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Continuous-discontinuous sheet moulding compounds – Effect of hybridisation on mechanical material properties

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A B S T R A C T

Discontinuous fibre reinforced polymers offer a high design freedom to manufacture parts with complex geometries, but due to the finite fibre length and fibre orientation, mechanical performance is limited. To overcome this drawback continuous-discontinuous sheet moulding compounds (CoDicoSMC) aim to combine the advantages of discontinuous, chopped glass fibre reinforced as well as unidirectional, continuous carbon fibre reinforced composites. An adopted SMC process allowing for the manufacturing of continuous carbon fibre reinforced SMC was successfully implemented. The hybrid SMC was combined in a one-shot compression moulding process. Hybridisation of SMC enhanced mechanical material properties with a significant increase in tensile (+171%) and compressive (+151%) moduli of elasticity and tensile strength (+204%). The resulting stiffness of the laminate can be described by a modified rule of mixtures. Damage is characterized by a progressive failure of the continuous carbon fibre layers, due to interfibre fractures and fibre breakage, followed by interlaminar delamination and failure of the discontinuous phase.

1. Introduction

Driven by the need of advanced material properties, composite structures get more and more complex and diverse in terms of fibre type and reinforcement architecture. The demand to decrease processing time and cost of new components and structures as well as the challenge of reliable life-time predictions increase the complexity of mechanical material characterisation and enhance the need for a continuous interaction between characterisation and simulation. The more complex a composite structure, the more distinct the challenge of manufacturing. A novel material class, continuous-discontinuous sheet moulding compound (CoDicoSMC), aims to combine discontinuously (Dico) reinforced SMC with local continuous (Co) reinforcements to obtain higher load-bearing capacities at highly loaded areas of structures. To successfully consider hybrid continuous-discontinuous materials for structural applications, a profound understanding of resulting mechanical material properties is necessary. This work is a first step to investigating the mechanical material properties and damage of hybrid continuous-discontinuous SMC exposed to uniaxial loadings.

In general, sheet moulding compounds, as they are known today, are thermoset based discontinuous fibre reinforced composites, which date back to the 1960's. Due to specific stiffness and strength, combined with a cost-efficient manufacturing process and high formability, SMC are especially interesting to the automotive and aeronautic industry [1–3]. SMC (in combination with Bulk Moulding Compounds) were the most widely produced glass fibre reinforced composites in Europe in 2016 [4].

To continue to enhance mechanical material properties of SMC and to meet the increasing interest in this material class, different approaches recently focused on structural and advanced resin formulations. The common idea of these approaches is to increase the fibre volume content by decreasing the amount of fillers [5], reducing the density for example by adding hollow glass spheres to the resin [6] or by substituting glass with carbon fibres [7].

Although all these approaches led to advanced SMC with better mechanical properties compared to SMC of the 1960's, the fillers in the resin system prevent a further increase of the fibre volume content. Recently, it was successfully demonstrated that filler-free resin formulations can be considered for SMC processing [8].

One disadvantage of discontinuously fibre reinforced composites is the limited mechanical performance in terms of stiffness and strength. In contrast, unidirectional continuous fibre reinforced composites stand out due to superior mechanical properties but exhibit a lack of formability. The idea to combine discontinuous fibre reinforced SMC with continuous reinforcements is a promising approach to overcome this drawback. Recent contributions have already demonstrated the positive effect of hybridisation of SMC. For this purpose, different research groups combined chopped fibre reinforced SMC with preimpregnated,

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tailored continuous fibre reinforcements in a single-stage compression moulding process [9–13]. Since material and manufacturing costs of continuous carbon fibre prepregs are very high, this approach has a decisive disadvantage.

With an integration of dry textile preforms in a standard SMC process Gortner et al. [14,15] presented an alternative to realize a hybrid SMC. The impregnation of the textile preform during compression moulding is a critical factor for resulting material properties and hence a significant drawback of the presented approach.

In order to decrease material and manufacturing costs for unidirectional carbon fibre reinforcements, an adopted SMC process was introduced by Bücheler and Henning [16]. By using a novel two-step curing resin system, the viscosity of the paste could be controlled throughout the whole SMC manufacturing process, which enabled the consideration of unidirectional carbon fibres in form of a non-crimp fabric (NCF) in a unidirectional (UD) layout to be manufactured on a slightly modified standard conveyor plant. Resulting mechanical properties were comparable to the mechanical properties of unidirectional carbon fibre composites made by conventional manufacturing techniques like autoclave, for example [17].

To the extent of the author's knowledge, this contribution is the first publication on hybrid continuous-discontinuous SMC, for which both components were individually manufactured in a sheet moulding compound process.

Additionally, a thorough search for relevant literature yielded that this is the first time that both components of a continuous-discontinuous SMC were based on an unsaturated polyester-polyurethane two-step curing resin system. It allows a perfect chemical bond which is a significant advantage compared to other hybridisation strategies. To start with the investigation of hybrid CoDicoSMC, laminates have been manufactured by combining continuous carbon fibre and discontinuous glass fibre reinforced semi-finished material in a one-shot compression moulding process.

The quasi-static tensile and compressive properties of this hybrid continuous-discontinuous SMC were determined and the stiffness was analytically modelled by a rule of mixtures. Micro computed tomography (μ-CT) analysis enabled the investigation of the microstructure of the novel hybrid fibre reinforced material and helped to understand evolving damage resulting from uniaxial loadings.

2. Analytical stiffness-modelling

In material science, micromechanical approaches are powerful tools for predicting different properties of a composite material [18,19]. The interest in hybridisation also increases the demand to define modelling strategies for these complex composite materials. The most important property to consider for structural applications is the stiffness of a material. For this purpose different modelling strategies applied to SMC materials based on micromechanics [20] or finite element approaches [21] were already introduced. The resulting stiffness of the composite materials can also be predicted in an easier way by a rule of mixtures [13,22]. Classical rules of mixtures, valid for stacks of continuous fibre reinforced laminates, assume that the different layers feature uniformly distributed fibres throughout the matrix with a perfect bonding and no voids. In addition, this approach is valid, if loads are applied either parallel or normal to the fibres of an initially stress free laminate. Fibres and matrix are considered as elastic materials. The hybrid material considered within this study can also be analytically modelled as a laminate (index L) consisting of three different layers – two unidirectional carbon fibre SMC outer layers (l_1 and l_3) and one discontinuously reinforced glass fibre SMC core layer (l_2) (Fig. 1). The layers have dimensions of width *b*, length *a*, thickness *h* and a longitudinal (*l*) and transverse (*t*) modulus of elasticity E_l and E_t.

The mechanical material properties of the two different materials are experimentally homogenized and the tensile and compressive modulus of elasticity resulting from experiments of these individual

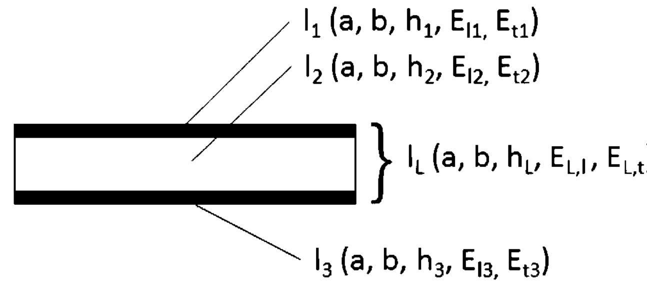

Fig. 1. Schematic laminate structure of hybrid continuous-discontinuous SMC.

materials are considered as input parameters for the analytical model of the resulting stiffness of the hybrid material. This leads to a modified rule of a mixtures described below.

The resulting stiffness, E_L of a uniaxially loaded laminate, can be determined according to Hooke's law by

$$\sigma_L = E_L \cdot \varepsilon_L \tag{1}$$

with the stress σ_L, and the strains ε_L, resulting from mechanical loading.

To fulfil static equilibrium, the acting force *F*, and thus resulting stresses, σ_L, must be equal to the sum of the force acting on the different layers of the composite (Eq. (2)). Assuming that the geometrical and material properties (*a*, *b*, *h*, *E*) of layer 1 are equal to layer 3 it follows:

$$\sigma_L \cdot A_L = \sigma_{l1} \cdot A_{l1} + \sigma_{l2} \cdot A_{l2} + \sigma_{l3} \cdot A_{l3} \tag{2}$$

Additionally, one can assume that the thickness of layer 1 and layer 3 are equal. Taking into account Eq. (1), and the volume fractions of layer 1 to 3 it follows for the longitudinal modulus of elasticity ($E_{L,l}$), of the hybrid laminate:

$$E_{L,l} \cdot \varepsilon_L = E_{l1} \cdot \varepsilon_{l1} \cdot \frac{2h_{l1}}{h_L} + E_{l2} \cdot \varepsilon_{l2} \cdot \frac{h_{l2}}{h_L} \tag{3}$$

For uniaxial tensile and compressive loads one can assume that strains are equal in all layers of the composite,

$$\varepsilon_L = \varepsilon_{l1} = \varepsilon_{l2} = \varepsilon_{l3} \tag{4}$$

and Eq. (3) finally leads to:

$$E_{L,l} = E_{l1} \cdot \frac{2h_{l1}}{h_L} + E_{l2} \cdot \frac{h_{l2}}{h_L} \tag{5}$$

Assuming that stresses are equal in all layers, transverse stiffness of the laminate $E_{L,t}$, can be predicted with the transverse moduli of the individual materials E_{t1},E_{t2},E_{t3}:

$$\frac{1}{E_{L,t}} = \frac{2h_{l1}}{h_L} \cdot \frac{1}{E_{t1}} + \frac{h_{l2}}{h_L} \cdot \frac{1}{E_{t2}} \tag{6}$$

3. Materials and manufacturing

3.1. Material manufacturing

The manufacturing of the discontinuous as well as of the continuous semi-finished material was carried out on a flat conveyor plant type HM-LB-800 by Schmidt & Heinzmann (Bruchsal, Germany) at the Fraunhofer ICT in Pfinztal, Germany. The two individual SMC components were based on a two-step curing polyester-polyurethane-based resin system. The individual components of the resin system were slightly modified (Tables 1 and 2) to ensure impregnation and to meet the manufacturing requirements of the different fibre types. The novel unsaturated polyester-polyurethane two-step curing resin system allowed the adaption of the paste's viscosity throughout the whole process chain to enhance the impregnation of the different fibre types. By using the same resin system for both, the glass and carbon fibre SMC, a perfect chemical bond in the final hybrid SMC is possible.

To manufacture the continuous carbon fibre semi-finished material,

Table 1
Resin components and fibre type of discontinuous (Dico) glass fibre SMC.

Component	Product name	Supplier
Unsaturated polyester-polyurethane resin	Daron ZW14141	Aliancys
Release agent	BYK 9085	BYK
De-airing	BYK-A-530	BYK
Inhibitor	pBQ	Fraunhofer ICT
Peroxide	Trigonox 117	Akzonobel
Thickener (Isocyanate)	Lupranat M20R	BASF
Glass fibre	Multistar 272	Johns Manville

Table 2
Resin components and fabric type of continuous (Co) carbon fibre SMC.

Component	Product name	Supplier
Unsaturated polyester-polyurethane resin	AQR 9001	Aliancys
Release agent	BYK 9085	BYK
Impregnation additive	BYK 9076	BYK
Inhibitor	pBQ	Fraunhofer ICT
Peroxide	Trigonox 117	Akzonobel
Thickener (Isocyanate)	Lupranat M20R	BASF
Styrene	Mono Styrol	BASF
Accelerator	BorchiKat 0243	Borchers
Stitch-bonded unidirectional carbon fibre non-crimp fabric	Panex 35	Zoltek

a unidirectional carbon fibre non-crimp fabric was fed to the conveyor belt. At the end of the conventional conveyor belt, a heating and cooling unit increased the paste's viscosity by a controlled partial curing of the resin system to allow for handling and cutting of the continuously semi-finished material with a nominal fibre volume content of 47 vol.%.

The discontinuous glass fibre semi-finished material was manufactured on the same flat conveyor belt without the heating and cooling unit and stored for several days. During manufacturing, glass fibre rovings were cut to a length of 25.4 mm (one inch). The speed of the conveyor belt and the cutting system were set to achieve a nominal fibre volume content (FVC) of 23 vol.%.

After maturation, the discontinuous and continuous semi-finished materials were cut into plies, stacked and compression moulded into sheets at approximately 150 °C, 2500 kN and 112 s mould closing time. To manufacture the 1D flow discontinuous SMC, the stack was placed in the middle of the rectangular mould to achieve a mould coverage of approximately 35%. The material flew in one dimension. To manufacture the continuous carbon fibre SMC a mould coverage of 100% was implemented and the material did not flow during compression moulding. To manufacture the hybrid SMC laminates, the two different semi-finished materials were stacked and then compression moulded in a one-shot process (Fig. 2). The rectangular compression moulded discontinuous, continuous and continuous-discontinuous SMC sheets featured a section of 800 mm by 250 mm. The nominal thickness of all discontinuous glass fibre and hybrid continuous-discontinuous glass/carbon sheets was 3 mm. The purely continuous carbon fibre SMC sheets featured a nominal thickness of either 1 mm, 2 mm or 3 mm.

3.2. Specimens preparation

Eight sheets of discontinuous glass fibre SMC and continuous-discontinuous hybrid glass/carbon fibre SMC were considered for

Fig. 3. From bottom to top: specimens made of continuous carbon fibre SMC, discontinuous glass fibre SMC and continuous-discontinuous hybrid glass/carbon fibre SMC.

mechanical characterisation. Continuous carbon fibre SMC specimens were extracted from three different sheets. The specimens for mechanical testing and microstructural observation were cut using abrasive water jet cutting (Fig. 3) by SNZ Schneidbetrieb GmbH (Mühlacker, Germany), stored at room temperature (approximately 23 °C) and a medium relative humidity for several days before testing. To avoid damage to especially the continuous carbon fibre reinforced outer layers due to clamping during testing, end tabs were used on all tensile and on 0° continuous carbon fibre SMC as well as hybrid CoDico compression specimens. For this purpose, the ends of both sides of the specimens were abraded using sand paper (180-grit) to roughen the surface. The abraded surfaces were wiped with isopropyl alcohol to get them ready for adhesive bonding. End tabs (PREGNIT GMBE glass fibre reinforced epoxy plastic laminates by Krempel, Vaihingen an der Enz, Germany) with a nominal thickness of 1.3 mm were glued on the specimens.

The end tabs had a length of 50 mm, a width of 15 mm and were tapered (tapered section was 5 mm) for tensile specimens. For compression specimens the end tabs featured 44 mm × 15 mm and were not tapered. The choice of adhesive was 3 M Scotch-Weld ™ Low Odor Acrylic Adhesive DP810 (black). The acrylic was dispensed on the tab and SMC specimens generously before the tabs were bonded on the ends of each side of the specimen and let to cure at room temperature for at least 24 h.

4. Methodology

4.1. Test method for tensile properties

Tensile tests were carried out in a conditioned laboratory at 23 °C on a ZMART.PPRO universal testing machine by ZwickRoell with a load cell capacity of 200 kN. The specimens for tensile testing were designed according to [23] and featured a length of 200 mm and a width of 15 mm. The discontinuous glass fibre SMC had an average thickness 2.85 mm (Coefficient of variation, CV = 3.8%). The continuous carbon fibre SMC specimens in fibre direction had a thickness of 0.98 mm (CV = 1.6%), specimens perpendicular to fibre direction featured a thickness of 1.98 mm (CV = 0.6%). The hybrid continuous-discontinuous glass/carbon fibre SMC featured an average thickness of 2.9 mm (CV = 1.9%). Before testing, specimens were hydraulically clamped with a clamping distance of 100 mm. A 4 M GOM ARAMIS 3D (stereo) Digital image correlation system featuring an adjustable base with two 4MP Teledyne Dalsa cameras with 50 mm Schneider Kreuznach objectives was used to measure the displacement. To evaluate resulting strains a section of approximately 70 mm × 10 mm was considered and technical strains were calculated. Uniaxial tensile tests were conducted with a nominal velocity of 1.8 mm min^{-1} ($\dot{\varepsilon} \approx 2{\cdot}10^{-4}$) until fracture. The frame rate was 5 Hz. Tensile modulus of elasticity

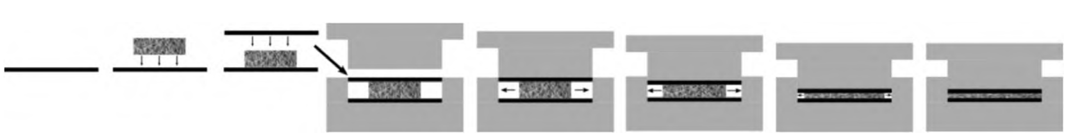

Fig. 2. Compression moulding of hybrid continuous-discontinuous SMC.

and Poisson's ratio were determined with a least squares method according to [24] in the strain range of 0.05%–0.25% and the arithmetic mean value of the technical strains was taken into account. Mechanical material properties were evaluated for a total of at least seven specimens of each material configuration. A specimen was only considered as valid, if final failure occurred within the considered gauge section and the regression coefficient r^2 was higher than 0.9.

4.2. Test method for compressive properties

Compression tests were performed in a conditioned laboratory at 23 °C on a ZMART.PRO universal testing machine by ZwickRoell with a load cell capacity of 100 kN. The machine was equipped with a hydraulic composite compression fixture. Rectangular specimens were considered for testing, which featured a length of 100 mm and a width of 15 mm. The discontinuous glass fibre SMC featured a thickness of 2.8 mm (CV = 3.0%). The continuous carbon fibre SMC specimens in fibre direction featured a thickness of 1.94 mm (CV = 1.26%). The continuous carbon fibre SMC specimens, which were extracted perpendicular to the fibres, featured a thickness of 3.0 mm (CV = 0.6%). The hybrid continuous-discontinuous glass/carbon fibre SMC specimens featured an average thickness of 2.9 mm (CV = 1.4%) The specimens with end tabs featured a free length of 12 mm. Clamping distance was set to 15 mm for all specimen types. Uniaxial compression tests were carried out with a nominal velocity of 0.8 mm min^{-1} ($\dot{\varepsilon} \approx 2{\cdot}10^{-4}$) until fracture and displacement was measured with a clip on extensometer at both sides of the specimen. This enabled to control bending of the specimen, by calculation of a bending factor according to [25]. Compression modulus was determined with a least squares method according to [24] in the strain range of 0.05%–0.25% with average strain resulting from displacement measurement of two sides of the specimen. Mechanical material properties were evaluated for a total number of at least five specimens of each material configuration. A specimen was only considered for evaluation if final failure occurred in the gauge section, the bending factor did not exceed 0.1 and the regression coefficient r^2 was higher than 0.9.

4.3. X-ray computed tomography

To investigate the microstructure of the hybrid SMC, a selected number of specimens were scanned in an YXLON CT Precision computed tomography system (Yxlon International CT GmbH, Hattingen, Germany) containing an open micro-focus X-ray transmission tube with tungsten target and a 2048 × 2048 pixel^2 flat panel detector from Perkin Elmer (Waltham, MA, USA). The acceleration voltage was 100 kV and the tube current 0.05 mA. The scans were acquired with a focus–object distance of 31.27 mm and a focus–detector distance of 750 mm, leading to a voxel size of 8.04 µm.

4.4. Determination of fibre volume content

To determine the real fibre volume content (FVC) of the SMC sheets, circular specimens with a diameter of 20 mm were extracted and a thermogravimetric analysis (TGA) was completed with a Leco TGA701 (LECO Corporation, St. Joseph, MI, USA). For the investigation of the discontinuous glass fibre SMC nine specimens of each sheet were considered for investigation. The chamber was heated up to 550 °C with a heating rate of 37 °C min^{-1}. This temperature stayed constant for 2 h. For the investigation of the continuous carbon fibre SMC at least 11 specimens of each sheet were considered and the TGA was carried out according to the method proposed by Bücheler et al. [26].

The fibre weight content, Ψ of a specimen is determined by the mass of the fibres, m_f, remaining in the crucible after burning of the matrix divided by the mass of the composite, m_c.

Table 3
Fibre volume content of discontinuous glass fibre SMC.

Sheet number	Fibre volume content		
	Arith. mean value in vol.%	Standard deviation in vol.%	Coefficient of variation in %
1	24.2	0.9	3.4
2	26.4	1.1	4.1
3	26.1	1.2	4.6
4	25.7	1.3	5.2
5	27.1	1.0	3.7
6	27.5	1.6	5.6
7	27.8	0.8	2.8
8	21.5	1.4	6.4
Σ	**25.8**	**1.2**	**4.5**

$$\Psi = \frac{m_f}{m_c} \tag{7}$$

The resulting fibre volume content, φ, can be determined by:

$$\varphi = \frac{1}{1 + \frac{1-\Psi}{\Psi} \cdot \frac{\rho_f}{\rho_m}} \tag{8}$$

with ρ_f the density of the fibre and ρ_m density of the matrix [27].

5. Results

5.1. Microstructure of hybrid continuous-discontinuous sheet moulding compounds

5.1.1. Fibre volume content of discontinuous glass fibre and continuous carbon fibre SMC

Real fibre volume content (Table 3 and Table 4) was calculated according to Eq. (8) based on the results of the thermogravimetric analysis. The arithmetic mean value of the fibre volume content of the discontinuous glass and continuous carbon fibre SMC sheets was 25.8% and 52.8%, respectively. For both materials, the real fibre volume content was significantly higher than the theoretically set value due to manufacturing parameters.

5.1.2. Fibre orientation and interface characterisation of hybrid continuous-discontinuous glass/carbon fibre SMC

The µCT scan of a hybrid continuous-discontinuous glass/carbon fibre SMC specimen (Fig. 4) shows a transition zone at the interface between the continuous and discontinuous reinforced layers. The individually stitched unidirectional carbon fibre bundles were sheared and pushed apart during compression moulding due to the 1D flow of the discontinuous component. The material flow also forced the glass fibre bundles to split up at the interface and to orient toward flow direction. In the middle of the specimen, the glass fibre bundles are randomly oriented and the individual glass fibre rovings can still clearly be identified.

Table 4
Fibre volume content of continuous carbon fibre SMC.

Sheet number	Fibre volume content		
	Arith. mean value in vol.%	Standard deviation in vol.%	Coefficient of variation in %
1	52.3	0.5	1.0
2	54.0	0.4	0.8
3	52.2	2	3.8
Σ	**52.8**	**1.0**	**1.9**

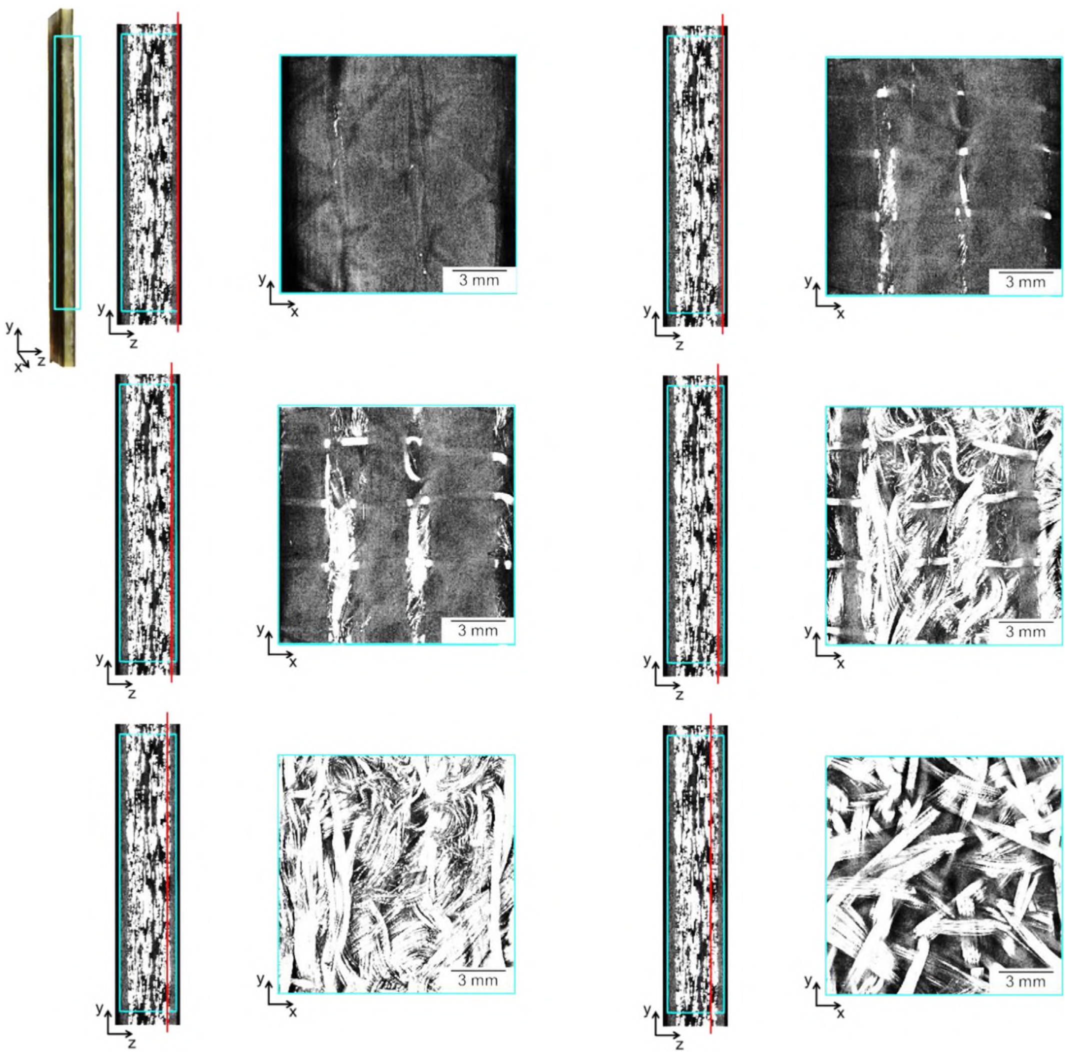

Fig. 4. µCT scan of a hybrid continuous-discontinuous SMC specimen.

5.2. Mechanical material properties of continuous, discontinuous and continuous-discontinuous SMC

The results of mechanical testing are presented in the following section. Moduli of elasticity and strength of the materials are represented in boxplot diagrams. The grey box indicates the 25th and 75th percentile. The arithmetic mean value is marked by a black dot inside the box and the whiskers represent the 1-σ standard deviation. The mechanical material property of each individual specimen is mapped with a black dot on the right hand side of the corresponding box. This allows a better understanding of the scatter of mechanical material properties depending on material type.

The tensile testing of discontinuous glass and continuous-discontinuous glass/carbon fibre SMC indicated, that there is no significant difference of tensile modulus of elasticity and tensile strength between charge and flow region specimens (Figs. 5, 7, 9, 11). Thus, for compressive testing, mechanical material properties of charge and flow region specimens were combined in one box. In the following sections, “in fibre” direction refers to a loading along the longitudinal fibre axis of the continuous carbon fibre SMC and 0° refers to the direction of flow of the discontinuous glass fibre SMC.

5.2.1. Tensile and compressive properties of discontinuous glass fibre SMC

Figs. 5–8 show the tensile and compressive properties of the discontinuous glass fibre SMC considered within this study. The moulded

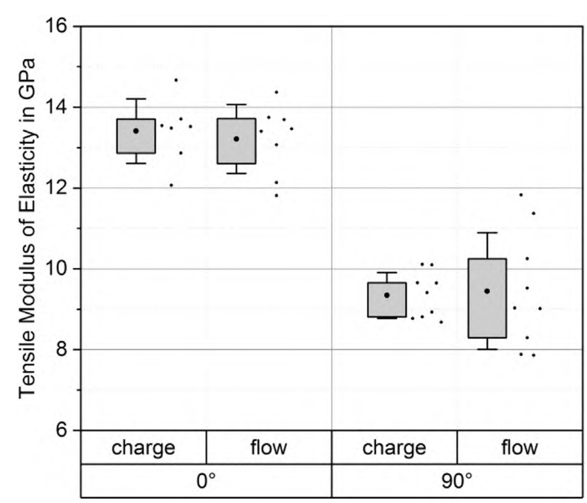

Fig. 5. Tensile modulus of elasticity of discontinuous glass fibre SMC.

sheets exhibited anisotropic mechanical material properties considering tensile and compressive modulus of elasticity and strength.

With regard to tensile properties, the modulus of elasticity was significantly higher for specimens extracted in flow direction (0°). The arithmetic mean value and coefficient of variation (CV) were 13.4 GPa

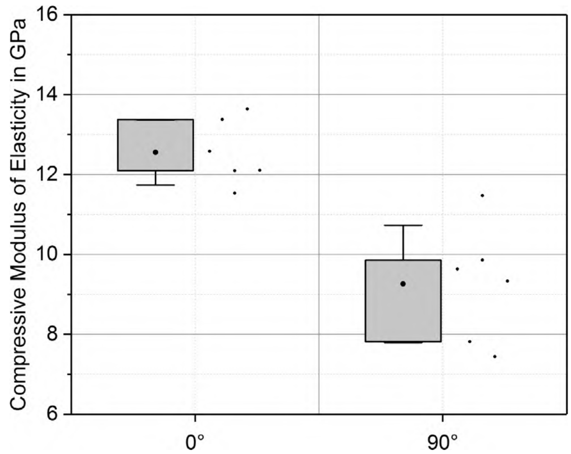

Fig. 6. Compressive modulus of elasticity of discontinuous glass fibre SMC.

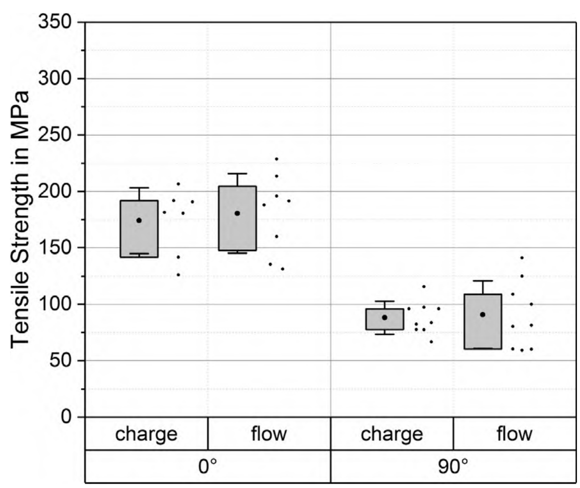

Fig. 7. Tensile strength of discontinuous glass fibre SMC.

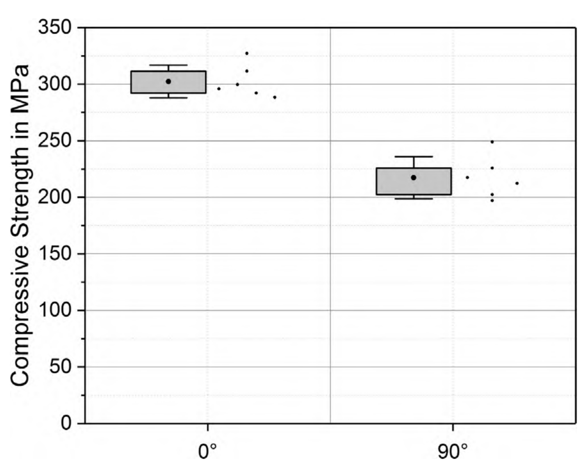

Fig. 8. Compressive strength of discontinuous glass fibre SMC.

(CV = 5.9%) for charge and 13.2 GPa (CV = 6.5%) for flow region specimens, compared to specimens extracted perpendicular to the material flow (90°) with 9.3 GPa (CV = 5.7%) for charge and 9.5 GPa (CV = 15.3%) for flow region specimens (Fig. 5). This led to a ratio of anisotropy of 1.4 for charge and flow region specimens, respectively.

In a similar manner, 0° specimens showed a higher compressive modulus of elasticity, with an average stiffness of 12.6 GPa (CV = 6.5%), compared to 90° specimens (9.3 GPa (CV = 15.9%)) (Fig. 6). Similar to uniaxial tensile loadings the ratio of anisotropy was also 1.4 for uniaxial compression. Quantitatively spoken, tensile and compressive moduli of elasticity did not significantly differ regarding the discontinuous glass fibre SMC considered within this study.

The Poisson's ratio of the discontinuous glass fibre SMC in flow direction was 0.38 (CV = 5.3%) for charge and 0.37 (CV = 5.5%) for flow region specimens. Perpendicular to flow (90°) charge region specimens featured a Poisson's ratio of 0.27 (CV = 8.8%) in charge and 0.31 (CV = 13.5%) in flow region.

With an average value of 174.1 MPa (CV = 16.7%) for charge and 180.5 GPa (CV = 19.5%) for flow region specimens, tensile strength also showed only a slightly higher value for specimens extracted in flow direction (0°). The tensile strength for specimen extracted perpendicular to flow direction was 87.1 MPa (CV = 17.5%) for charge and 90.7 MPa (CV = 33.0%) for flow region specimens. The ratio of anisotropy for both groups was 2.0.

With 302.4 MPa (CV = 4.8%) in 0° and 217.3 MPa (CV = 8.7%) in 90° (ratio of anisotropy of 1.4) compressive strength was significantly higher than tensile strength for the discontinuous glass fibre SMC material considered within this study.

5.2.2. Tensile and compressive properties of continuous carbon fibre SMC

The tensile and compressive properties of continuous carbon fibre SMC in and perpendicular to fibre direction are listed in Table 5 and Table 6.

5.2.3. Tensile and compressive properties of continuous-discontinuous glass/carbon fibre SMC

The hybrid continuous-discontinuous glass/carbon fibre SMC featured a tensile modulus of elasticity of 36.4 GPa (CV = 8.6%) for charge and 35.8 GPa (CV = 5.5%) for flow region specimens, if loaded in fibre direction (Fig. 9). Thus, if loading coincides with the orientation of the fibres, stiffness increased 171% compared to purely discontinuous glass fibre SMC. Tensile modulus of elasticity in 90° (perpendicular to the fibres) showed a slight decrease (-7%) due to hybridisation.

With a compressive modulus of elasticity of 31.6 GPa (CV = 7.7%) hybridisation led to a stiffness increase of 151%, if properties in fibre direction are considered. Compressive modulus of elasticity in 90° (perpendicular to the fibres) slightly decreased (-10%) due to hybridisation (Fig. 10).

Poisson's ratio in fibre direction was not affected by hybridisation (0.37, CV = 5.7% in charge and 0.37, CV = 1.8% in flow region).

Poisson's ratio perpendicular to fibre direction decreased to 0.1 (CV = 7.1% for charge and CV = 6.1% for charge and flow region specimens).

Tensile strength in fibre direction increased to 533.9 MPa (CV = 11.7%) for charge and to 544.9 MPa (CV = 11.4%) for flow region specimens and could thus be tripled due to hybridisation. Perpendicular to the fibres, tensile strength decreases 27% (Fig. 11).

Hybrid continuous-discontinuous glass/carbon SMC showed slightly reduced compressive strength (−17% in fibre direction and −6% perpendicular to fibre direction) compared to purely discontinuous glass fibre SMC (Fig. 12).

Table 5
Tensile properties of continuous carbon fibre SMC.

	Tensile Modulus of Elasticity			Poisson's ratio			Tensile Strength		
	mean in GPa	σ_{SD} in GPa	CV in %	mean	σ_{SD}	CV in %	mean in MPa	σ_{SD} in MPa	CV in %
0°	114.2	5.7	5.0	0.32	0.01	4.1	1536.0	108.5	7.1
90°	8.2	0.1	1.8	0.03	0.01	17.8	34.0	4.7	13.8

Table 6
Compressive properties of continuous carbon fibre SMC.

	Compressive Modulus of Elasticity			Compressive Strength		
	mean in MPa	σ_{SD} in GPa	CV in %	mean in MPa	σ_{SD} in MPa	CV in %
0°	87.1*	2.1	2.4	575.8*	37.6	6.5
90°	7.5	0.2	2.6	164.9	1.77	1.1

* Only four specimens could be evaluated.

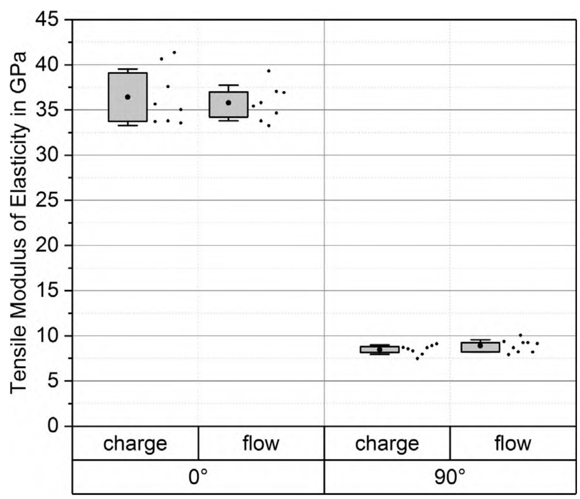

Fig. 9. Tensile modulus of elasticity of continuous- discontinuous glass/carbon fibre SMC.

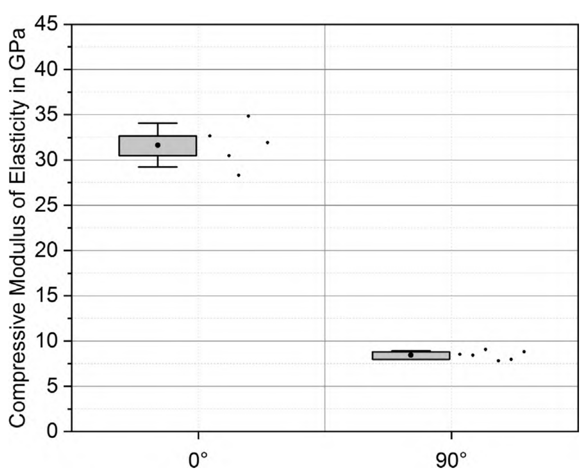

Fig. 10. Compressive modulus of elasticity of continuous-discontinuous glass/carbon fibre SMC.

5.3. Damage evolution of continuous-discontinuous glass/carbon fibre SMC due to uniaxial loading

In general, initiation of damage of discontinuously glass fibre reinforced SMC materials is linked to failure mechanisms at the microscopic scale, like interface failure between fibres and matrix or matrix cracks. Accumulation of these microscopic failure mechanisms combined with mesoscopic failure mechanisms (pseudo-bundle delamination) finally leads to global macroscopic failure of the material [28]. In the following, damage of hybrid continuous-discontinuous glass/carbon fibre SMC exposed to uniaxial tension is investigated by identifying failure mechanisms at the meso- and macroscopic scale which evolve due to increasing uniaxial loading. Lastly, SEM observation of a post-mortem specimen exposed to uniaxial tensile loading enabled to

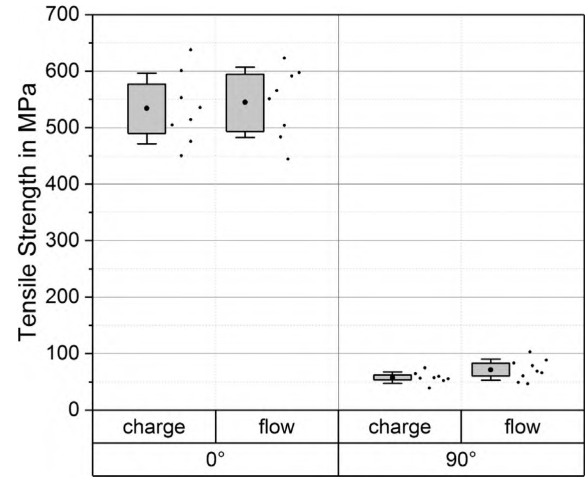

Fig. 11. Tensile strength of continuous-discontinuous glass/carbon fibre SMC.

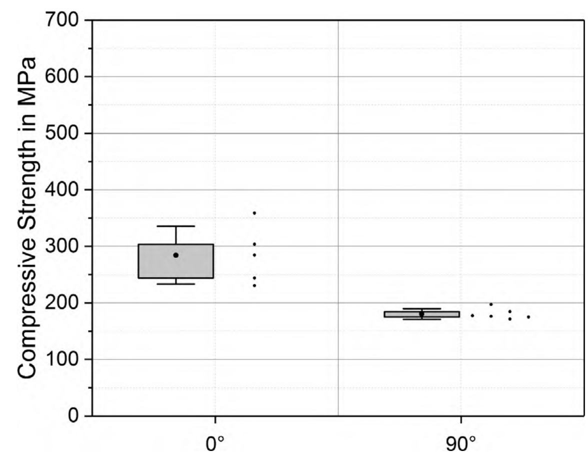

Fig. 12. Compressive strength of continuous-discontinuous glass/carbon fibre SMC.

intensify the understanding of damage by identifying microscopic failure mechanisms of both components of the hybrid specimen.

The strain field resulting from uniaxial tension was qualitatively spoken homogeneous in the beginning of loading (Fig. 13 A and B). Considering failure of hybrid continuous-discontinuous glass/carbon fibre SMC exposed to uniaxial tension, damage was initiated in resin rich regions by inter-bundle fractures of the continuous carbon fibre outer layers, mostly at the edges of both sides of the specimen (Fig. 13, D and E). The resulting strain filed also showed localized tensile strains in these regions and became slightly heterogeneous (Fig. 13). The appearance of these mesoscopic cracks was linked to a drop in the stress-strain curve, which indicated partial failure of the specimen. Inter-bundle crack initiation points were most probably regions, where continuous carbon fibre bundles were sheared and pushed apart during compression moulding in a way that the discontinuous glass fibre SMC is locally no longer reinforced in these sections. Besides that, there was a high probability that damage is initiated, where misaligned fibre bundles met the edge of the specimen The inter-bundle fractures propagated easily (Fig. 13, F and G) and this crack propagation was linked to a macroscopic interlaminar delamination between the discontinuous and continuous phase (Figs. 14 and 15).

With increasing tensile load, the hybrid continuous-discontinuous SMC specimen was thus partially weakened and final macroscopic failure was marked by a brittle fracture of the hybrid SMC specimen (Fig. 13, G and Fig. 14) based on fibre fracture of the continuous phase.

SEM investigations of a post-mortem specimen (Fig. 16) showed,

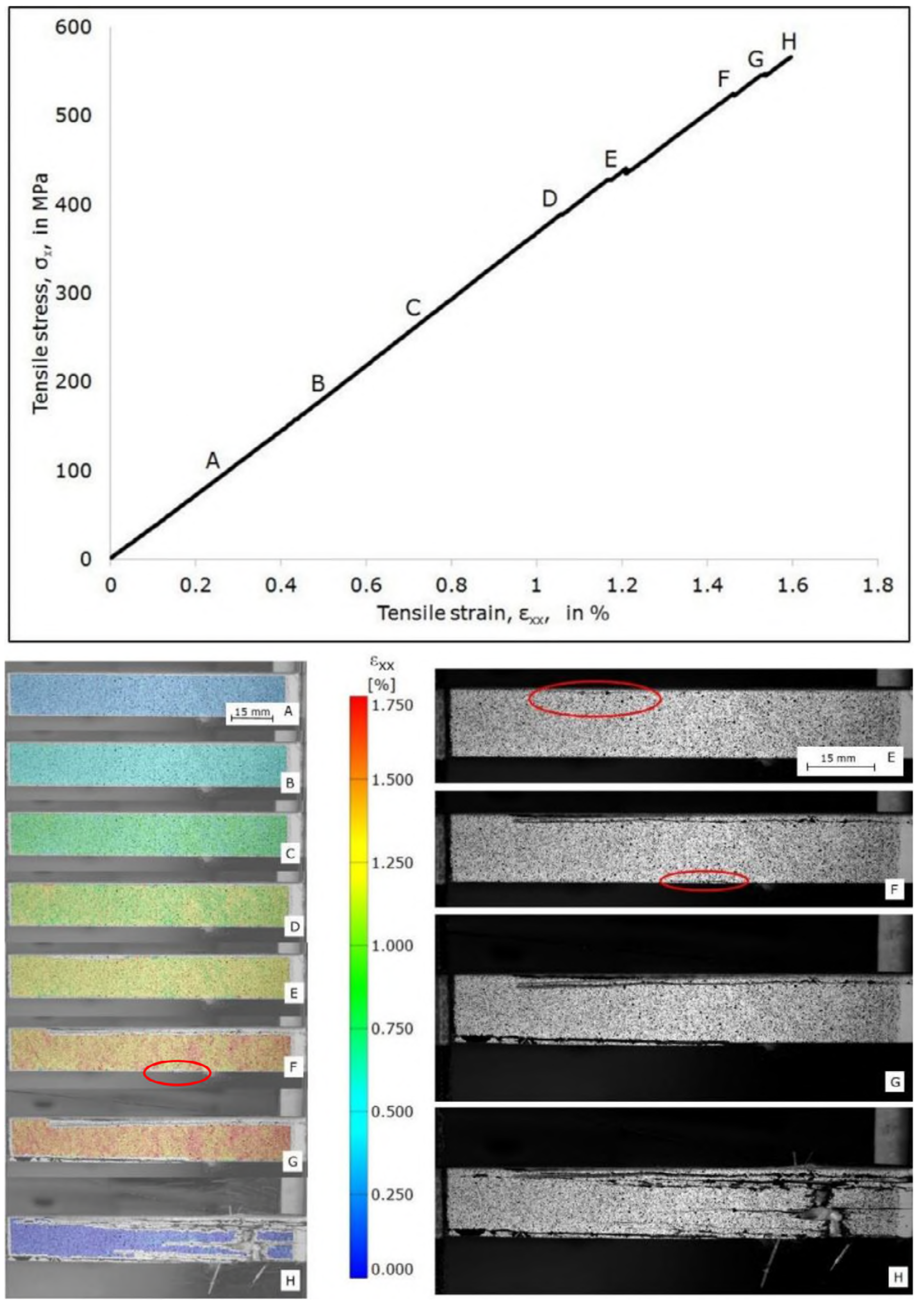

Fig. 13. Uniaxial tension of hybrid continuous-discontinuous SMC: Stress-strain curve (top), evolving strains (bottom left) and damage evolution (top view) (bottom right).

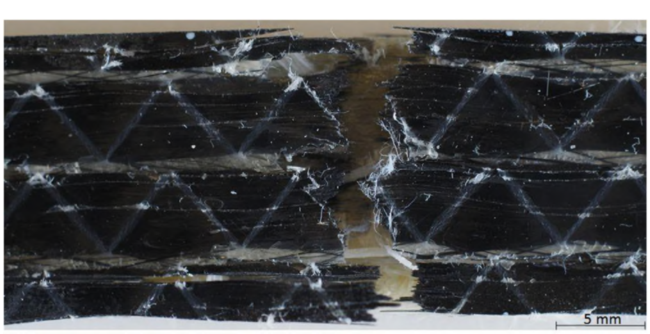

Fig. 14. Damaged hybrid continuous-discontinuous SMC specimen resulting from uniaxial tension (top view).

that macroscopically visible inter-bundle fractures were accompanied by interfibre fractures of the continuous material (Fig. 17). In addition, matrix cracks, which grew perpendicular to the tensile direction were present. Interface failure between fibres and matrix and breakage of individual glass fibres determined failure of the discontinuous phase in the transition zone. The discontinuous material mainly failed due to (intralaminar) pseudo-bundle-delamination. Damage of hybrid continuous-discontinuous glass/carbon fibre SMC exposed to uniaxial compression was initiated by an abrupt failure of continuous carbon fibre layer due to fibre fractures (Fig. 18, a and Fig. 19, 2). Although fibre fractures happend on the microscopic scale they became visible at the macroscopic scale since entire fibre bundles failed at the same moment. The fibre fractures were followed by an interfibre failure between different fibre bundles (Fig. 18, b). Fractured fibres led to a local interlaminar delamination (Fig. 19, 2–5), to a spalling of the matrix

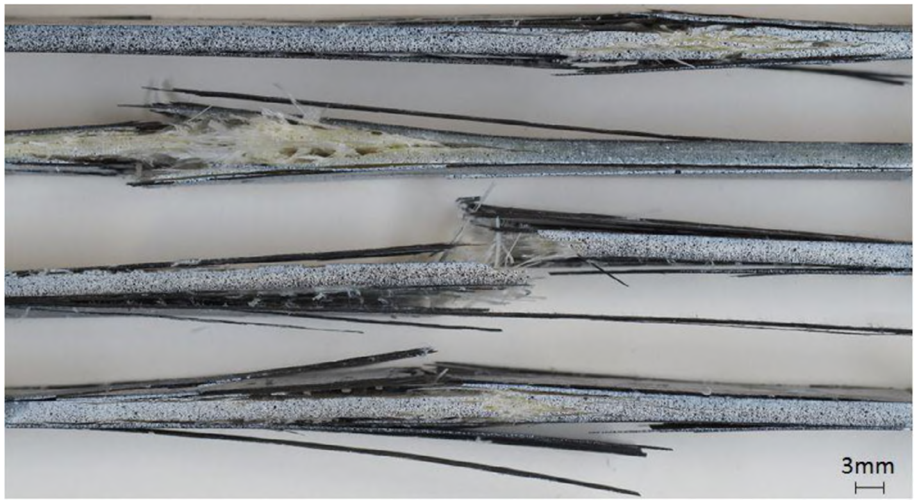

Fig. 15. Damaged hybrid continuous-discontinuous SMC specimen resulting from uniaxial tension (side view).

(Fig. 18, c) and to a progressive weakening of the specimen, which slightly started to bend (Fig. 19, 5). If the applied load exceeds the residual compressive strength of the laminate, final failure was suddenly initiated. It could mainly be characterized by intralaminar pseudo-delamination of the discontinuous glass fibre SMC (Fig. 19, 6).

5.4. Analytical prediction of tensile and compressive modulus of elasticity of continuous-discontinuous glass/carbon fibre SMC

The resulting longitudinal (in fibre direction of the continuous phase) tensile and compressive modulus of elasticity of the hybrid continuous-discontinuous SMC were predicted by a rule of mixtures

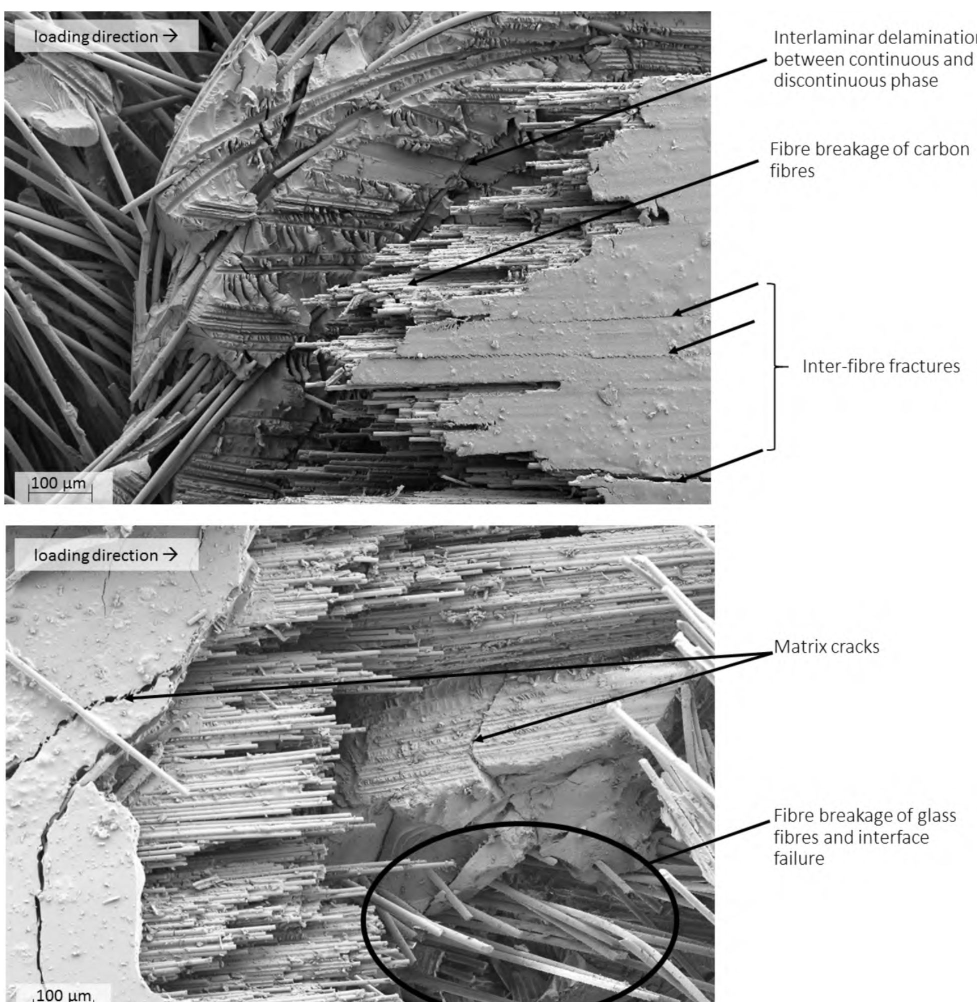

Fig. 16. SEM investigation of microscopic failure mechanisms of post-mortem continuous-discontinuous hybrid SMC specimen exposed to tensile loading.

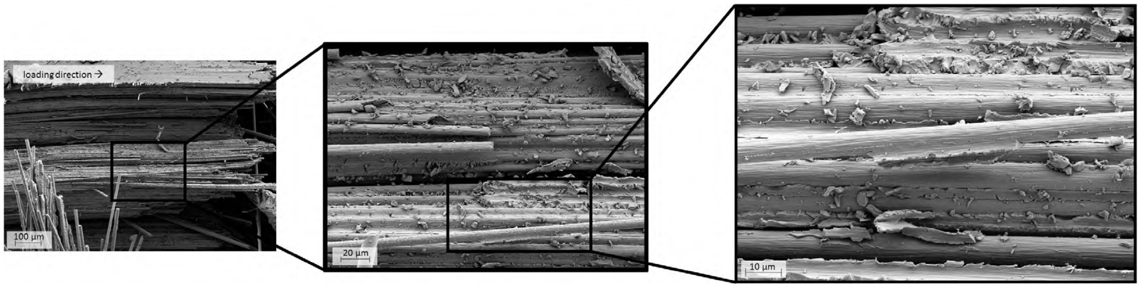

Fig. 17. SEM investigation of microscopic failure mechanisms of continuous phase of post-mortem continuous-discontinuous hybrid SMC specimen exposed to tensile loading.

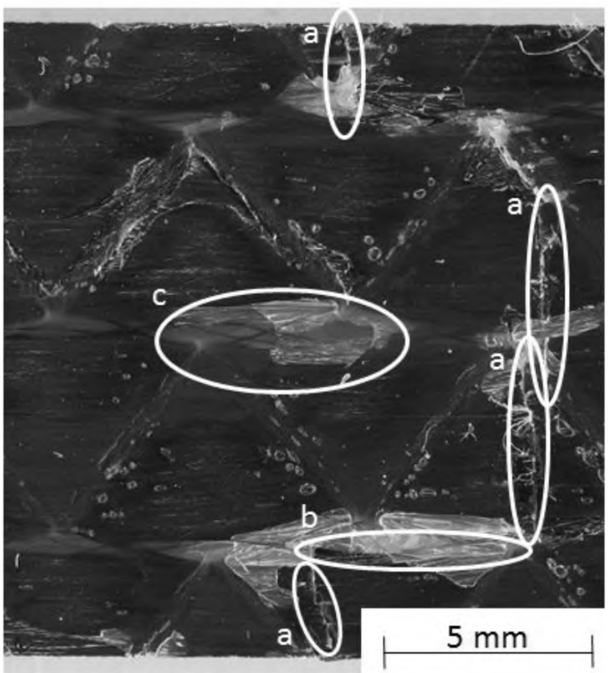

Fig. 18. Damaged hybrid continuous-discontinuous SMC specimen resulting from uniaxial compression (top view).

according to Eqs. (5) and (6). Fig. 20 shows the upper and lower bounds of the resulting transverse and longitudinal tensile and compressive moduli of elasticity, which are based on the minimum and maximum experimentally determined stiffness of the continuous and discontinuous phase. The dashed line indicates the resulting average. The arithmetic mean value of the experimentally determined stiffness of the hybrid continuous-discontinuous SMC is indicated by a black square, with a horizontal and vertical whisker to show the 1-σ standard variation of the thickness of the discontinuous glass fibre SMC layer and of the stiffness of the hybrid continuous-discontinuous SMC laminate.

In both loading cases, the presented analytical approach enabled the prediction of the resulting material stiffness of the hybrid continuous-discontinuous material considered within this study.

6. Discussion

The continuous-discontinuous glass/carbon fibre hybrid SMC was successfully manufactured in a one-shot compression moulding process.

The discontinuous glass fibre SMC featured an average fibre volume content of 25.8 vol.%, which was higher than the theoretically set value of 23 vol.%. During manufacturing, resin at the edges of the foil was pressed out due to calendaring and rolling up of the semi-finished material, leading to a slightly higher FVC of the moulded sheets. The continuous carbon fibre SMC sheets showed no significant variations in terms of fibre volume content, except from the thinnest sheet with a thickness of approximately 1 mm and a variation of CV = 3.8%. Depending on the degree of crosslinking and thus the resulting impregnation of the fibres, the continuous carbon fibre sheets, may sporadically show dry spots, which can be a possible cause of the locally different fibre volume content and a higher real fibre volume content than theoretically predicted.

The mechanical material properties of the discontinuous glass fibre SMC showed significant scatter in terms of modulus of elasticity and strength. Mechanical testing of discontinuous (long) fibre reinforced polymers is challenging in terms of specimen geometry and there are no standards for hybrid composite structures yet. In general, the mechanical characterisation of continuously reinforced composites is more complicated than the testing of discontinuous fibre reinforced materials. For this reason, specimen geometries for all tests and material types considered within this study were adapted to the continuous carbon fibre SMC materials, to facilitate comparison and to prevent slipping of this material during loading. Marissen et al. [29] indicated the influence of the specimen's geometry on material characterisation and resulting properties. Thus, it has to be considered to proceed with a

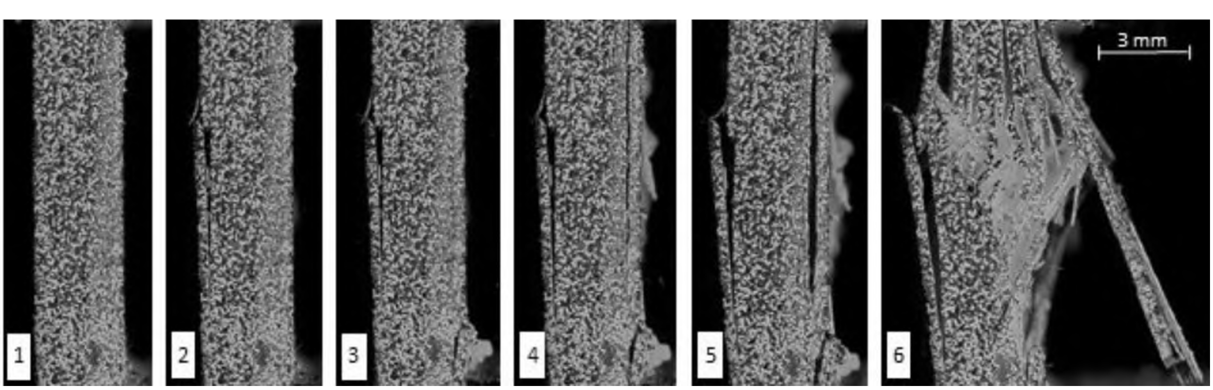

Fig. 19. Hybrid continuous-discontinuous SMC: Damage evolution resulting from uniaxial compression (side view).

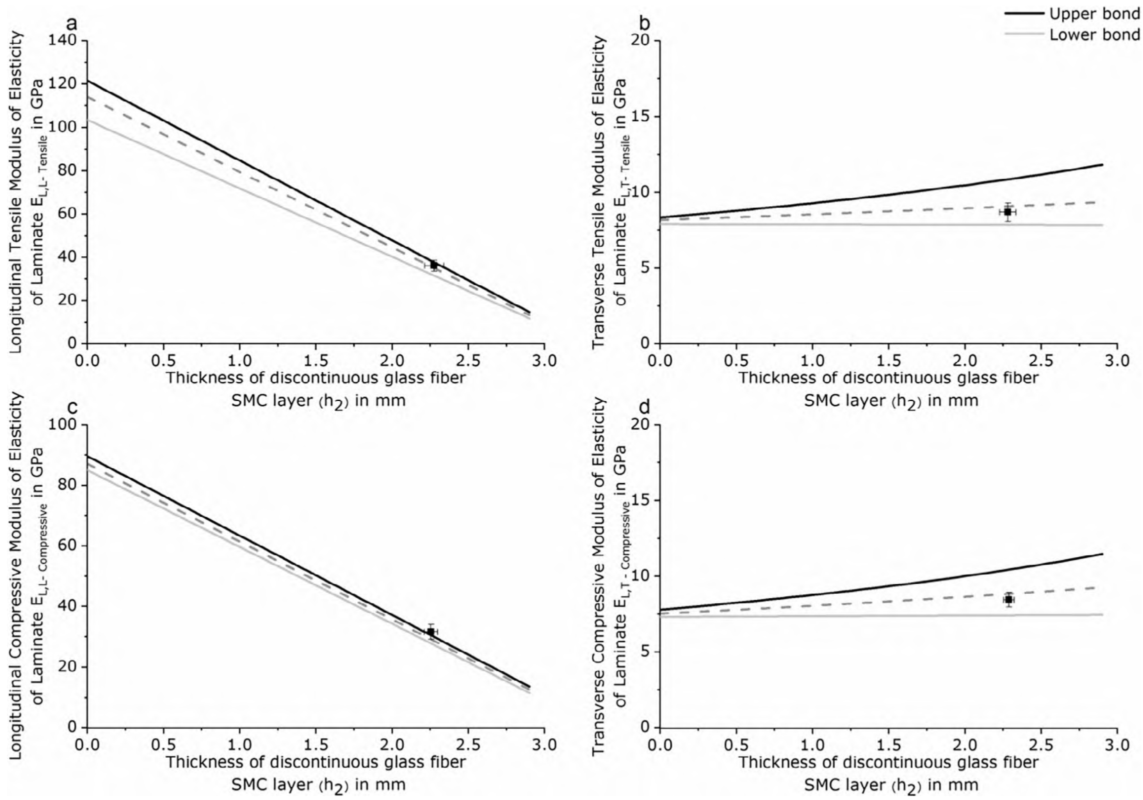

Fig. 20. Analytical modelling of longitudinal (a and c) and transverse (b and d) tensile and compressive modulus of elasticity.

further testing series which consider different specimen geometries for the discontinuous glass fibre SMC material, adapted to fibre length and local variations of fibre volume content within one sheet to possibly reduce the scatter of mechanical properties. Resulting from the variation of thickness of the individual semi-finished sheets stacked in the mould and the 1D flow, there are non-equal flow conditions across the width of the sheet. Hence the ends of the longitudinal sides of the moulded sheets showed some flow effects. One can assume that these effects also influence the local fibre distribution and fibre orientation and thus the resulting mechanical material properties. These effects may also be present in hybrid continuous-discontinuous SMC sheets and should be investigated by further µCT scans of specimens extracted at the edges of a sheets.

Tensile and compressive modulus of elasticity and strength of the continuous carbon fibre SMC in fibre direction showed a significant scatter. Taking into account the already discussed dry spots is important to understand the variation of mechanical material properties. Besides that fibre misalignment, resulting from manufacturing of the non-crimped fabric and extraction of specimens may significantly influence the material's stiffness and strength [30]. As a consequence of micro-buckling of the fibres, the compressive modulus of elasticity was significantly lower than the tensile modulus of elasticity.

Hybridisation of SMC significantly enhanced material's tensile properties with an increase of tensile modulus of elasticity of 171% and a tripled tensile strength, if loaded in fibre direction. With an increase of 151% of the compressive modulus of elasticity, the increase was less important than for tensile loading and reflects the lower compressive modulus of elasticity of the purely continuous carbon fibre SMC compared to the tensile modulus of elasticity of the same material.

Since the mechanical material properties of the unidirectional carbon fibre SMC loaded perpendicular to the fibres were mainly matrix dominated and lower than the material properties of the purely discontinuous glass fibre SMC in 90°, the resulting material properties of the hybrid continuous-discontinuous SMC were slightly decreased if loaded in this direction.

The misalignment of the carbon fibres and the shearing of the individual bundles during flow of the discontinuous phase are critical if tensile loads are applied to a hybrid continuous-discontinuous SMC, since failure is mainly initiated in these regions. The tensile failure was progressive, which was reflected by small load drops in the stress strain curve. Each drop is marked by the formation of a new interfibre crack of the continuous phase.

As a consequence of the significantly lower compressive strain at the moment of failure of the continuous carbon fibre SMC compared to the discontinuous glass fibre SMC, the material damage was initiated due to fibre breakage. A progressive weakening of the specimens led to final failure.

Longitudinal and transverse tensile modulus of elasticity could successfully be predicted by a rule of mixtures. Analytically determined, the longitudinal compressive modulus of elasticity was slightly underestimated, although the proposed method refers to the Voigt approach which neglects inherent distortion and slightly overestimates homogenized properties [31]. It is possible that the discontinuous glass fibre SMC core supports the continuous carbon fibre outer layers, reducing the micro-buckling effect of this material and leading to a higher compressive modulus of elasticity in reality than analytically predicted. Mostly, a resulting stiffness of a hybrid material is more than the sum of its parts and it can be concluded that the proposed modified rule of mixtures is a conservative method to predict resulting stiffness of a hybrid continuous-discontinuous glass/carbon fibre SMC.

7. Conclusion and outlook

In this paper, discontinuous glass fibre SMC and continuous carbon fibre SMC were combined in a one-shot compression moulding process to manufacture hybrid continuous-discontinuous SMC laminates. Both semi-finished materials were manufactured on a conventional flat conveyor belt and were based on an unsaturated polyester-polyurethane two-step curing resin system, allowing optimized chemical bonding between the different layers.

Using this approach, tensile and compressive modulus of elasticity in fibre direction increased significantly, (+171% and +151%, respectively) due to hybridisation. A modified rule of mixtures was presented enabling to predict the resulting elastic material properties. Tensile strength was also significantly increased (+204%). Compressive strength slightly decreased. Hybridisation did not significantly change the material properties perpendicular to the fibres. Hybrid SMC specimens exposed to uniaxial tensile and compressive loading showed a progressive failure, which started with failure of the continuous carbon fibre SMC outer layers. The most important failure mechanisms were interfibre fractures for tensile and fibre breakage followed by interfibre fractures for compression loadings.

The results obtained from this paper underline the potential of hybrid continuous-discontinuous SMC. In the automotive industry, SMC is especially considered for large scale components like trunks and thus predominantly loaded in bending as plate elements. For this reason, bending and puncture loadings on component and structural level have to be considered for following experimental investigations.

In addition, modification of reinforcement architecture to achieve a local continuous carbon fibre reinforcement of discontinuous glass fibre SMC components is conceivable with respect to manufacturability.

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References

[1] Bruderick M, Denton D, Shinedling M, Kiesel M. Application of Carbon Fiber SMC for the Dodge Viper, http://www.quantumcomposites.com/pdf/papers/Viper-SPE-Paper.pdf [accessed 24.01.2018].
[2] Gardiner G. Is the BMW 7 Series the future of autocomposites? http://www.compositesworld.com/articles/is-the-bmw-7-series-the-future-of-autocomposites; 2016 [accessed 24.01.2018].
[3] The European Alliance for SMC/BMC, Design for Success: A Design & Technology Manual for SMC/BMC; 2005.
[4] Witten E, Kraus T, Kühnle M. Compos Market Rep 2016;2016.
[5] Lamanna G, Ceprano A. Mechanical characterization of sheet moulding composites for the automotive industry. TOMSJ 2014;8:108–13.
[6] Oldenbo M, Fernberg SP, Berglund LA. Mechanical behaviour of 5SMC6 composites with toughening and low density additives. Compos A Appl Sci Manuf 2003;34:875–85.
[7] Boylan S, Castro JM. Effect of reinforcement type and length on physical properties, surface quality, and cycle time for sheet molding compound (SMC) compression molded parts. J Appl Polym Sci 2003;90:2557–71.
[8] Trauth A, Pinter P, Weidenmann KA. Investigation of quasi-static and dynamic material properties of a structural sheet molding compound combined with acoustic emission damage analysis. J Compos Sci 2017;1.
[9] Fette M, Hentschel M, Santafe JG, Wille T, Büttemeyer H, Schiebel P. New methods for computing and developing hybrid sheet molding compound structures for aviation industry. 1st CIRP Conference on Composite Materials Parts Manufacturing (CIRP CCMPM 2017); 2017: 45–50.
[10] Fette M, Hentschel M, Köhler F, Wulfsberg J, Herrmann A. Automated and cost-efficient production of hybrid sheet moulding compound aircraft components. 16th Machining Innovations Conference for Aerospace Industry – MIC 2016 6; 2016: 132–139.
[11] Wulfsberg J, Herrmann A, Ziegmann G, Lonsdorfer G, Stöß N, Fette M. Combination of carbon fibre sheet moulding compound and prepreg compression moulding in aerospace industry. Procedia Eng 2014;81:1601–7.
[12] Fette M, Reiß M, Wulfsberg J, Stoess N, Hentschel M. New approach for the efficient manufacturing of sandwich structures based on sheet moulding compounds. Adv Mater Res 2016:264–71.
[13] Corbridge DM, Harper LT, de Focatiis DSA, Warrior NA. Compression moulding of composites with hybrid fibre architectures. Compos A Appl Sci Manuf 2017;95:87–99.
[14] Gortner F, Medina L, Mitschang P, editors. Advanced SMC-Processing in Combination with Textile Reinforcements; 2015.
[15] Gortner F, Medina L, Mitschang P. Influence of textile reinforcement on bending properties and impact strength of SMC-components. Int J Appl Sci Technol 2015;8:259–69.
[16] Bücheler D, Henning F., Hybrid resin improves position and alignment of continuously reinforced prepreg during compression co-molding with sheet molding compound, 17th European Conference on Composite Materials, ECCM 17; 2016: 6699–6703.
[17] Trauth A, Bücheler D, Henning F, Weidenmann KA. Mechanical Porperties of Unidirectional Continuous Carbon Fiber Reinforced SMC. 17th European Conference on Composite Materials; 2016.
[18] Desrumaux F, Meraghni F, Benzeggagh ML. Generalised Mori-Tanaka scheme to model anisotropic damage using numerical Eshelby tensor. J Compos Mater 2001;35:603–24.
[19] Tucker CL, Liang E. Stiffness predictions for unidirectional short-fiber composites. Compos Sci Technol 1999;59:655–71.
[20] Jendli Z, Meraghni F, Fitoussi J, Baptiste D. Multi-scales modelling of dynamic behaviour for discontinuous fibre SMC composites. Mech Resp Fibre Reinf Compos 2009;69:97–103.
[21] Chen Z, Huang T, Shao Y, Li Y, Xu H, Avery K, et al. Multiscale finite element modeling of sheet molding compound (SMC) composite structure based on stochastic mesostructure reconstruction. Compos Struct 2018;188:25–38.
[22] Swolfs Y, Gorbatikh L, Verpoest I. Fibre hybridisation in polymer composites: a review. Compos A Appl Sci Manuf 2014;67:181–200.
[23] ASTM International. D3039/D3039M − 14: Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials, United States.
[24] ASTM International. E111–04 (Reapproved 2010): Standard Test Method for Young's Modulus, Tangent Modulus, and Chord Modulus, United States.
[25] ASTM International. Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials with Unsupported Gage Section by Shear Loading, ASTM International, West Conshohocken, PA 19428-2959. United States, Reapproved 2008.
[26] Bücheler D, Kaiser A, Henning F. Using thermogravimetric analysis to determine carbon fiber weight percentage of fiber-reinforced plastics. Compos B Eng 2016;106:218–23.
[27] Schürmann H. Konstruieren mit Fraser-Kunststoff-Verbunden. 2nd ed. Berlin Heidelberg: Springer-Verlag; 2007. p. 2007.
[28] Jendli Z, Meraghni F, Fitoussi J, Baptiste D. Micromechanical analysis of strain rate effect on damage evolution in sheet molding compound composites. Compos A Appl Sci Manuf 2004;35:779–85.
[29] Marissen R, Linsen J. Variability of the flexural strength of sheet moulding compounds. Compos Sci Technol 1999;59:2093–100.
[30] Mallick P. Effect of fiber misorientation on the tensile strength of compression molded continuous fiber composites. Polym Compos 1986;7.
[31] Voigt W. Über die Beziehung zwischen den beiden Elastizitätskonstantenisotroper Körper. Ann Phys 1887;38:573–87.