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Experimental investigation of automotive component in hybrid fibre reinforced thermoplastic design

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Abstract

A tailored use of continuous fibre reinforced plastics enables application in high volume car body structures. The combination of pultruded, load carrying, unidirectional, continuous fibre reinforced thermoplastic (FRTP) profiles and injection moulds, named “skeleton design”, is a promising approach to meet structural requirements and economical needs. This design offers the advantages of FRTP such as short cycle times of approx. 75 s and functional integration via injection moulding. A pre-serial BMW iX geometry of a windshield panel is used to analyse the impact of different fibre configurations in the profiles on the mechanical properties of the part. Therefore, different pultruded profiles with a cross-section of 10 mm x 10 mm made of polyamide 6 (PA6) with carbon fibres (CF) and glass fibres (GF) as well as a CF/GF hybrid were used. Furthermore, an optimized part using different materials within one part was investigated. Therefore, quasi-static and dynamic compression tests were performed on part level. It could be shown that the optimized parts meet mechanical requirements while decreasing material costs significantly.

1 Introduction

Due to their high lightweight construction potential, continuous fibre reinforced plastics are increasingly used in the automotive industry [1]. The high costs of the material and the manufacturing process limit their use in high-volume car body structures. Thermoplastic composites offer easy processing for complex geometries, a good cost/performance ratio and their recyclability [2]. To be able to be economically viable, a tailored use of the composite material must be ensured. A design taking this into account is the so-called “skeleton design”. This design was developed within the MAI-Skelett research project. It combines the advantages of continuous fibre reinforced thermoplastic (CFRTP) composites with those of injection moulding into a highly integrative design manufactured in three process steps. First the CFRTP profiles are manufactured using pultrusion. Those are thermoformed into the final geometry and subsequently overmoulded using injection moulding in order to join separate profiles and reach required mechanical performance. This symbiotic fusion of different materials is necessary to exploit the lightweight construction potentials [3]. Within the design, the CFRTP profiles are bearing the load. The injection mould is responsible for torsional stiffness and the shear force transmission [4]. Their manufacture using a pultrusion process in combination with a high material usage ratio and short cycle times due to a fully automated production process enables cost-effective lightweight design. More potential regarding economic compatibility can be exploited if glass fibres (GF) can be used in the design due to their low cost compared to carbon fibres (CF) while at the same time offering good performance in terms of compressive and flexural strength. Hybridisation of carbon with glass fibres offers potential regarding damping, impact and structural integrity [5].

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2 Experimental procedure

2.1 Materials

As base materials pultruded material with polyamide 6 (PA6) matrix, hereinafter referred to as PA6-CF, PA6-CF/GF and PA6-GF were investigated. The name identifies the fibre and matrix used for pultrusion. The profiles have a cross-section of 10 mm x 10 mm. PA6 was chosen as [6] has shown that it can withstand the automotive process chain including painting and cathodic dip painting. PA6-CF/GF is a hybrid profile consisting of two thirds PA6-CF placed around a square cross-section of PA6-GF. All profiles have a fibre volume fraction of 47 %. Due to the hygroscopic nature of PA6 the mechanical properties are dependent on moisture in addition to the dependency on temperature [7]. The compression modulus of the profiles are 110 GPa, 85 GPa and 43 GPa showing no significant difference in dry and conditioned state. The compression strength in dry state is 220 GPa, 184 GPa and 220 GPa for PA6-CF, PA6-CF/GF and PA6-GF respectively. Compression strength is decreased by around 50 % by conditioning. Furthermore, it was shown that the different materials and hybridisation can be used to customise mechanical properties to meet defined structural requirements [8]. The pultruded profiles were manufactured at SGL Technologies GmbH, Meitingen, in a continuous pultrusion process which allows the hybrid fibre content ratio to be controlled precisely and the cross-sectional distributions to be designed. Cross-sections are shown in Figure 1.

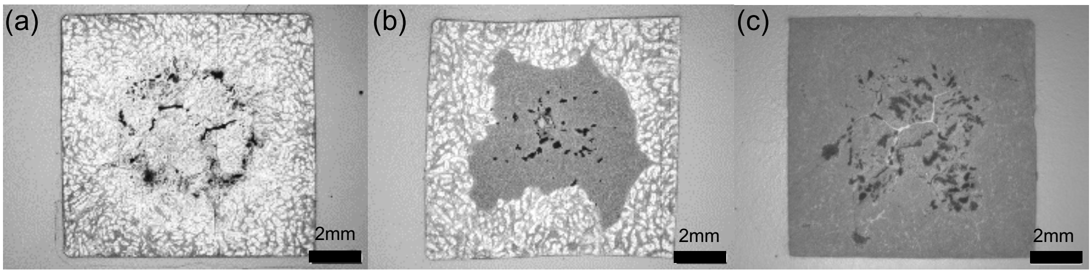

Figure 1: Cross-sectional images of (a) PA6-CF, (b) PA6-CF/GF and (c) PA6-GF

The third material used in this design is the injection mould material. This is critical as, the interface in hybrid parts always shows gradients in mechanical properties, which normally leads to stress concentrations in this area. To ensure a good adhesion between the profiles and the injection mould, a PA6 material with 15 m% CF short fibre reinforcement (PA-CF15) from WIPAG was chosen.

2.2 Part design and manufacturing

The part is a pre-series BMW iX windshield panel (Figure 2). It consists of four profiles, metal inserts and the injection mould structure. This ensures the mechanical properties of the part as well as a easy integration into the automotive body-in-white production process.

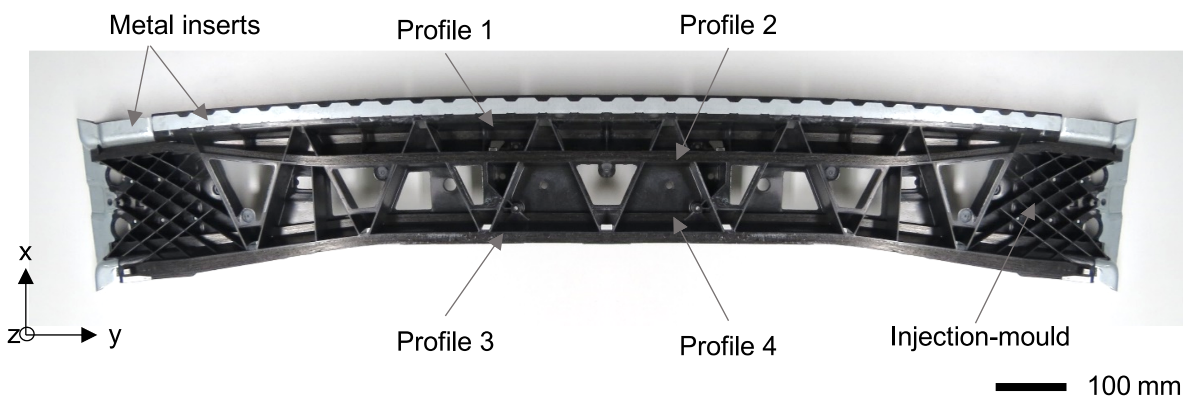

Figure 2: Pre-series BMW iX windshield panel in skeleton design

The manufacturing process is mainly structured in three steps. After the pultrusion of the profiles, the profiles are thermoformed. Finally, the metal inserts and the profiles are joined within the injection moulding process.

The manufacturing process takes place in a partly automated production cell, which ensures a reproducible process. After the heating via infrared, the profiles are transferred to the forming tool using a robot. After forming the fibre reinforced profiles, the metal inserts are taken by the robot and all parts are transferred to the injection mould tooling.

Four different configurations were investigated (Table 1). Apart from parts with all four profiles made of the same material, one configuration consists of two PA6-CF profiles (profile 1 and 4) as well as two PA6-GF profiles (profiles 2 and 3). This configuration was manufactured based on the assumption that the combination of different materials in one part can successfully reduce material costs while meeting mechanical boundary conditions. This was shown for complex parts in [9].

Table 1. Investigated parts with respective profile and injection mould materials

	Profile material	**Injection mould material**
PA6-CF	PA6-CF	WIC PA6 15 BK IM MI384
PA6-CF/GF	PA6-CF/GF	WIC PA6 15 BK IM MI384
PA6-GF	PA6-GF	WIC PA6 15 BK IM MI384
PA6-CF+PA6-GF	PA6-CF+PA6-GF	WIC PA6 15 BK IM MI384

Due to the influence of moisture on the mechanical properties, the parts are tested in conditioned state. Conditioning of the parts was done according to DIN EN ISO 1110 at 70 °C and 62 % relative humidity for 10 days.

2.3 Compression test

The dimensioning load cases for this part within the body-in-white structure are the roof strength test of the insurance institute for highway safety [10] as well as the oblique pole side impact test from European new car assessment programme [11]. The first is performed in a quasistatic manner. This is transferred to a single part test using a universal testing machine Zwick Z250 equipped with a 25 kN load cell. Five specimens were tested for each configuration. The cross-head displacement was set to 1 mm/min. The part is connected rigid with test fixtures. The set up is shown in Figure 3 left.

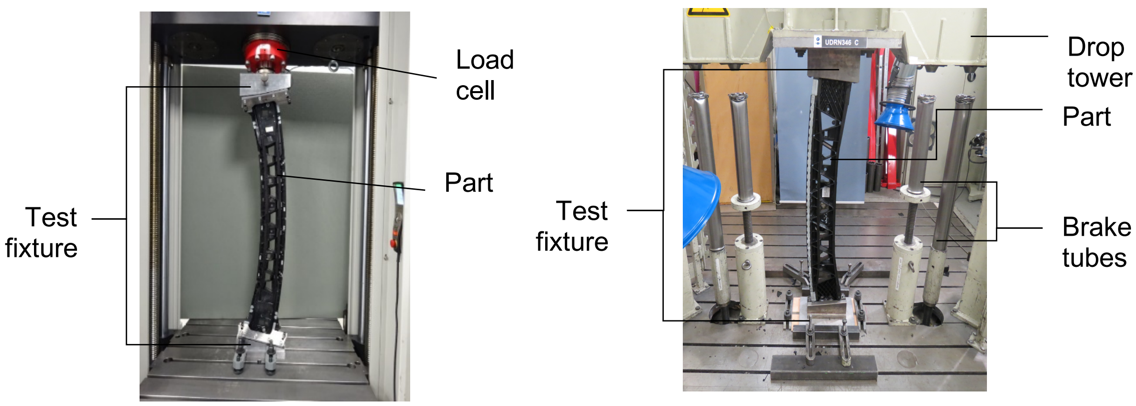

Figure 3: Testing setup for quasistatic (left) and dynamic (right) compression test

Dynamic testing is performed using a drop tower (Figure 3 right). The part is therefore mounted on drop tower head. The falling mass including the part and fixtures is 283 kg. Impact velocity is 3.33 m/s. This value refers to the velocity measured at the part in a entire car simulation of the oblique pole side impact.

The intrusion of the part is set to 110 mm using four brake tubes. The intrusion is defined as the displacement of the part in y-direction (Figure 2) until the stop of the drop tower head by the brake tubes.

A typical force-displacement diagram for quasi-static loading is shown in Figure 4. The evaluated performance metrics are stiffness and maximum force for quasi-static testing. The force displacement plot shows non-linear behaviour before peak force. Therefore, the stiffness is calculated using linear regression up to the half of the peak force using the method of least squares. Peak force is the overall force maximum of the plot.

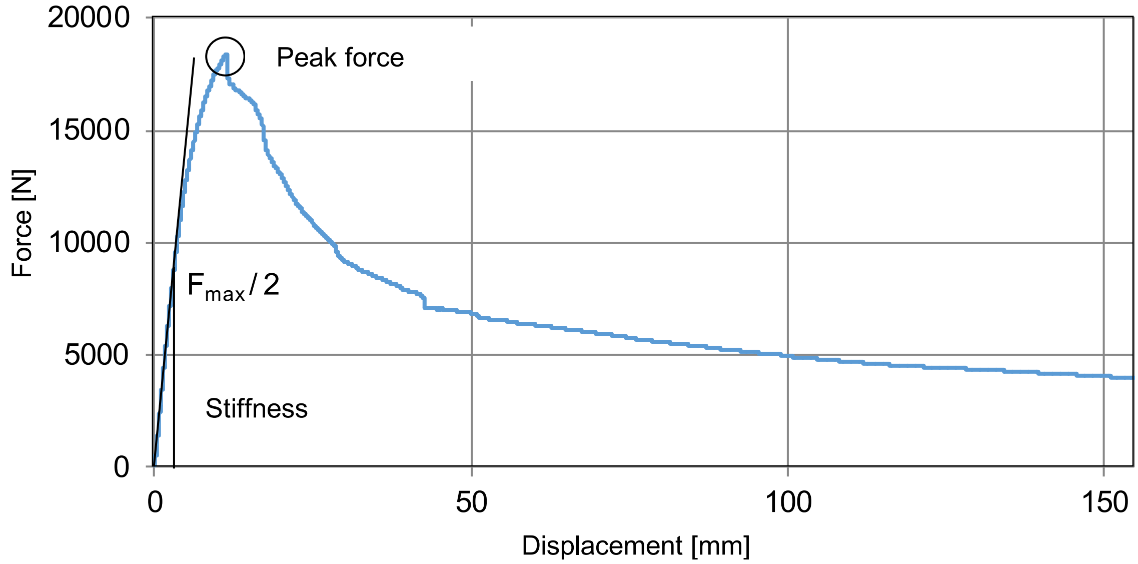

Figure 4: Exemplary force-displacement plot for quasistatic compression test of PA6-GF part

A exemplary force displacement plot for dynamic testing is shown in Figure 5. The respective performance metrices are peak force and mean force level. Mean force level is evaluated between the starting of the stable crushing at around 20 mm and 80 mm displacement. Peak force is the overall force maximum corresponding with the initial failure of the part.

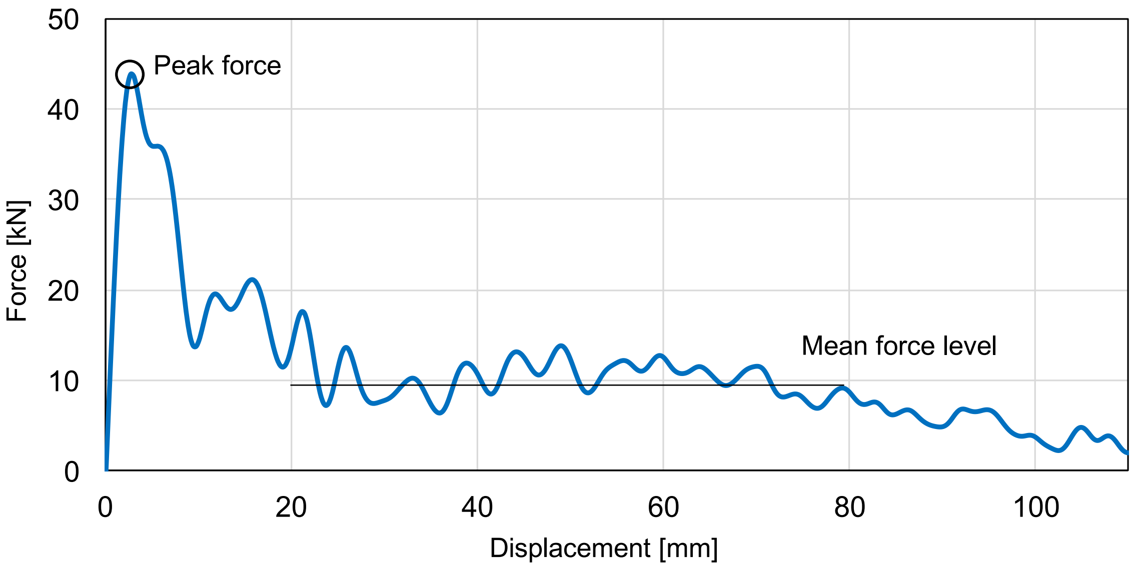

Figure 5: Exemplary force-displacement plot for dynamic compression test of PA6-CF part

The mean force level is a metric for the energy absorption of the part. The higher the mean force level the higher the ability of the part to absorb energy. Furthermore, the structural integrity during the test of the part can be evaluated using this metric. For this investigation, a high mean force level indicates a structural integer part.

3 Results

PA6-CF/GF equals PA6-CF in terms of stiffness and strength. Compared to PA6-CF, PA6-GF shows a reduction of the determined stiffness by -33% and the peak force by -11 %.

To validate the optimisation of the part using different materials within one component a hybrid component with PA6-CF profiles at positions 1 and 4 and PA6-GF profiles at positions 2 and 3 was manufactured. According to the simulation, the part reaches 95% of the stiffness and 96 % of the maximum strength of PA6 CF.

The results could be confirmed in the experiment. The stiffness of 2732 N/mm and the maximum force of 19240 N are not significantly below the parameters of the PA6-CF reference variant (Figure 6).

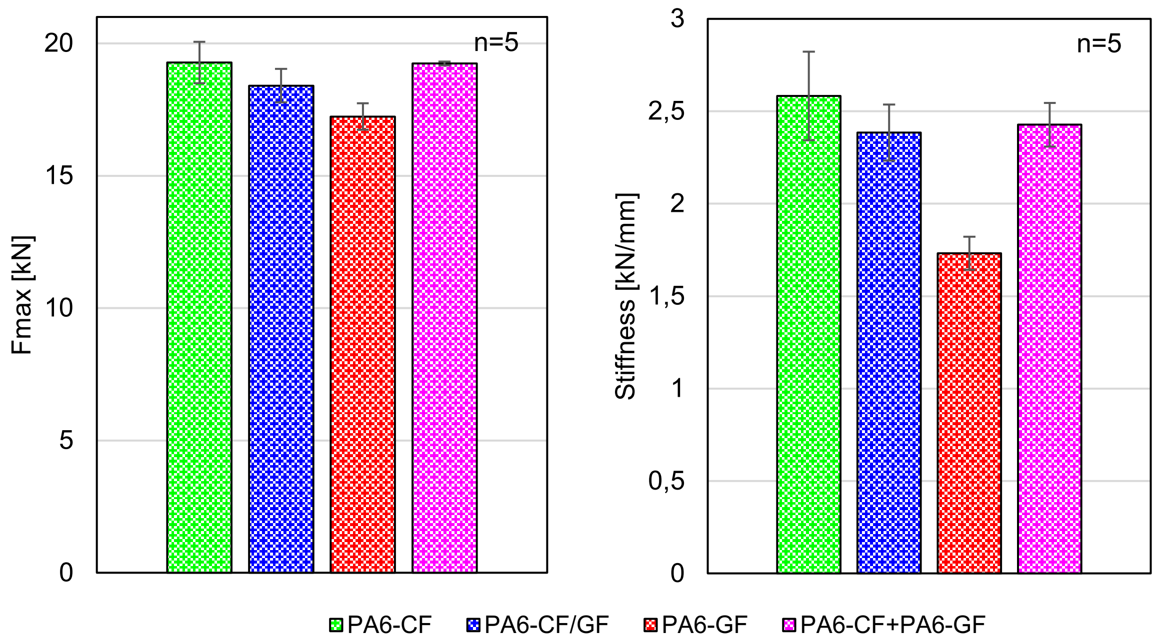

Figure 6: Maximum force Fmax (left) and stiffness (right) for quasistatic compression test

With regard to the failure pattern in quasi-static compression, the first failure can be observed on the profiles at position 1 and 4. Compressive failure is induced by compression and bending due to the curvature of the part. The first failure occurs at around a third of the total y length of the component. Due to the symmetry of the component, the failure can be seen on both sides of the component. After the first failure of the FRP profiles, profiles 2 and 3 are still mechanically integer. The integrity remains until the end of the test.

Regarding the dynamic compression test, the maximum force of PA6-CF, PA6-CF/GF and PA6-CF + PA6-GF is equal (Figure 7 left). This is due to the same material used in profiles 1 and 4, which initially define failure and thus the maximum force. PA6-GF shows a 12 % significantly lower maximum force compared to PA6-CF on.

Figure 7 right shows the mean force level of the dynamic compression test. With regard to this, a high standard deviation can be determined, which can be attributed to different failure modes within the test series. For this reason, there is no significant difference between the tested material combinations.

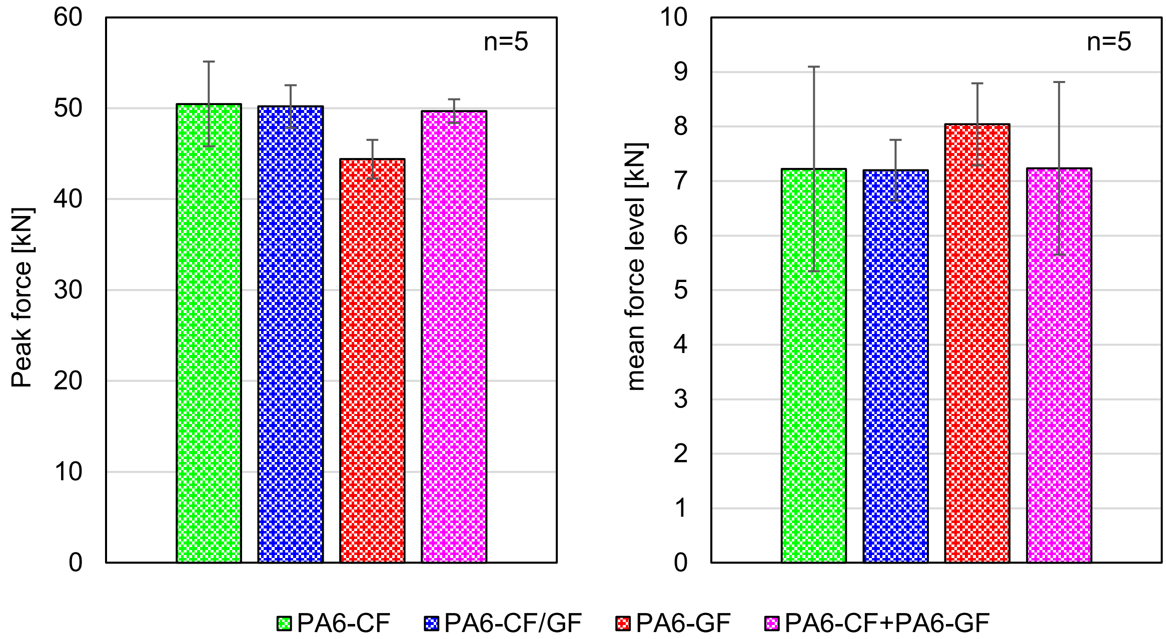

Figure 7: Peak force (left) and mean force level (right) for dynamic compression test

Figure 8 shows the failure process of the dynamic test using a PA6-CF part. The initial failure pattern is comparable to that of the static compression test. The two profiles 1 and 4 fail under pressure and buckle. After initial failure only the profiles 2 and 3 are still load-bearing.

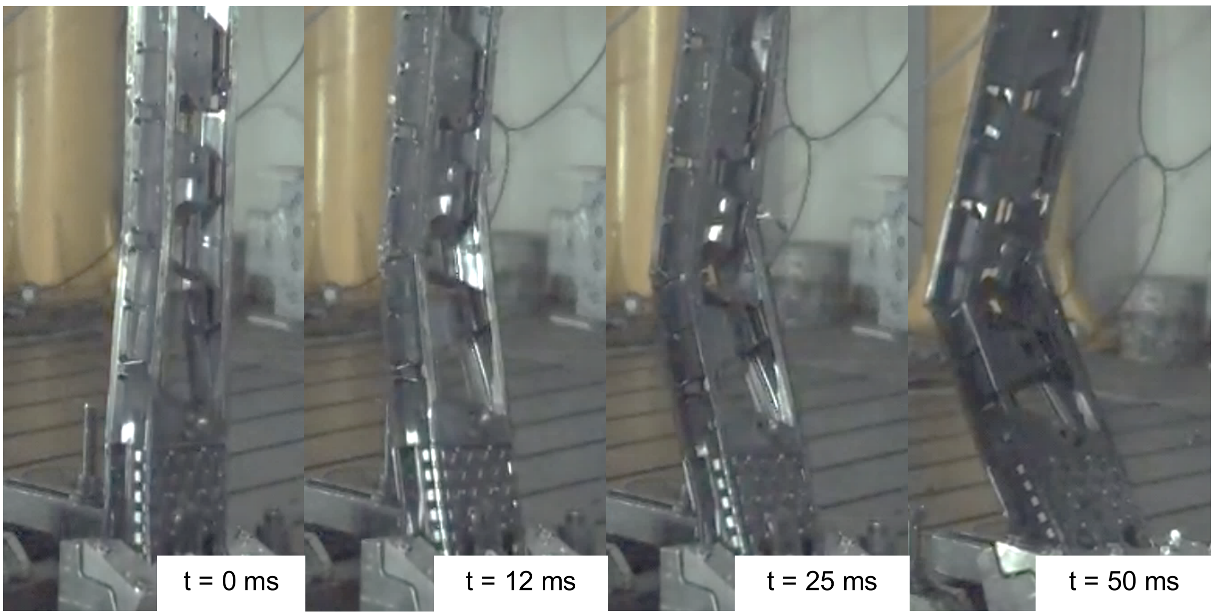

Figure 8: Exemplary failure propagation for dynamic compression test PA6-CF

The first failure with the corresponding maximum force occurs with an intrusion path of less than 5 mm, which is associated with a low energy consumption. The high remaining energy, together with a remaining intrusion path of > 105 mm, can also lead to failure of the two profiles 2 and 3.

4 Discussion

At the component level, PA6-GF has a stiffness that is 33 % less than that of PA6-CF. At the profile level, the difference is significantly higher, which is due to the fact that the stiffness of the part is not exclusively determined by the profile. Both the material and the geometric arrangement of the injection moulding compound are important. The bending stiffness of the PA6-CF/GF hybrid profiles can be transferred to the stiffness of the component. The good strength values of the PA6-GF profiles in compression and bending cannot be transferred to the component. The PA6-GF part reaches 90 % of the maximum force of the PA6-CF part. Due to the significantly reduced stiffness of the component, the maximum force is achieved at a higher displacement and thus deflection of the component. This leads to higher strain in the injection moulding material in the PA6-GF component, which ensures the stability of the FRP profiles. As a result, the support structure locally fails and results in a significantly lower maximum force of the PA6-GF component compared to PA6-CF.

The dynamic properties of the part, such as the force-displacement curve or energy absorption and structural integrity, are decisive for use in vehicles. The compressive strength of fibre reinforced PA6 increases by up to 60 % at high strain rates [12]. This is due to the strain rate-dependent mechanical properties of the matrix [13]. In addition, the failure pattern and its timing can change compared to the quasi-static test [14].

The failure behaviour can occur in dynamic bending tests as failure on the tension side, the compression side, in-plane or as a mixed failure. Tensile failure is characterised by the highest maximum force with fatal failure and correspondingly low energy consumption. In the event of compression failure, a non-linear course of the force-displacement curve can be observed. The maximum force is reduced and the energy consumption increased. In-plane shear failure is characterised by a low maximum force, which, however, is kept stable over a long distance. A superposition of the three failure patterns explained is referred to as mixed failure.

The corresponding fracture patterns were also observed in the dynamic compression tests. In the case of mixed failure, after the initial failure of the highly loaded profiles, an additional tensile failure occurs due to the high residual kinetic energy, which leads to a fatal failure of the profiles. The failure of the individual profiles is shown in the diagram as an abrupt drop in force. Finally, it should be noted that a compression failure with long retention of the upsetting force is best for the dynamic properties of the component. In this case, a large amount of energy is absorbed without an abrupt, fatal failure of the component. However, if there is a sudden tensile failure of the material, the requirements with regard to energy absorption and structural integrity for dynamic loading are not met.

5 Conclusion

The components with different profile material configurations were manufactured in a partially automated production cell. As a result, both a quasi-static and a dynamic replacement test were carried out. In general, the component stiffness decreases with increasing glass fibre content in the profile. The performance of the optimised profile material configuration is comparable with the design reference with PA6-CF profiles in terms of rigidity and strength. This enables a material cost reduction of -23% from a mechanical point of view.

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