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Puncture properties of a hybrid continuous-discontinuous sheet moulding compound for structural applications

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ABSTRACT

A novel two-step curing resin system and adapted moulding approach enables the manufacturing of hybrid continuous-discontinuous SMC in a one-shot process. Hybridization led to a significant increase of maximum force (+36%) and puncture energy (+35%) if specimens were punctured in a quasi-static manner. The effect of hybridization was less distinct under dynamic loading (increase of 13% and 7%, respectively), due to a negative rate dependency of the continuous carbon fibre SMC. An increase from $4.4{\cdot}10^{-5}\,\mathrm{m{\cdot}s^{-1}}$ to $4.4\,\mathrm{m{\cdot}s^{-1}}$ resulted in a positive rate dependence of the hybrid SMC with increased maximum force (+33%) and puncture energy (+18%). Important failure mechanisms were inter-bundle and inter-fibre fracture of the continuous SMC and pseudo-delamination (intra-laminar) of the discontinuous component. Delamination took place at both considered loading rates but was more important if hybrid SMC was punctured in a dynamic manner.

1. Introduction

The increasing demand in lightweight vehicle concepts has drawn significant interest in fibre reinforced composites for structural applications. Due to significantly lower material and manufacturing costs compared to continuously fibre reinforced materials, discontinuous fibre reinforced composites have become a focus of research to replace structural components. Among this type of composite, sheet moulding compounds (SMC) (in combination with bulk moulding compounds) ranked first among the most manufactured thermoset glass fibre reinforced materials in Europe in 2016 [1]. The field of application of SMC materials is diverse, with increasing interest in the automotive sector [2,3]. Sheet moulding compounds, as they are known today, date back to the 1960s, but in contrast to these standard SMC composties, more recent SMC formulations aimed to increase mechanical performance and lightweight potential by substituting glass fibres with carbon fibres [4] or by considering special fillers and additives [5] to achieve a reduced density of the material. In general, sheet moulding compounds consist of a thermoset resin and embedded chopped (discontinuous) fibres. A major advantage of discontinuous fibre reinforced polymers is the high design freedom to manufacture parts with complex geometries. In contrast, due to the finite fibre length and random orientation of fibre bundles in two directions, mechanical properties in terms of stiffness and strength are limited. Continuous fibre reinforced polymers feature superior mechanical properties. However, material and manufacturing costs as well as a significantly reduced formability represent important drawbacks of this material class.

The idea to combine discontinuous SMC with continuous fibrous reinforcements was introduced by Mallick [6] and Taggart [7]. Although these contributions already demonstrated the positive hybridization effect of SMC composites in the 1970s, to the best of the authors' knowledge, further studies, related to gain understanding of hybrid SMC materials, date back to no more than approximately five years. The combination of chopped fibre SMC with pre-impregnated woven fabric or unidirectional fibres, in a single-stage compression moulding process led to improved tensile and flexural properties. Depending on local reinforcement, Charpy impact properties were also significantly increased [8,9]. Nevertheless, the high material and manufacturing costs of continuous fibre reinforced pre-impregnated materials were a significant drawback of this approach. In addition, effect of hybridization was strongly affected by the flow of the chopped fibre SMC during moulding, due to shearing of the continuous fibres resulting from transverse flow of the discontinuous material or due to ply migration resulting from low alignment in the fibre direction [8]. Gortner et al. presented an alternative processing route by combining dry textile preforms and a discontinuous SMC composite. Although this approach enabled the enhancement of mechanical material properties under tensile and bending loadings, the remaining void content due to

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poor impregnation and the relatively low fibre volume content of the discontinuous SMC was a crucial factor in material mechanical performance [10].

To investigate the hybrid continuous-discontinuous glass/carbon fibre SMC considered within this study, two semi-finished components were individually manufactured on an (adopted) SMC conveyor belt and compression moulded in a one-shot compression moulding process. Both components were based on an unsaturated polyester-polyurethane two-step curing hybrid resin system, which allowed for a perfect chemical bond. This is a significant advantage compared to other strategies to hybridise SMC materials. The presented hybridization approach significantly enhanced mechanical material properties when exposed to quasi-static uniaxial loads [11]. Locally reinforced components with enhanced mechanical performance were also already realized [12]. In reality, structural components are often exposed to multiaxial loading conditions. In addition, impacts due to foreign objects during maintenance, manufacturing or in service are important to consider and especially low-velocity impacts with large masses reflecting severe impact situations.

From a material point of view, impact properties of SMC are strongly affected by the individual constituents of the composite, specifically, fibre and matrix type [13,14]. In addition, specimen geometry, especially thickness of the specimen, as well as test setup and properties of the penetrating impactor [15,16] play an important role in puncture performance. In contrast to discontinuous glass fibre SMC, which showed a positive strain rate dependence when punctured with a hemispherical impactor, discontinuous carbon fibre SMC was insensitive to a variation in strain rate [17].

Hybridization of composites has been shown to be an effective way to increase puncture properties in terms of energy absorption and puncture resistance [18]. Quasi-static puncture properties of glass/polyester Kevlar/polyester hybrid composites were improved due to hybridization and maximum load and absorbed energy significantly increased depending on position of the Kevlar layer [19]. Hybrid plain weave S2-glass and Twill weave carbon -fibre reinforced composites showed enhanced puncture properties in terms of stiffness and damage tolerance when exposed to low-velocity impacts [20].

A first attempt to investigate puncture properties of hybrid SMC according to EN ISO 6603–2 [21] with a drop tower pointed out, that a single or double-sided reinforcement of a chopped glass fibre SMC considering a ± 45° non-crimp fabric can increase maximum force and maximum absorbed energy in a significant way [10]. The results from these first investigations of puncture properties of hybrid composites were promising. To continue, the present contribution not only focus on puncture properties of hybrid continuous-discontinuous SMC manufactured in a one-shot compression moulding process, but also on damage evolution and failure mechanisms of this hybrid continuous-discontinuous SMC material resulting from quasi-static or low-velocity puncture. A comparison with the puncture properties of purely discontinuous glass fibre SMC furthermore enabled to evaluate the hybridization effect in terms of puncture properties and loading rate sensitivity.

2. Materials

2.1. Material manufacturing and specimen preparation

The discontinuous as well as the continuous semi-finished sheets were manufactured on a flat conveyor belt (type HM-LB-800 by Schmidt&Heinzmann, Bruchsal, Germany) at the Fraunhofer ICT in Pfinztal, Germany, by feeding either chopped 25.4 mm long glass fibre bundles or a unidirectional carbon fibre non-crimp fabric to the conveyor belt. Both materials were based on an unsaturated polyester-polyurethane two step curing hybrid resin system, which allows for the adaption of the paste's viscosity throughout the whole process chain [22]. In addition, a perfect chemical bond in the final hybrid continuous-discontinuous SMC was possible. Nominal fibre volume content of the discontinuous glass and the continuous carbon fibre SMC was 23 vol.% and 47 vol.%, respectively. A detailed description of the resin composition for the two different semi-finished materials can be found in Ref. [11].

Fig. 1. Investigated SMC materials. From top to bottom: discontinuous glass fibre SMC (Dico SMC), continuous carbon fibre SMC (Co SMC) and hybrid continuous-discontinuous glass/carbon fibre SMC (CoDico SMC).

After maturation, the discontinuous and continuous semi-finished materials were cut into plies, stacked and compression moulded into plaques with a moulding temperature of approximately 150 °C, at 2500 kN and a mould closure time of 112 s. To investigate puncture properties and the effect of hybridization, discontinuous glass fibre SMC, continuous carbon fibre SMC and continuous-discontinuous glass/carbon fibre SMC were considered for testing (Fig. 1, Table 1). All plaques were manufactured in a rectangular mould (800 mm × 250 mm). The stack of the discontinuous glass and the continuous-discontinuous glass/carbon fibre SMC sheets was placed in the middle of the mould (with a mould coverage of approximately 35%) to achieve a 1D flow of the discontinuous SMC material during moulding. The continuous SMC material did not flow. The nominal thickness of all plaques was 3 ± 0.2 mm.

The flat square-shaped specimens featured an area of 140 mm × 140 mm and were cut using abrasive water jet cutting by SNZ Schneidbetrieb GmbH (Mühlacker, Germany). Specimens for mechanical investigation were extracted from flow and charge region of the plaques to identify the influence of material flow during compression moulding on material properties.

3. Methods

3.1. Quasi-static puncture testing

Quasi-static puncture tests were carried out on an MTS Criterion Model 45 electromechanical load frame. The lubricated (PC Waylube 68) hemispherical impactor, featuring a diameter of 20 mm, punctured the specimen perpendicular to its surface with a nominally uniform velocity of 2.6 mm min^{-1} (approx. $4.4{\cdot}10^{-5}\,\text{m}{\cdot}\text{s}^{-1}$) up to a defined maximum deflection of 20 mm. The flat square-shaped specimens were mechanically clamped with a custom made fixture to provide a circular puncture area with a diameter of 100 mm (Fig. 2). A load cell with a capacity of 150 kN, integrated in the load frame, captured resulting force during puncture of the specimen. In addition, displacement of the impactor was measured by the crosshead displacement of the MTS load frame.

To capture damage evolution during loading, a Point Grey Research Grasshopper GRAS-50S5M 5.0 megapixel monochrome camera incorporating a 35 mm CM120 Schneider-Kreuznach lens was placed at one side of the fixture underneath the specimen. Digital photographs were acquired at one frame per second and photographic observations were captured throughout the quasi-static loading up to the maximum deflection. These images were used to assess damage and its evolution; no measurement of displacement or strains were completed using the acquired digital imagery. To ensure sufficient illumination an external light source and an inclined mirror were placed beneath the specimen. A Correlated Solutions VIC-Snap transistor to transistor logic (TTL) interface established the synchronization between the load frame and camera with a signal from the load frame at a user defined digital output connected to a National Instruments (NI) USB 6221 BNC data

Table 1
Fibre type, nominal fibre volume content and fibre length of investigated SMC materials.

Material	Fibre type	Nom. fibre content in vol. %	Fibre length
discontinuous SMC (Dico SMC)	chopped glass fibres	23	25.4 mm
continuous SMC (Co SMC)	unidirectional carbon fibres (non-crimp fabric)	47	continuous
continuous-discontinuous SMC (CoDico SMC)	chopped glass and unidirectional carbon fibres (non-crimp fabric)	–	glass fibres: 25.4 mm, carbon fibres: continuous

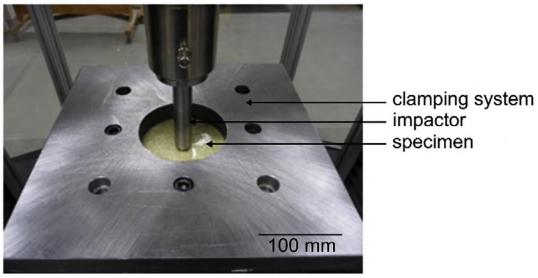

Fig. 2. Test setup to fully clamp specimen.

acquisition device. Measured force and displacement signals to derive force-displacement curves were not filtered. Six specimens of each configuration were considered for testing.

3.2. Dynamic puncture testing and data processing

Low-velocity impact tests, referred to as 'dynamic puncture tests' within this manuscript, were conducted using a custom drop tower testing machine modified to complete ISO 6603–2 [21] instrumented impact tests. The flat, square-shaped specimens were mechanically clamped under a metal plate to provide a circular impact area with a diameter of 100 mm, consistent to the quasi-static puncture testing (Fig. 2). Considering that external forces, which are applied to the specimen, are limited to the impactor and the clamping system, the only work done to the specimen is by the impactor, as there is no deflection at the clamping ring. According to the ISO 6603-2 standard [21] the specimens were punctured with a velocity of 4.4 ± 0.2 $m{\cdot}s^{-1}$. Furthermore, in order to fulfil the requirement to realize puncture with a nominally uniform velocity a significant large mass of the impacting unit (61 kg) ensured that changes in velocity during impact were negligible.

Resulting forces and crosshead displacement were measured with a Dytran Model 1050 Integrated Electronic Piezoelectric (IEPE) load cell and an Acuity laser displacement transducer with a sensitivity of 30 mm/V and a measurement range of 300 mm, respectively. The load cell, which was integrated in the shaft of the impactor, ensured a measurement of the impact load very close to the location of contact. A custom LabVIEW program allowed for acquisition of the force-deflection data and also permitted appropriate triggering and synchronization of the high speed photographic images with the transducer data acquisition. A 24 bit resolution National Instrument (NI) 9233 IEPE data acquisition module incorporated into a NI CompactDAQ chassis acquired force-time data at 50 kHz with a 24 bit resolution. Deflection-time data was also acquired at 50 kHz with a 16 bit NI 9205 analog input module.

Force-deflection data was post-processed with Matlab® 2017a. In this matter, the raw data captured by the laser displacement transducer and load cell during dynamic impact was filtered considering a four pole Butterworth filter with a channel frequency class (CFC) of 600 (approximately 1000 Hz cutoff) consistent with the Society of Automotive Engineers standard SAE J211 [23]. Energy was computed by integrating the force-displacement response with the trapezoid method, according to ISO 6603–2 [21].

A Photron SA4 camera was positioned in a suitable configuration to enable for high speed imagery acquisition during the dynamic puncture event. The high speed camera, which was triggered with a transistor to transistor logic (TTL) signal from a NI 9401 digital input/output module, captured high speed images for a total duration of 10 ms with a frame rate of 50000 frames per second, a shutter speed of 1/70000 s and a resolution of 320 pixel by 192 pixel. High speed imagery enabled to in-situ capture damage evolution of the SMC materials exposed to dynamic puncture. Similar to the quasi-static test configuration, digital imagery was not used for any assessment of strains or displacement. Fig. 3 schematically depicts test setup and measuring devices considered to capture the dynamic force-displacement response of the punctured SMC composites. Six specimens of each configuration were considered for testing.

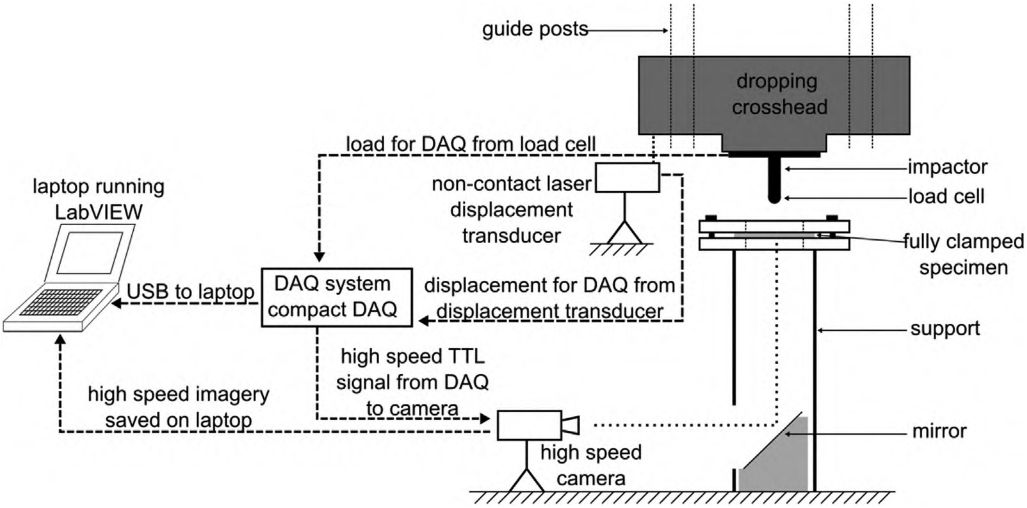

Fig. 3. Schematic illustration of dynamic puncture testing.

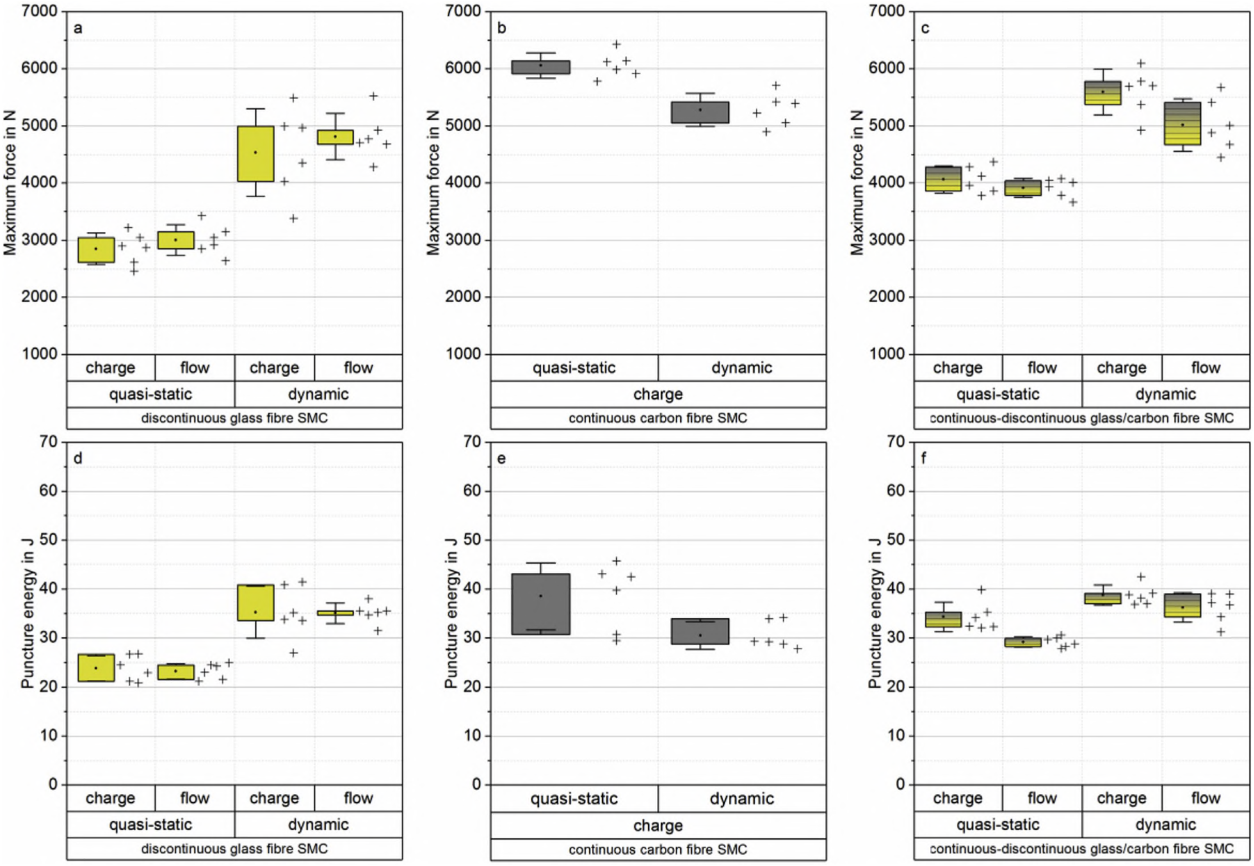

Fig. 4. Puncture properties of SMC composites. Top row: Maximum force of discontinuous glass fibre SMC (a), continuous carbon fibre SMC (b) and continuous-discontinuous glass/carbon fibre SMC (c). Bottom row: Puncture energy of discontinuous glass fibre SMC (d), continuous carbon fibre SMC (e) and continuous-discontinuous glass/carbon fibre SMC (f). The boxes represent the 25th and 75th percentile of experimental results, average mean value is marked by a black dot inside each box and the whiskers represent the standard deviation. The crosses next to each box identify experimental results of every individual specimen.

3.3. *Observation of damaged specimens*

Selected post-mortem specimens, which were punctured in a quasi-static and dynamic manner, have been investigated by means of Scanning Electron Microscopy (SEM) to observe damage mechanisms on a microscopic scale. SEM examinations were carried out using a SUPRA 55 VP SEM by Zeiss.

4. Results

4.1. *Effect of hybridization on puncture properties and rate sensitivity*

Fig. 4 shows puncture properties, namely maximum force and puncture energy, resulting from quasi-static and dynamic puncture of continuous carbon fibre SMC (Co CF SMC), discontinuous glass fibre SMC (Dico GF SMC) and hybrid continuous-discontinuous glass/carbon fibre SMC (CoDico GF/CF SMC).

In this investigation the (absorbed) puncture energy of the specimen during quasi-static or dynamic loading was computed as follows:

$$E_p = \int_0^{x_p} F dx \tag{1}$$

with the force F and the deflection x. A numerical approximation to this integration was completed by utilizing a trapezoid rule. To mitigate or eliminate the aspect of friction between the impactor and the punctured surface, the puncture energy, E_p, was calculated up to the puncture deflection (x_p) according to ISO 6603–2 [21]. Within this ISO standard, x_p is defined as the position were the instantaneous measured load is half of the precedent maximum load occurred during puncture.

Within Fig. 4, the boxes represent the 25th and 75th percentile of experimental results. The average mean value is marked by a black dot inside each box and the whiskers represent the standard deviation of the evaluated property. The crosses next to each box identify the mechanical performance of every individual specimen to get a deeper insight about scatter and distribution of the evaluated property.

Charge and flow region specimens of discontinuous glass fibre SMC showed no significant difference in terms of maximum force, resulting from quasi-static or dynamic puncture (Fig. 4a and d). However, if exposed to dynamic puncture, scatter of charge region specimens was more distinct. The same held true for puncture energy. The discontinuous glass fibre SMC showed a positive rate dependence and maximum force and puncture energy increased 60% and 50%, respectively, with no distinction made between charge and flow region specimens.

Considering continuous carbon fibre SMC, the dynamic puncture loading condition led to a decrease in maximum load (−13%) and energy absorption capability (−21%) of the specimens (Fig. 4b and e).

The continuous reinforcement of discontinuous glass fibre SMC significantly increased maximum force (+36%) and puncture energy (+35%) for specimens punctured in a quasi-static manner (Fig. 4c). The reinforcing effect was also present in the dynamic loading case, however it was less distinct with an increase of 13% for maximum force and 7% for puncture energy. Furthermore, the continuous-discontinuous glass/carbon fibre SMC specimens also showed a positive rate dependence with an increase of 33% for maximum force and 18% for puncture energy when loaded in a dynamic manner (Fig. 4f). In general, flow region CoDico specimens exhibited slightly lower structural properties compared to charge region CoDico specimens.

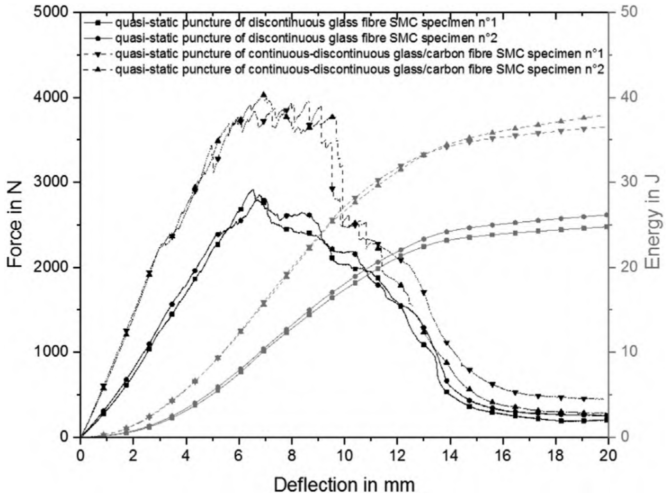

Fig. 5. Force-deflection and energy-deflection responses of discontinuous glass fibre SMC and continuous-discontinuous glass/carbon fibre SMC exposed to quasi-static puncture.

4.2. *Damage evolution and failure mechanisms of punctured CoDico SMC*

4.2.1. *Quasi-static force-deflection and energy-deflection response*

Discontinuous glass fibre SMC and continuous-discontinuous glass/carbon fibre SMC showed a similar force-deflection response when punctured in a quasi-static manner (two representative force-deflection and energy-deflection responses for the two materials are depicted in Fig. 5), however, differences in the magnitude of the loads were observed. At very low deflections evolution of the force-displacement curves are characterized by a combination of indentation (Hertzian contact [24]) and deflection. In the following, force increases linearly with deflection. In this initial part, energy absorption was negligible. The first part of the force-deflection response of the hybrid materials was dominated by the stiffness of the continuous carbon fibre SMC material, which also led to an overall stiffness increase of the hybrid continuous-discontinuous specimen compared to the discontinuous glass fibre SMC. The ascending part of the force-deflection response was marked by a change in specimen stiffness (at approximately 3 mm), linked to partial failure at the lower surface of the specimen. Within this section, low energy amounts were absorbed, reflecting an almost completely linear deformation behavior at the beginning of loading and low deflections. The yield point (defined as the first major deviation from linear force-deflection evolution [25]), indicating a transition from linear increase to an increase with reduced sloped linked to partial failure of the specimen. This transition was more distinct for the hybrid SMC composite and linked to a comparable load but to lower deflection with respect to the discontinuous SMC. Strength of the hybrid continuous-discontinuous SMC, expressed by maximum force appearing during puncture, was significantly higher compared to the discontinuous glass fibre SMC. Average deflection linked to maximum force of the hybrid SMC was approximately 8.3 mm (Coefficient of variation (CV) = 12%). For the discontinuous glass fibre SMC, maximum force was reached after approximately 7.1 mm (CV = 10%). The second part of the force-deflection response of the hybrid CoDico SMC was defined by a plateau, before force suddenly decreased due to final failure of the hybrid specimen (at a deflection of approximately 10 mm). The plateau region of the force-deflection response was a significant contributor to increased levels of energy dissipated due to deformation and failure.

The descending part of the force-deflection response of the discontinuous glass fibre SMC was marked by a gradual decrease after maximum force was reached up to approximately 12 mm followed by a significant load drop. Energy absorption was most important within this section until the impactor fully penetrated the specimen At the end of the puncture event, the friction between the impactor and the CoDico SMC specimen was slightly more significant than for the purely Dico SMC specimen.

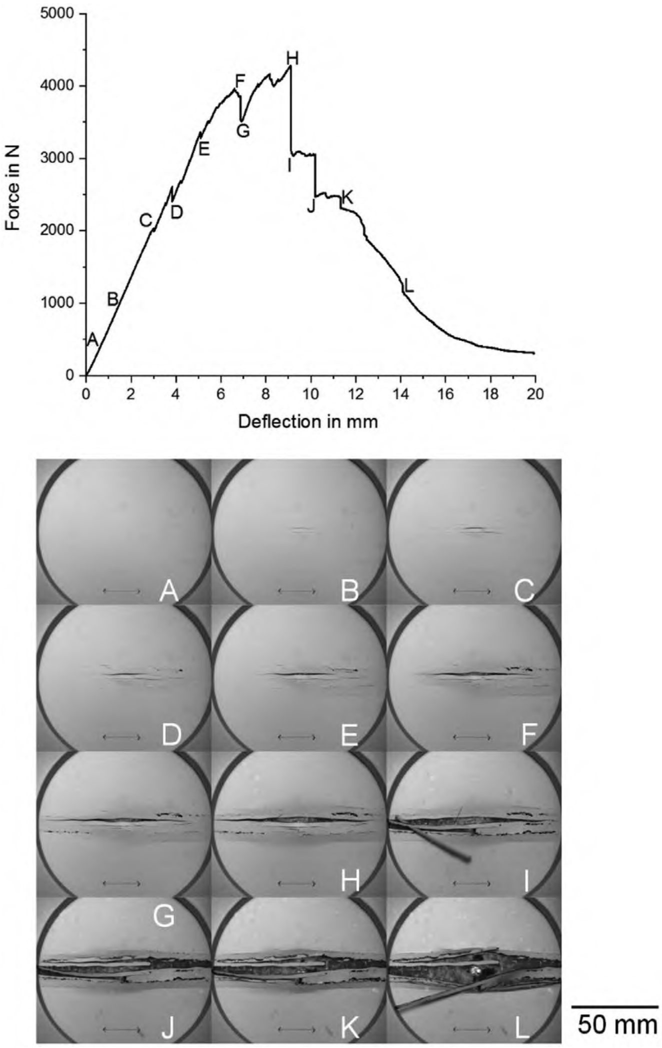

Fig. 6. Damage evolution of hybrid continuous-discontinuous glass/carbon fibre SMC exposed to quasi-static puncture.

4.2.2. *Macro- and mesoscopic damage evolution and failure mechanisms due to quasi-static puncture*

Damage evolution resulting from quasi-static puncture of CoDico SMC is depicted in Fig. 6. As force increased, small cracks in fibre direction of the continuous carbon fibres SMC became visible at the lower surface even at very low magnitudes of applied load (A). A further increase in load resulted in the formation of additional cracks and their propagation in fibre direction (inter-fibre and inter-bundle cracks). Although, the macroscopic stiffness of the hybrid specimens was hardly effected by the existence of these small cracks (B). The jagged evolution of the force-deflection response up to maximum load was due to a stepwise and spontaneous crack growth, spread of the crack network and the initiation of numerous inter-fibre and inter-bundle cracks (C-G). The significant load drop (F-G) was marked by a sudden crack propagation and this point could be identified as failure of the outer layer of the hybrid composite. The discontinuous glass fibre SMC was observed to maintain the load resulting from puncture of the impactor from points (G) through (H). In the following, fibre fractures of the continuous carbon fibres were observed below the impactor. (H-I). Due to

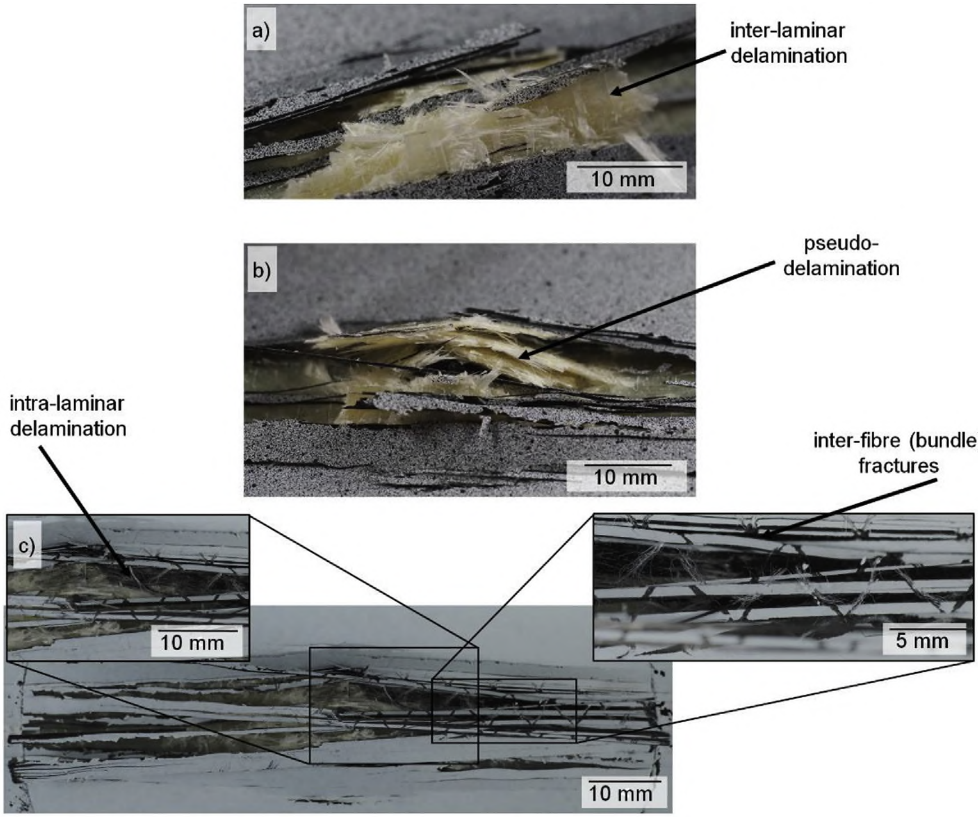

Fig. 7. Damaged hybrid continuous-discontinuous glass/carbon fibre SMC specimen exposed to quasi-static puncture.

delamination of the continuous carbon fibre bundles, the load significantly droped (H-J). At point (L) the specimen was fully penetrated and energy was only absorbed due to friction between the impactor and the specimen.

Post-mortem observation of the damaged specimen (Fig. 7) showed, that inter-laminar delamination between the discontinuous glass fibre and the continuous carbon fibre layer occurred, with the stitching yarns also fully delaminating from the discontinuous phase (Fig. 7a). At some points an intra-laminar (delamination within one component) delamination in form of splitting of the continuous SMC material took also place (Fig. 7c). Not only inter-bundle fractures but also inter-fibre fractures within the continuous carbon fibre reinforced material were noted to be an important damage mechanism resulting from quasi-static puncture of hybrid continuous-discontinuous SMC (Fig. 7c). Although the latter considers a microscopic failure mechanism of continuously fibre reinforced materials it also became visible on the macroscopic scale. In Fig. 7b, the pseudo-delamination of the discontinuous material becomes clearly visible. This term refers to a result of matrix failure and the propagation of microcracks which leads to the appearance of a large matrix surface between the glass fibre bundles [26]. Pseudo-delamination is favored by the pseudo-stratified microstructure and local delamination between bundles can significantly participate to energy absorption during crash situations [27].

4.2.3. *Dynamic force-deflection and energy-deflection response*

When dynamically loaded, the observed force-deflection response illustrated repetitive force vibrations for both materials in the beginning of loading (Fig. 8). This finding may be attributed to the vibratory response of the specimens during impact as was qualitatively assessed in the high speed images. These fluctuations in force were noted to be more severe for the discontinuous glass fibre SMC, featuring a lower stiffness. Consistent with the quasi-static findings, the force-deflection response could be divided in three sections. In the first part an increase in force for increasing deflection up to maximum load was observed, which was linked to an average displacement of 8 mm (CV = 5.3%) for the Dico SMC and 7.5 mm (CV = 11.5%) for the CoDico SMC. Up to a deflection of 2 mm energy absorption was negligible for both material types. In the following section, due to the continuous carbon fibre outer layers, hybrid CoDico SMC specimens absorbed more energy in an early stage of dynamic puncture. Thus, more energy was needed to initiate failure of the continuous carbon fibre. As soon as the outer layer of continuous carbon fibre SMC could not maintain load anymore, the energy absorption characteristics of the Dico and the CoDico SCM specimens, showed the same qualitative evolution.

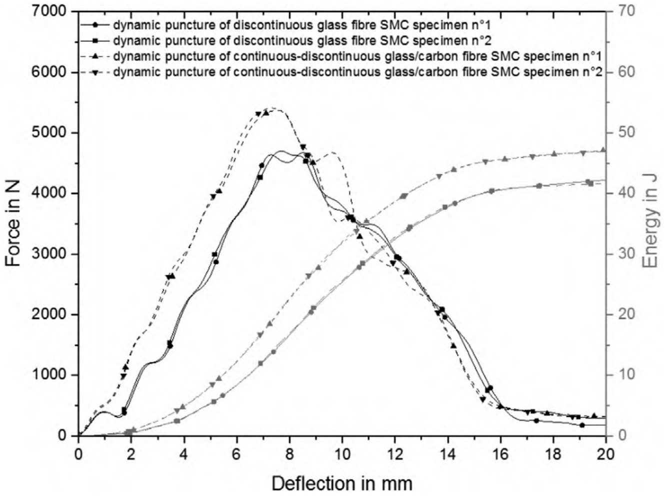

Fig. 8. Force-deflection response of discontinuous glass fibre SMC and continuous-discontinuous glass/carbon fibre SMC exposed to dynamic puncture.

Hence, the Dico SMC was more important to absorb energy in this

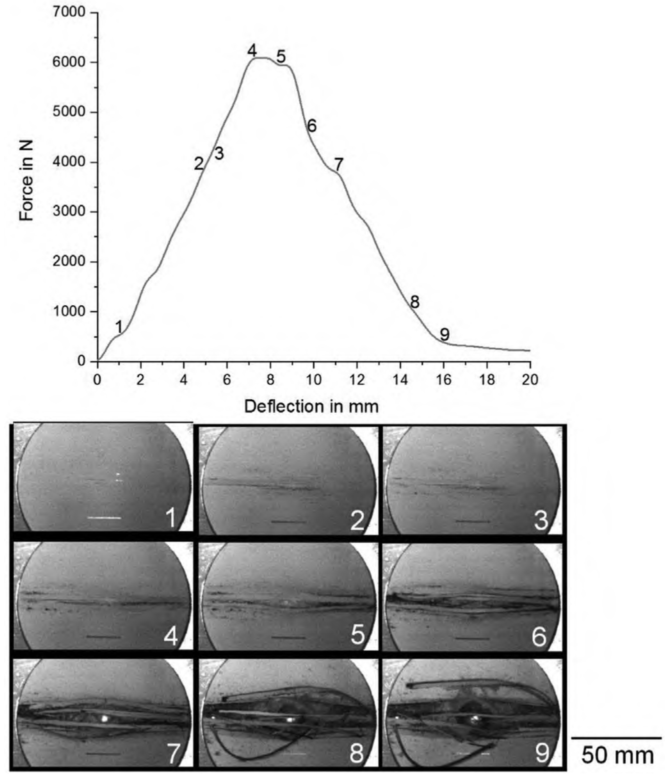

Fig. 9. Damage evolution of hybrid continuous-discontinuous glass/carbon fibre SMC exposed to dynamic puncture.

state of puncture loading. The descending part of the force-deflection response for both material types was defined by a gradual decrease in force and consistent between these two materials. The plateau region of the force-deflection response of the hybrid CoDico specimens, which resulted due to partial and gradual failure of the specimen, was not as significantly evident as for quasi-static puncture. Thus, the hybrid material had a lower damage tolerance if punctured in a dynamic manner.

4.2.4. Macro- and mesoscopic damage evolution due to dynamic puncture

Damage evolution of CoDico SMC exposed to dynamic puncture is depicted in Fig. 9. Damage initiation was linked to the formation of inter-bundle cracks which rapidly propagated in fibre direction until they reached the clamping apparatus (2–4). As puncture continued, delamination took place. Fibre fracture of the continuous carbon fibres was not observed. Delamination was linked to a significant load drop and failure of the specimen (5–7). In point 8 the specimen was fully penetrated by the impactor. The remaining non-zero load plateau, following point (9) resulted from friction between the impactor and the specimen.

Fig. 10a clearly indicates, that the inter-laminar delamination between the continuous and the discontinuous material was more severe if specimens were loaded in a dynamic manner. Besides that, the continuous carbon fibres separated from the stitching yarns, which stick to the discontinuous glass fibre SMC. Although inter-fibre fractures within the continuous carbon fibre SMC also resulted from dynamic loading, they were observed to be less numerous but entire bundles or packets of fibres were separated from the specimen. Additionally, the damaged discontinuous glass fibre SMC was characterized by a high number of individual fibre-bundles visible at the edges of the pushed out section, thus pseudo-delamination liked to fibre pull-out were important failure mechanisms of the Dico SMC.

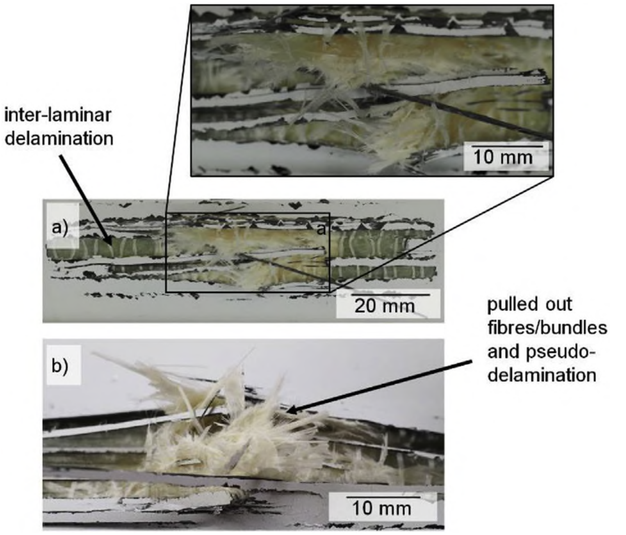

Fig. 10. Damaged hybrid continuous-discontinuous glass/carbon fibre SMC specimen exposed to dynamic puncture.

4.2.5. Microscopic failure mechanisms of punctured specimens

A microscopic examination of a post-mortem hybrid continuous-discontinuous glass/carbon fibre SMC specimen punctured in a quasi-static manner (Fig. 11) indicated that at significant portions of the damaged surface, (intra-laminar) delamination within the continuous material took also place due to matrix failure between the continuous carbon fibres (bundles) (①). Only small matrix cracks, few in number, resulted from quasi-static puncture of the hybrid material (③). Although pseudo-delamination (②) was the main failure mechanism of discontinuous glass fibre SMC punctured in a quasi-static manner, some individual fibres also failed due to fibre breakage (④).

Fig. 12 shows microscopic failure mechanisms resulting from dynamic puncture of a hybrid continuous-discontinuous glass/carbon fibre SMC specimen. Compared to the quasi-static loading case (Fig. 11) matrix cracks became more important and grow in size and number (③). The failure mechanisms which have already been identified for a specimen punctured in a quasi-static manner (pseudo-delamination of the discontinuous SMC (②), failure of some individual glass fibres (④) also resulted from a dynamic loading. Under dynamic loading, (inter-laminar) delamination between the continuous and discontinuous component took place (①). Different to the failure resulting from quasi-static puncture, which was mainly determined by an intra-laminar delamination within the continuous component, dynamic puncture led to important inter-laminar delamination. In addition, interface failure and debonding of individual glass fibres (⑤) have to be considered on the microscopic scale.

5. Discussion

In a previous study, it was shown, that discontinuous glass fibre SMC, which was based on the same unsaturated polyester-polyurethane resin system, exhibited a positive rate dependency of punctured at higher loading rates [17]. The same tendency was observed within this present study. Comparable to the results presented in Ref. [17], which considered a 2D flow during moulding of the discontinuous glass fibre SMC, a 1D flow did not lead to significantly different puncture properties of pure discontinuously glass fibre reinforced SMC for charge and flow region specimens if maximum force and puncture energy are considered.

The positive rate dependence, may result from the higher tensile strength of glass fibres exposed due to a higher rate loading [28]. Due to the higher strength of the individual fibres, interface properties became more important and increased interface failure, which favored fibre-

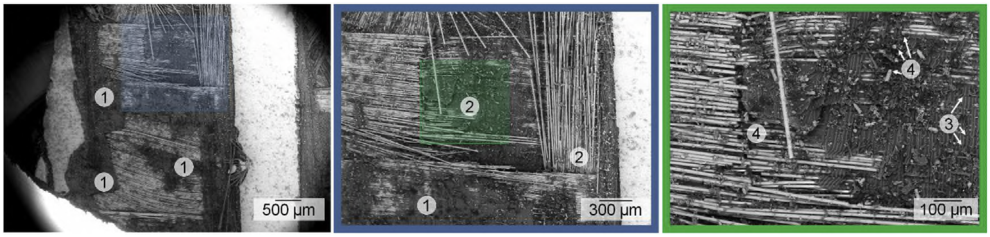

Fig. 11. SEM observation of post-mortem hybrid continuous-discontinuous glass/carbon fibre SMC specimen punctured in a quasi-static manner.

pull out, possibly led to higher absorbed energy during puncture.

In contrast, continuous carbon fibre SMC illustrated a negative rate dependence if punctured in a dynamic manner. As previous investigations showed, unidirectional carbon fibre reinforced polymers illustrated a non-rate dependency if exposed to tensile loads at different strain rates [29]. Due to the susceptibility to inter-fibre (inter-bundle) failure of continuously reinforced materials, damage evolved easily within this material class if loaded perpendicular to the plane of reinforcement. The significantly increased impact energy at higher loading rates even facilitated the puncture of the impactor.

Considering the hybrid continuous-discontinuous glass/carbon fibre SMC specimen, hybridization led to an increase of maximum force and puncture energy for quasi-static and dynamic puncture loadings. However, the effect was more significant for a quasi-static loading, due to a reduced damage tolerance of the continuous carbon fibre layers for higher loading rates. Although the continuous carbon fibre SMC showed a negative rate dependence, structural properties of hybrid continuous-discontinuous SMC were observed to increase with higher loading rates. Hence, it can be concluded that under the condition of dynamic puncturing of hybrid CoDico SMC, the Dico SMC determined the structural properties for laminated structures with the layer stacking considered within this study. Nevertheless, fibre type considered in the surface layers most importantly influenced failure evolution and energy absorption capability [18]. Failure evolution of hybrid CoDico SMC exposed to puncture was based on a superposition of failure mechanisms, which are characteristic of Dico SMC or Co SMC, as already shown for uniaxial quasi-static loading [11]. The slightly decreased puncture properties of flow region specimens indicated that the interface between the continuous and the discontinuous component might be influenced due to material flow and since delamination was an important failure mechanism resulting from puncture the interface properties were important to consider. To further improve impact properties a slightly different layer sequence, with the continuous carbon fibre layer in the middle of the laminate or a stacking of continuously reinforced layers in a 0°–90° or ± 45° sequence could improve impact properties of hybrid SMC [10]. Although the continuous carbon fibre outer layers failed at an early state of loading, load further increased due to puncture of the specimen. This indicates that the discontinuous glass fibre SMC is more important for load bearing capacity of the punctured structure. In contrast to a quasi-static loading, which led to a successive failure of the hybrid specimen with several distinct load drops in the force-deflection response, the failure of the hybrid SMC due to dynamic loading could hardly be divided into several steps. This may be due to smoothing of the captured raw-data but is also an effect resulting from material and structural properties of the hybrid SMC with the reduced damage capacity of the continuous carbon fibre SMC at higher loading rates.

6. Conclusions

The SMC process presented within this study enabled the manufacturing of hybrid continuous-discontinuous glass/carbon fibre SMC sheets based on the same novel two-step curing resin system. Puncture properties in terms of maximum force and puncture energy as well as damage mechanisms and failure evolution were investigated for two different loading rates ($4.4 \cdot 10^{-5}\,\mathrm{m \cdot s^{-1}}$ and $4.4\ \mathrm{m \cdot s^{-1}}$). The effect of hybridization was significantly present for quasi-static puncture loading with an increase of 36% for maximum force and +35% for puncture energy. Due to the limited material properties in terms of damage tolerance and energy absorption capability of a single layer of continuous carbon fibre SMC, the effect of hybridization was less important for dynamic puncture loading, noting an increase of 13% and 7%, respectively. The hybrid continuous-discontinuous glass/carbon fibre SMC showed a positive rate dependency with maximum load and puncture energy increasing 33% and 18%, respectively if the material was punctured in a dynamic manner.

Important failure mechanisms, depending on loading rate, were inter-laminar delamination between the continuous and the discontinuous material as well as intra-laminar delamination within one component. The discontinuous glass fibre SMC mainly failed due to pseudo-delamination and fibre-pull out. Whereas failure of individual glass fibres was more important at lower loading rates, interface failure of entire bundles determined failure at higher loading rates. Additionally, matrix cracks increased in number and size with an increase in loading rate.

To further increase puncture properties of hybrid continuous-discontinuous glass/carbon fibre SMC a different laminate stacking, consisting of a 0°–90° layer of carbon fibre SMC for example, may possibly further improve puncture properties in terms of maximum load and energy absorption capability.

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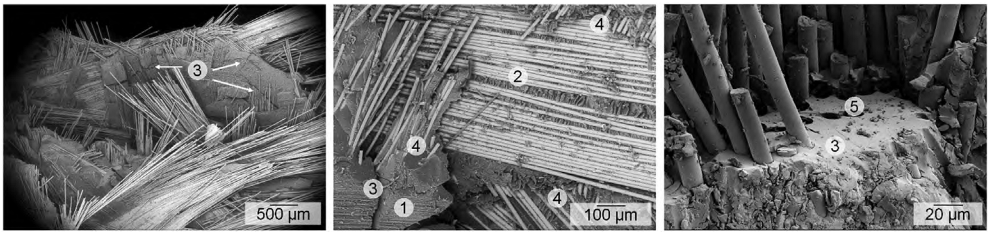

Fig. 12. SEM observation of post-mortem hybrid continuous-discontinuous glass/carbon fibre SMC specimen punctured in a dynamic manner.

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