CRASH TESTS OF HYBRID STRUCTURES CONSISTING OF SHEET METAL AND LOCAL CFRP REINFORCEMENTS

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Keywords: Automotive lightweight construction, Hybrid structure, Prepreg press technology, Crash test.

Abstract
In the available paper current research results in the field of hybrid materials are presented. First, the prepreg press technology to manufacture automotive structural components in hybrid design is illustrated. In particular the advantages of this technology compared to conventional processing methods for FRP are highlighted, such as a reduction of cycle times from more than 15 minutes to below 5 minutes. Subsequently, results for crash tests on hybrid double-Z-profiles are shown. For these investigations an ultramodern carriage test facility was used. Different investigations on mere steel structures as well as on hybrid structures made of steel and FRP were carried out. Thereby the steel type, the wall thickness or the process parameters were varied. It was shown that hybrid materials offer a large weight saving potential for crash-loaded automotive components compared to mere steel structures.

1 Introduction

Lightweight design in industrial applications like automotive engineering is one approach to meet the objectives of climate protection. To take further steps in this context, new innovative and holistic approaches are needed. For example, by reducing the vehicle weight by 100 kg, a reduction of CO_2 emissions of about 8.5 g/km respectively a reduction of fuel consumption of about 0.3 l/100 km can be realised. Nevertheless the average weight of automobiles increased over the past years mainly because of safety and comfort requirements.
Nowadays a main trend is the utilisation of fibre reinforced plastics (FRP) for automotive applications. Materials like carbon (CFRP) or glass fibre reinforced plastics (GFRP) offer excellent specific mechanical properties [1] [2], which are significantly higher than those of steel, aluminium or magnesium alloys. Consequently, FRP offer a large weight saving potential for example for automotive lightweight construction, too. At the moment FRP-structures are predominantly used for high-priced vehicles, prototypes or race cars. Main challenges for the automotive industry are to integrate FRP into existing processes, to reduce high costs of processing these materials and manufacturing FRP-structures.
A promising approach in this context is the use of hybrid structures. These structures consist of formed sheet metal structures and local FRP-patches. The wall thickness of the sheet metal can be reduced, which leads to a decreasing weight. Highly loaded areas are reinforced with FPR [3]. With this combination it is possible to minimise the disadvantages of mere FRP-structures and to realise an efficient lightweight construction.

2 State of the art

Lightweight design has become a core competence especially in the automotive industry in the past years. A weight reduction of a construction can be realised in different ways, for example by using superior metal alloys or by substituting metal by FRP. Materials like CFRP possess high specific modulus and strength. These parameters are required for loadbearing structures in the automotive, aerospace or energy sector [4] [5]. In these and other applications CFRP is widely used to improve the component performance of premium products [5]. Research works have shown that the use of FRP results in significant functional and economic benefits. These benefits range from increased strength and durability features to weight reduction and lower fuel consumption. Research results show for example the improvement of structural vehicle crashworthiness by using FRP in specific automobile structures as collapsible absorbers of crash energy [6].

Main disadvantages of FRP structures for large volumes are material and production costs. Thus, the competitiveness of these structures depends on reducing costs for example by optimising technologies that enable simple and robust manufacturing processes or shorter lead times [7]. To improve the utilisation of material it is favourable to use high-strength, but also high-priced materials like CFRP as local reinforcements in sheet metal structures. These reinforcements can be applied to high loaded areas for example of a hat section or a b-pillar [3] [8]. Corresponding combinations of CFRP and metals are increasingly used in the automotive and aerospace industry, but also in general mechanical engineering [3]. With the use of this construction technique an aluminium section reinforced with adhesively bonded CFRP could be realised 33 % lighter than a mere aluminium optimised structure [9].

3 Steel-CFRP-hybrid structures

Hybrid materials consist of a sheet metal basic layer, a locally applied fibre reinforced plastic (FRP) reinforcement layer and an optional sheet metal covering layer. The layered structure offers the possibility to tailor components to their expected loading (Figure 1).

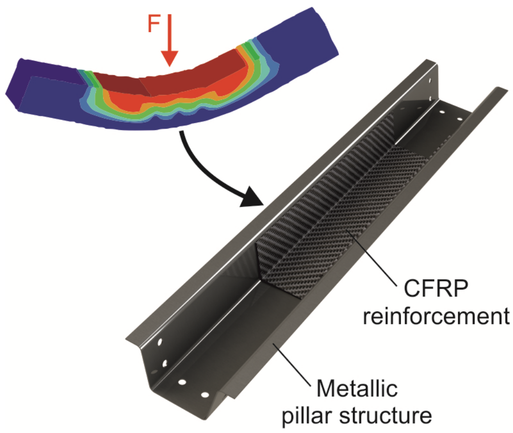

Figure 1. Tailored hybrid pillar structure consisting of sheet metal and local CFRP reinforcement

Such tailored structures do not only bear a high potential for lightweight design but also show an optimised use of the expensive FRP materials, which finally leads to cost-optimized lightweight constructions. Amongst others press hardened steels can be used as sheet metals. Due to the FRP reinforcements, the wall thickness of the steel parts can be reduced. Hybrid components can easily be integrated into existing processes of vehicle production, because their metallic surface enables the use of conventional joining technologies like spot welding or clinching. The integration into existing body constructions is also possible.

4 Prepreg press technology

The prepreg press technology is one approach to produce hybrid structural automotive parts in large volumes. The process can be divided into four main parts (Figure 2). First, prepregs (pre-impregnated, semi-finished fibre products) are produced continuously on special machines and shipped on coils. The layer structure is realised according to the expected loads in the component, for example a B-pillar. The laminate is cut corresponding to the later structure geometry. Second, a robot handles the prepregs. After inserting an already formed steel structure into a heated steel tool, the prepreg is applied to the steel structure by automated handling. Then the tailored prepreg is pressed onto the sheet metal by a heated punch. As the epoxy resin functions as an adhesive the joining of sheet metal and CFRP is realised in this third step, too. After a pre-curing of about 90 to 120 seconds, depending on the thickness of the prepreg, the hybrid component is removed by a robot and stacked. The post-curing of the components is realised during a downstream cataphoretic painting process.

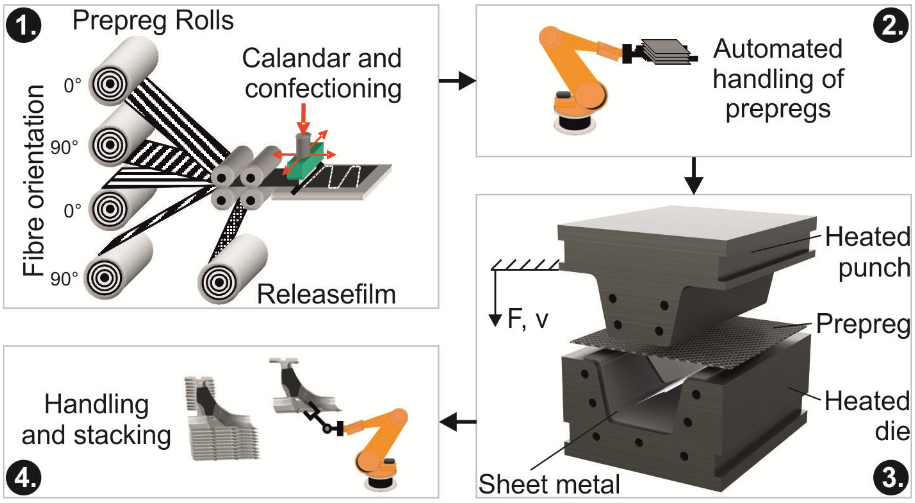

Figure 2. Process steps for prepreg-pressing to produce hybrid automotive structural parts, for example a B-pillar

5 Materials and testing methods

Applications for hybrid structures manufactured by prepreg press technology are, for example, crash-relevant automotive structural components. To analyse the behaviour of hybrid materials under crash loads different tests have been accomplished. The crash tests were performed on a carriage crash test facility (Figure 3). The impact carriage is accelerated by a hydraulic drive system and guided on special rails. Different component jigs can be attached to a span, for example for tests with pressure or bending loads. The mass of the impact carriage can be varied between 50 and 500 kg. A maximum speed of 25 m/s can be reached. An optical measurement system with a frequency of up to 100 kHz gauges deformation and strain.

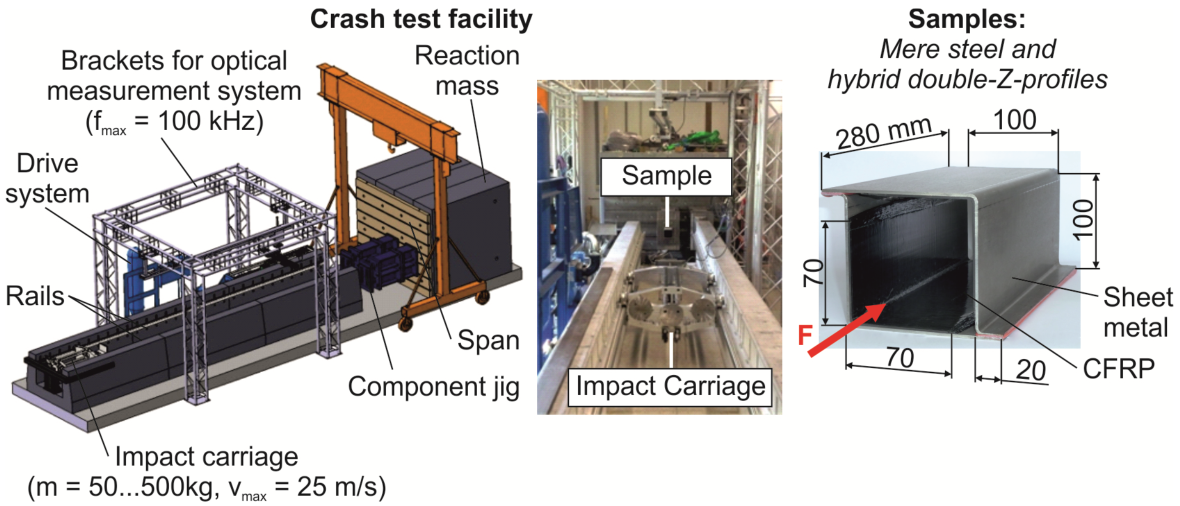

Figure 3. Crash test facility (left and middle), samples for crash tests with pressure load (right)

The crash tests with pressure load were performed with a 280 mm long double-Z-profile. The cross section had a width of w = 100 mm and a height of h = 100 mm without bonding flanges. The sheet metal was a DD11 with a wall thickness of t = 1.0, 1.5 and 2 mm. For the manufacturing of the samples in a first step sheet metal with a length of 320 mm was bended. Second, a 300 mm long and 140 mm wide CFRP reinforcement was pressed centred into the sheet metal. The epoxy resin from SGL (Type E201) embeds carbon fibres in a 9 layer bidirectional scrim (90/0/0/90/0/90/0/0/90°). The samples were manufactured with a pre-curing time of t_{prc} = 120 seconds. The post-curing time was t_{poc} = 30 minutes. As a temperature for both curing processes T = 180 °C was used. The consolidation pressure exceeded p = 0.3 MPa. Third, the half-shells were cut to a length of 280 mm. This step was meant to realise a complete hybrid material over the whole length of the profile. In a last step the steel components were bonded in the flange area by a Betamate 1620 adhesive. The thickness of the bonding was 0.3 mm.

6 Results

The crash tests with pressure load were realised with 280 mm long double-Z-profiles. This load case is important for crash-energy absorbing structures, for example a crashbox. The tests were performed with several hybrid structures: {1} steel in 1.0 mm, {2} steel in 1.5 mm, {3} steel in 2.0 mm, {4} hybrid consisting of 1.0 mm steel and 2.0 mm CFRP, {5} hybrid consisting of 1.5 mm steel and 2.0 mm CFRP and {6} hybrid consisting of 2.0 mm steel and 2.0 mm CFRP. The crash energy for the samples {1} and {4} was 5.8 kJ and the impact velocity was 9.6 m/s. For the samples {2}, {3}, {5} and {6} the crash energy was 12.5 kJ and the impact velocity was 14.1 m/s.

To analyse and evaluate the results of the crashtests, several characteristic key figures were used according to [6] [10]. These parameters were medial specific force (1), maximum energy absorption (2), specific energy absorption (3) and total specific energy absorption (4) for the tested double-Z-profiles.

$$F_m = \frac{1}{\Delta s} \int_0^{\Delta s} F(s)\,ds \tag{1}$$

$$W_{max} = \int_0^{s_{max}} F(s)\,ds = F_m \cdot \Delta s_{max} \tag{2}$$

$$E_{tot} = \frac{W_{max}}{m} \tag{3}$$

$$E_{spec} = \frac{W(s)}{\Delta m(s)} \quad and \quad \Delta m(s) = \frac{\Delta s}{l_0} \tag{4}$$

Figure 4 shows medial forces and maximum displacements for crash tests of double-Z-profiles for the samples {1}, {2}, {4} and {5}. The corresponding curves in a force-displacement diagram are characterised by a peak force in the beginning. This point is called stability-peak. After this peak the curves fall off and go into an area of undulating. The medial force decreases slightly until the end of deformation. On the basis of this information the medial forces were calculated.

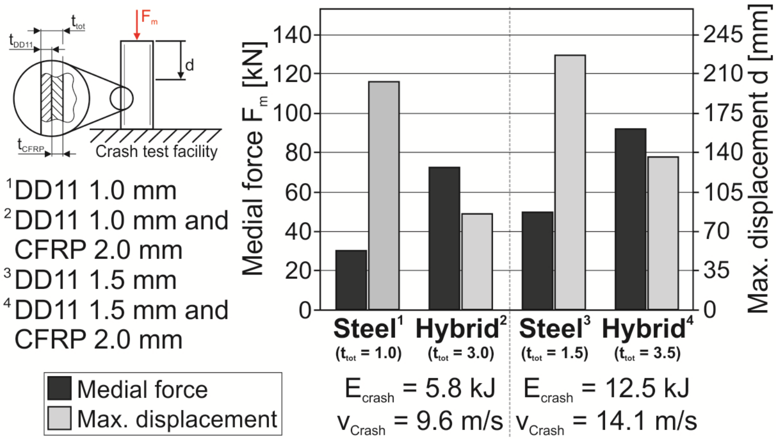

Figure 4. Medial forces and maximum displacements for crash tests of double-Z-profiles

The influence of the reinforcement for lower steel wall thicknesses is more pronounced because of the relative share of CFRP. For every sample the same reinforcement patch was used. To compare the results of the several crash tests the characteristic key figures (1) to (4) were calculated (Table 1).

No.	t_{steel} [mm]	t_{CFRP} [mm]	F_m	W_{max}	E_{spec}	E_{tot}
{1}	1.0	---	29,30	7324,17	6,09	7,15
{2}	1.5	---	50,27	12568,33	8,15	8,16
{3}	2.0	---	93,03	23257,50	4,86	11,35
{4}	1.0	2.0	67,07	16767,50	4,82	12,85
{5}	1.5	2.0	91,08	22770,83	7,77	12,51
{6}	2.0	2.0	131,41	32851,67	4,96	14,10

Table 1. Medial specific forces, maximum energy absorption, specific energy absorption and total specific energy absorption for the tested double-Z-profiles

Here, the results of the medial specific force (1), the maximum energy absorption (2), the specific energy absorption (3) and the total specific energy absorption (4) are illustrated. For example the mere steel structure {3} (t_{steel} = 2.0 mm, m = 2050 g) shows the same medial force of about 90 kN like the hybrid structure {5} (t_{tot} = 3.5 mm, m = 1820 g). The share of CFRP in the hybrid sample is only 280 g, which is similar to an increase of 45 % of the medial specific force by the CFRP compared to the mere steel structure {2} (t_{steel} = 1.5 mm, m = 1540 g). In this case the hybrid structure offers a weight saving potential of about 12.5 %. Another example is the specific energy absorption of the samples. Here, the mere steel solution {3} (t_{steel} = 2.0 mm, m = 2050 g) can be compared to the hybrid sample {4} (t_{tot} = 3.0 mm, m = 1305 g), which leads to a lightweight potential of about 36 %.

It can be stated that hybrid structures offer a large lightweight potential compared to mere steel structures. The weight saving potential is determined by several parameters, for example the load case or the parameters under which the structure is optimised (amongst others stiffness or strength respectively F_m or E_{spec}).

7 Conclusions

Multi-material systems consisting of sheet metal and fibre-reinforced plastics offer a major potential for lightweight design in the automotive industry. This combination opens up the realisation of load adapted structures, for example hat sections or B-pillars. This results in a high material utilisation and cost efficiency in combination with large volume manufacturing processes. By using the prepreg press technology CFRP prepregs are directly formed into steel structures. The prepreg press technology allows a significant reduction of process steps as well as process time. Mere steel and hybrid double-Z-profiles manufactured by this technology were afterwards tested at a carriage crash test facility. It has been shown that hybrid structures offer a good crash performance compared to mere steel solutions. Aside, hybrid structures are characterised by a large weight saving potential compared to mere steel structures of up to 36 % depending for example on the load situation.

Acknowledgements

We would like to thank the EFRE fund of the EU and the state of North Rhine-Westphalia for supporting the research project within the scope of the Ziel 2 program. Furthermore, we gratefully acknowledge the support by our project partners Benteler-SGL, Audi and Johann Meier Werkzeugbau and the cooperating Chairs of the University of Paderborn, LUF, LTM and LWK.

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