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Characterisation of strain rate dependent material properties of textile reinforced thermoplastics for crash and impact analysis

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Abstract

The strain rate dependent in-plane and through-thickness deformation and failure behaviour of textile reinforced polypropylene is investigated. An efficient in-plane parameter identification method based on rheological models is presented. Additionally, dynamic tensile, compression and shear tests were performed with woven and knitted textile reinforced thermoplastic composite specimens. As a result, the experimental methodology as well as strain rate dependent stiffness and strength properties within a strain rate range of 10^{-5} up to 10^{3} 1/s are presented. A phenomenological 3D material model based on the Cuntze failure criteria, accounting for strain rate dependency and damage evolution is implemented in Abaqus/Explicit. The user defined material model (VUMAT) is used for finite element (FE) studies of the crash and impact experiments. Exemplary numerical predictions are presented and compared.

Keywords: Textile reinforcements, Thermoplastics, Strain rate dependency, Through-thickness testing, Crash and impact analysis

1. Introduction

With short cycle times for a highly productive manufacturing process and excellent specific mechanical properties, textile reinforced thermoplastic composites are predestinated for the development and design of

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material and energy efficient lightweight structures. Especially due to their high energy absorption capacity, this material group is increasingly considered for applications in the field of crash and impact resistant design [1,2]. With respect to a reliable structural design however, there is a lack of well-founded knowledge regarding their strain rate dependent material behaviour and the corresponding design methodology.

Especially thermoplastic polymer reinforced composites exhibit significant strain rate dependent deformation behaviour, where stiffness and strength are highly rate dependent [3,4]. An efficient methodology for modelling polypropylene over a wide range of strain rates by rheological models was developed and used to determine material specific in-plane parameters of the constitutive equations as well as to predict the GF/PP laminate deformation behaviour subsequently.

The development of material models relies on experimental work focussing on parameter identification as well as model verification. The strain rate dependent deformation and failure behaviour of textile reinforced polypropylene in through thickness (TT) direction is investigated by highly dynamic tensile, compression and shear tests. As a result, the experimental methodology as well as strain rate dependent stiffness and strength properties within a strain rate range of 10^{-5} up to 10^{3} 1/s are presented.

A phenomenological 3D material model based on the Cuntze failure criteria, accounting for strain rate dependency and damage evolution is presented. In Abaqus/Explicit a user defined material model (VUMAT) is used to apply the elaborated material model within finite element (FE) studies of the crash and impact experiments. Exemplary numerical and experimental results are presented and compared

For the investigations two glass-polypropylene (GF/PP) hybrid yarn based textile composite configurations have been considered, namely a multi-layered flat bed weft-knitted fabric (MKF) and a woven fabric (Twintex®). The MKF with a fibre volume fraction of 48 % is uniquely produced by the Technische Universität Dresden, Institute of Textile Machinery and High Performance Material Technology (ITM) and offers excellent draping and crash properties [5]. Twintex® TPP 60 745 is supplied by Saint Gobain-Vetrotex and is a 2/2-twill weave with a fibre volume fraction of 35 %.

2. Rheological in-plane material modelling

Strain rate dependent material properties are essential for a numerical crash and impact analysis. To reduce time-consuming and costly material tests on composite laminate level, an efficient in-plane parameter identification method has been developed [4]. It is based on a Dynamic Mechanical Analysis (DMA) and quasi static tensile tests of matrix (polypropylene - PP) and fibre (glass - GF) material independently. Rheological models are used and combined in accordance to the fibre direction to model the stress-strain characteristics.

For modelling of the strain rate dependent deformation behaviour of PP a Burgers model (Fig. 1) was used, which combines three modelling constituents in series connection: a linear elastic stress–strain component (spring element), a viscoelastic component (parallel spring-dashpot element combination), and a viscoplastic flow component (dashpot element). This was investigated in detail in [3]. The Zener_k-model (Fig. 1) is used for GF to represent the brittle nature of this material, where a series connection of a viscoelastic component (parallel spring-dashpot element combination) and viscoplastic flow component (dashpot element) is used.

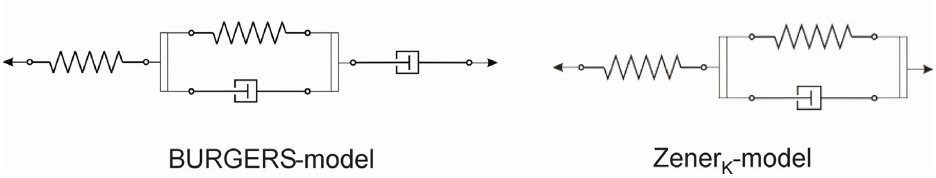


Fig. 1. Used rheological models

The two rheological models for PP and GF are combined in series or parallel to represent UD-plies (Fig. 2). Subsequently, the textile reinforced layer is represented by a cross ply arrangement of parallel UD-layers. A comparison between the modelled and experimentally determined tensile stress-strain behaviour in fibre direction is exemplarily determined in (Fig. 2).

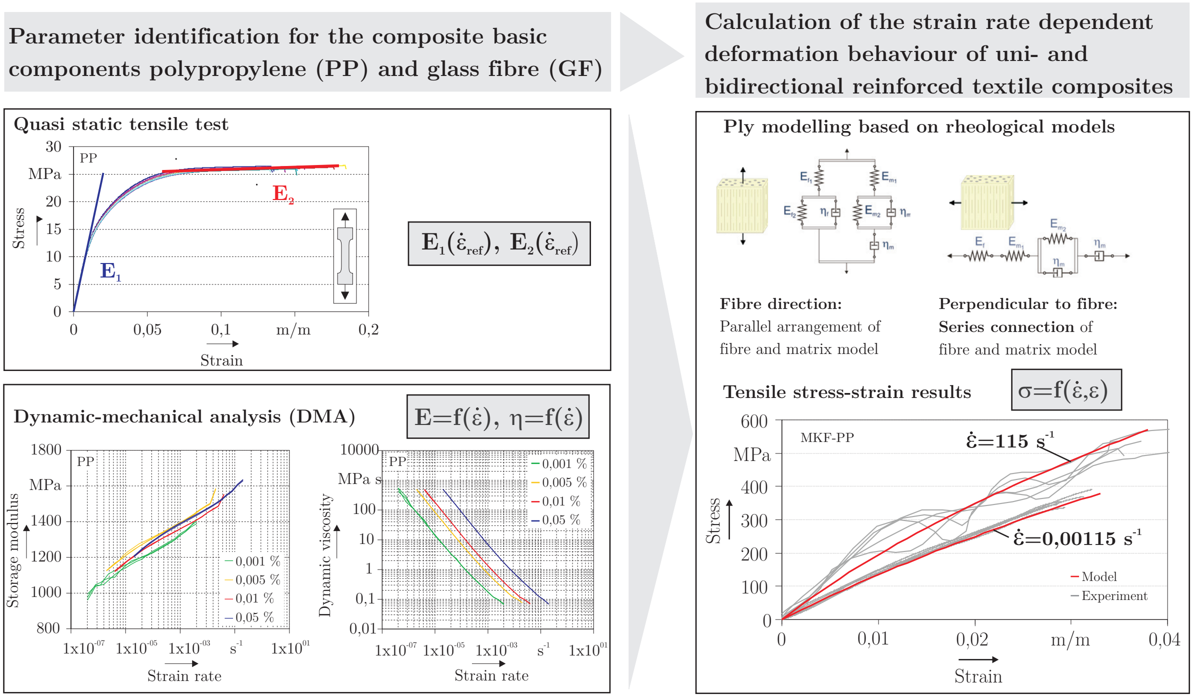


Fig. 2. Efficient in-plane parameter identification method based on rheological models

3. Through-thickness material characterisation

Besides in-plane properties, the through-thickness behaviour and corresponding strain rate dependency was characterised. A comprehensive overview of possible specimen shapes and the associated testing methods for TT tensile loading is given in [6] and in [7] a more recent overview with the focus on quasi static loading conditions can be found. With the scope on highly dynamic loading conditions adapted testing methods were developed with the aim of defined uniaxial tensile (Fig. 3a-c), shear (Fig. 3d) and compressive (Fig. 3e) loading conditions at different loading velocities. Based on the methodology to manufacture 'thick' composite specimens as proposed in [8], a multi-stage method was used to produce cylindrical specimen with a thickness of up to 200 mm.

With the usage of the Split-Hopkinson-Bar* strain rates up to 400 1/s were achieved (Fig. 3b). In this respect it is worth to mention that the specimen cross section area is only 40 mm^2. A wire suspended tension setup was used in addition to the Split Hopkinson Bar tests (Fig. 3a), allowing for the use of a cross section area with the chosen specimen shape of 130 mm^2. Additionally, an L-beam testing method was developed (Fig. 3c) [10]. It is based on the determination of interlaminar stresses in L-beam shaped specimens as proposed by Shivakumar [11] and extended for the determination of strain rate dependent properties. In this setup a state of uniaxial tensile strain in TT-direction in the curvature symmetry plane is achieved and subsequently the TT-strength was determined. The TT-shear-tests have been performed using a lightweight Iosipescu device (Fig. 3d) [8]. These experiments were supported by numerical FE studies to evaluate the occurring stress states in detail [12]. For compression, two specimen shapes were compared (Fig. 3e). As a result, the cylindrical geometry leads to reliable results due to absence of edge effects.

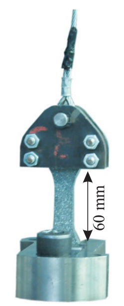
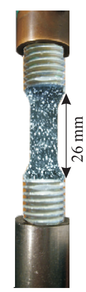
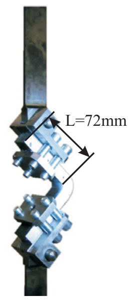
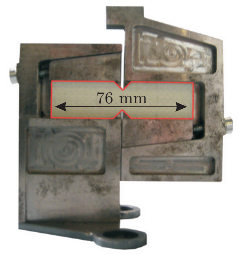
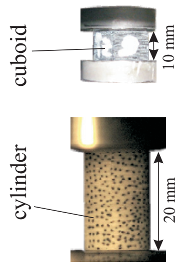
	a)	b)	c)	d)	e)
Setup					
Method	Wire suspended tension	Split-Hopkinson-Bar	L-beam	IOSIPESCU shear	Compression
Loading	σ_3^+	σ_3^+	(σ_3^+, τ_{31})	τ_{31}	σ_3^-
Strain rates	$\dot{\varepsilon} \leq 4 \cdot 10^3 \text{ s}^{-1}$	$\dot{\varepsilon} \leq 4 \cdot 10^3 \text{ s}^{-1}$	$\dot{\varepsilon} \leq 1 \cdot 10^1 \text{ s}^{-1}$	$\dot{\gamma} \leq 1 \cdot 10^1 \text{ s}^{-1}$	$\dot{\varepsilon} \leq 1 \cdot 10^2 \text{ s}^{-1}$

Fig. 3. Experimental configurations for strain rate dependent material characterisation in laminate through-thickness direction

In Fig. 4 a comparison of the TT tensile results with respect to the tested strain rates is shown. The strength and modulus of elasticity exhibit a significant apparent strain rate dependency. In contrast, this tendency can not be identified with respect to strains at fracture, which remain constant over the investigated strain rate range. The Split-Hopkinson-Bar is well established especially for testing metallic or other isotropic materials. Here, a considerable scatter leads to the conclusion that this method is not adequate for the investigated coarse textile architecture. A recently proposed new Split-Hopkinson-Bar tensile bar design is seen as promising to avoid such problems in the future [9]. Results of the L-beam testing were not considered in the comparison of the moduli of elasticity, due to the fact that a differing manufacturing method leads to a higher compaction during consolidation and therefore to higher values. The wire suspended tension tests are considered to be most reliable.

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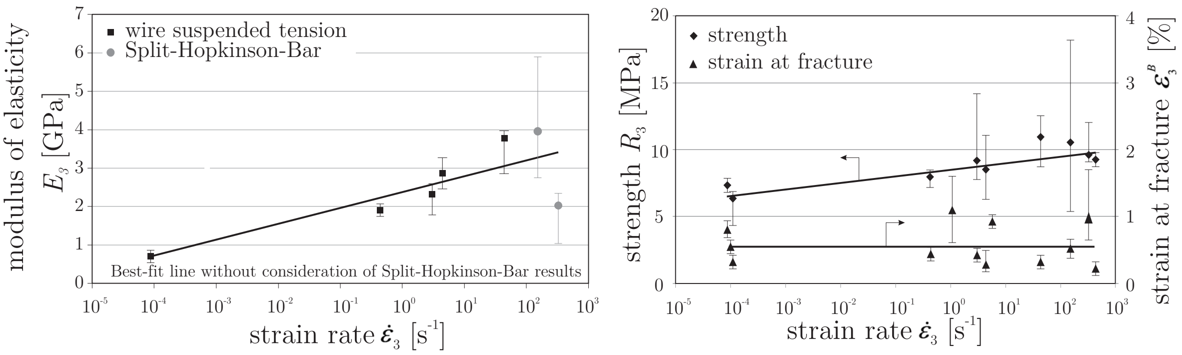

Fig. 4. Strain rate dependent through thickness tension results of Twintex

The shear deformation behaviour in 23-directection is a matrix dominated process and therefore highly non-linear (Fig. 5, left). This makes it difficult to determine stiffness characteristics. Reliable shear strength values were determined based on 32-experiments (Fig. 5, right). In equivalence to the TT tensile tests, a clear tendency to rising strength values with rising strain rates can be identified. Also, shear strain at failure remains constant within the tested strain rate range.

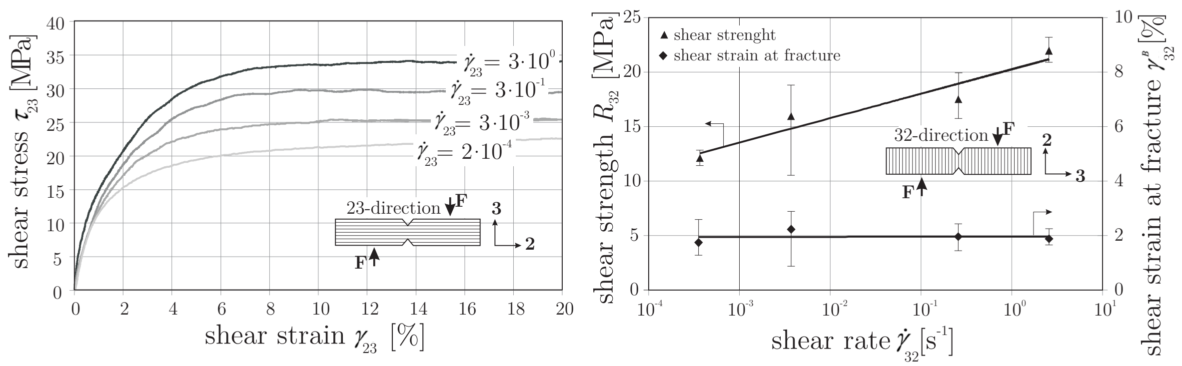

Fig. 5. Strain rate dependent through-thickness shear results of MKF

4. Experimental and numerical verification

The presented experimental results are the basis for numerical evaluation of structural components. The determined material characteristics in combination with a VUMAT in the FE software Abaqus were used for the numerical studies. This material model follows the failure mode concept of Cuntze and describes the accumulation of damage with respect to the failure modes [13,14]. A detailed description is given in [15]. An exemplary result of the material model capability is displayed in Fig. 6.

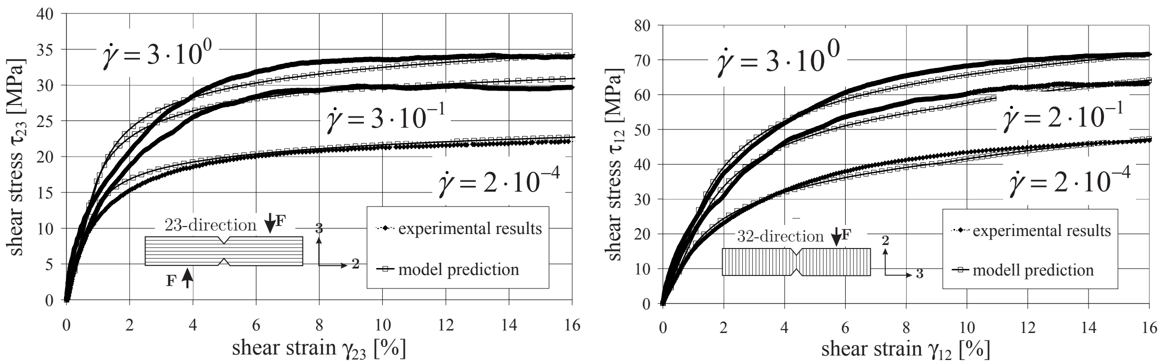

Fig. 6. Strain rate dependent through-thickness (left) and in-plane shear behaviour (right): Comparison of experimental results and numerical model predictions [15]

The shear stress - shear strain curves exhibit a highly non-linear behaviour in through-thickness (23) as well as in in-plane (12) direction. This is represented be means of damage mechanics within the material model. Also, a strain rate function is implemented to account for strain rate dependent elastic and strength parameters:

$$E_i^{(0)}(\dot{\varepsilon}_i) = E_i^{(0,\text{ref})}\left[1 + a_i \ln\left(\frac{\dot{\varepsilon}_i}{\dot{\varepsilon}_i^{(\text{ref})}}\right)\right] \quad \text{and} \quad R_i^{(0)}(\dot{\varepsilon}_i) = R_i^{(0,\text{ref})}\left[1 + c_i \ln\left(\frac{\dot{\varepsilon}_i}{\dot{\varepsilon}_i^{\text{ref}}}\right)\right] \quad . \tag{1}$$

This model has been applied in various high speed loading scenarios, where plane and curved specimens were impacted at velocities of up to 115 m/s. Crash experiments on structural level were performed within a drop tower setup with weights of up to 400 kg at different levels of complexity. Besides the axial compression behaviour of plane and curved spacer components, bonded components under different loading angles were in the focus. An exemplary result is shown in Fig. 7, where a MKF spacer structure is crushed axially. Additional experimental and numerical results can be found in [15]. The numerical deformation and failure evolution are in good agreement with the experimental ones. However, besides the consideration of delamination initiation characteristics, delamination propagation has a strong impact on the energy absorption performance. In that respect further investigations need to be performed.

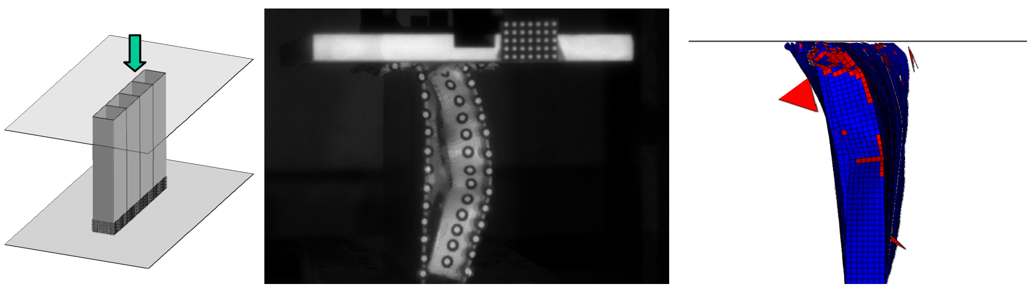

Fig. 7. Comparison of the experimental and numerical deformation and failure behaviour of an axially crashed MKF spacer structure (drop height: 0.95 m, drop mass: 390 kg, drop velocity: 4.3 m/s)

5. Conclusions

Despite of their many virtues, understanding the complex deformation and failure behaviour of composites under highly dynamic loads is still a challenge. The main objective of this paper was to present improved experimental methods for the characterisation of the strain rate material behaviour of fibre reinforced composites with thermoplastic matrix. Especially the response to rapidly applied loads in TT direction was addressed.

An efficient in-plane parameter identification based on modelled stress-strain characteristics was presented. Based on the Dynamic Mechanical Analysis (DMA) and quasi static tensile tests of matrix and fibre material separately and the application of rheological models (Burgers and $Zener_k$ model), an adequate modelling of the stress strain curves can be performed. Also, strain rate dependent deformation and failure behaviour in through-thickness direction were characterised. The results indicate a clear strain rate dependency in terms of rising elastic constants as well as tensile and compression strengths with rising strain rates. In contrast, fracture strains in TT direction remain constant. The presented methods are suitable for the evaluation of TT properties, except for the Split-Hopkinson-Bar approach which did not provide reliable data with the used bar diameter of 16 mm.

The strain rate dependent material characteristics have been used for explicit FE studies. The used material model was implemented in Abaqus/Explicit with a user defined material model (VUMAT). The numerical deformation and failure development are in good agreement with the experimental ones. Besides the predictive capabilities regarding the initial failure, further investigations regarding delamination propagation and according energy absorption mechanisms are considered as mandatory.

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