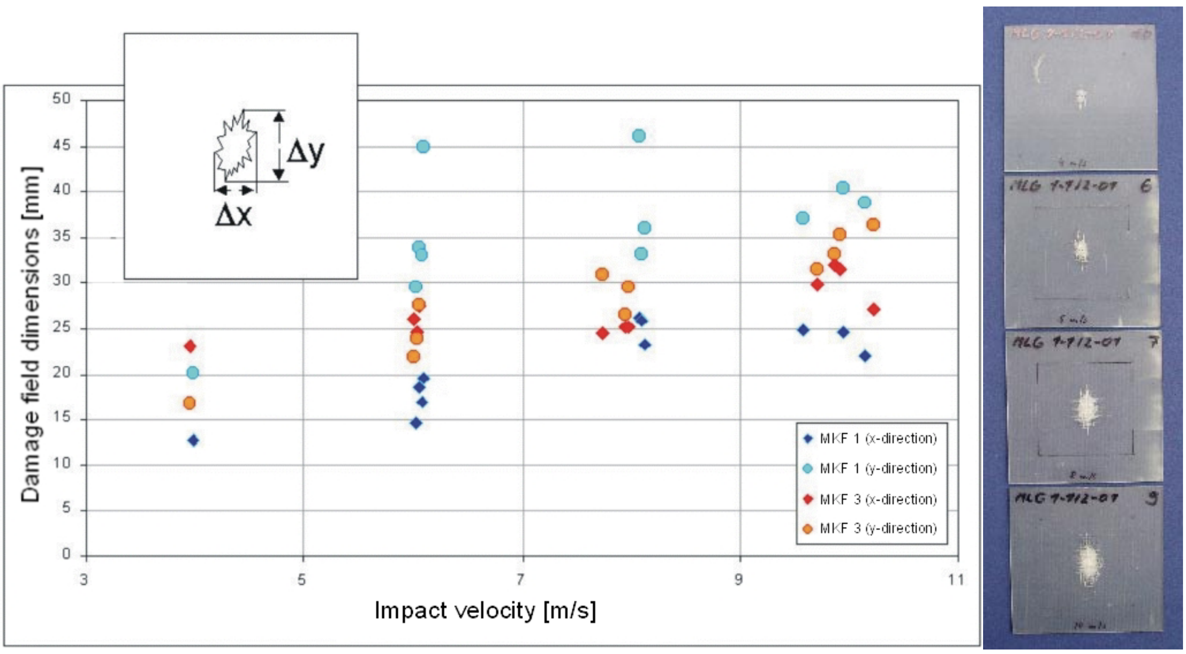

Fig. 10: Fracture extents of different MKF dependent on the impact velocity

CONCLUSIONS

Novel 3D-textile reinforced composites have very good specific mechanical properties and outstanding energy absorption capabilities, which makes them excellent candidates for the application in impact and crash elements of modern lightweight structures. With the help of the performed analyses, the materials behaviour and the energy absorption capabilities of composites with multi-layered flat bed weft knitted fabric could be determined and the influence of the strain rate on the materials properties was quantified. Based on the materials characteristics and adapted material and failure models, first simulations of 3D-textile composites under impact loads have successfully been carried out. A further improvement of the elaborated models will be done by subsequent investigations on the strain rate dependent damage and failure phenomena due to highly dynamic compression loads.

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