Technologies for
Lightweight Structures

Profile structures for economical hybrid lightweight design

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Keywords

Abstract

Especially in the transport sector, lightweight design with fiber reinforced plastics (FRP) is of major relevance due to CO_2 reduction through mass saving [1]. In sectors like automotive, FRP are mainly used in secondary structures such as seat shells. In order to be able to operate effective FRP lightweight design in load-bearing structural components, pultruded hybrid profiles are to be established as a new tool for engineers. The profile components are characterized by a FRP base structure and a metallic core that increases the ductility. The manufacturing of the components with pultrusion ensures a large scale production. To guarantee a high covalent bond between the metal cores and the FRP, the inserts are provided by using a newly developed powder coating, which acts like a latent reactive adhesive [2]. Three different profile constructions have been verified, which are identical in the external cross-sectional shape and size, but differing in core structure. A glass-FRP-steel-combination was chosen as material and a pure FRP sample was used as a reference. The mechanical properties were investigated by using a 4-point bending test. Depending on the core structure, various failure behavior and mechanical parameters like energy absorption could be determined.

1 Introduction

Lightweight design is of major relevance in countless applications and thus makes an essential contribution to energy-efficient, resource-saving and CO_2-minimized mobility. Due to their low density paired with high strength and rigidity properties, FRP are ideal for lightweight structures [3]. In contrast to metallic materials, FRP are characterized by a completely different mechanical behavior. In sectors like automotive, FRP are mainly used in secondary structures such as interiors, cladding or seat shells. In primary structures like chassis, metallic materials are still dominant. However, it is precisely in these components that there is still unused lightweight design potential. But for safety reasons, ductile material behavior is often required for primarily energy-absorbing components, so that a complete substitution of metallic elements by FRP is often not possible [4]. In order to functionalize FRP with ductile material behavior, hybrid design methods consisting of a combination of FRP with metallic materials are often used. For example, multi-layer composites made of steel or aluminum thin sheets are used in conjunction with FRP laminates. The aim is to improve crash, impact and crack propagation behaviour [5, 6]. Hybrid lightweight components made from a combination of FRP and metal are often produced in complex process chains or by gluing. The main disadvantages for series production are insufficient joining qualities, time- and cost-intensive pre- or post-treatment processes, long cycle times or the insufficient fatigue strength under changing climate conditions. Due to the different thermomechanical properties of metal and FRP, an excellent adhesion strength at the interface is necessary [7]. Gluing is one of the few processes that has been established on a large-scale production

for joining FRP with metals in such a way that high safety standards can be maintained with regard to the fatigue strength in automotive applications [8, 9]. Because the necessary pre-treatment, application and curing of the glue are usually associated with additional time and costs, current research has a significant claim to reduce or even to avoid the use of glue by appropriate methods.
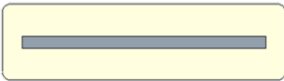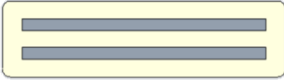
In order to still be able to operate effective FRP based hybrid lightweight design in load-bearing structural components, pultruded hybrid profile components developed at the Fraunhofer IWU in cooperation with the Leibniz IPF are to be established as new design possibilities for engineers. The profile components are characterized by a FRP base structure and a metallic core to increase the ductility. The manufacturing of the profile components with the pultrusion process ensures a large scale production in one step. To guarantee a high covalent bond between the metal cores and the FRP, the inserts are provided by using a newly developed two-step curing powder coating from the Leibniz IPF, which acts like a latent reactive adhesive [2]. The hybrid profiles are thus manufactured using the in-mold assembly technique, so that subsequent joining processes such as gluing are therefore not necessary. This article describes the manufacturing and investigation of the component properties of various hybrid profile variants.

2 Materials and methods

2.1 Components of the hybrid profile structures

Four different profile variants were produced and investigated. Variant A consists only of FRP. Variants B, C and D are hybrid designs, which differ in their core structure in terms of number, arrangement and proportions of the inserts. Variant B is characterized by a transverse insert, which is located exactly in the middle of the profile cross-section. Variant C is characterized by two transverse inserts, which are arranged symmetrically. The area proportion of variant C is twice as large as that of variant B. Variant D is characterized by five vertically oriented inserts. The area proportion is the same as for variant B. On the one hand, the influence of the proportions of metallic materials on the total cross-section of the hybrid profile and on the other hand, the influence of the shape and arrangement of the metal inserts are to be investigated. Table 1 gives an overview of the construction designs that have been implemented. The profiles are realized as solid rectangular profiles with the dimensions 34.9 x 9.3 mm².

Table 1: Construction variants of the hybrid profile structures

Variant	Cross-sectional design	Dimensions of the inserts	Cross-sectional-proportions
A		-	100 % FRP
B		30 x 1,5 mm²	86 % FRP 14 % metal
C		30 x 1,5 mm²	72 % FRP 28 % metal
D		1,5 x 6 mm²	86 % FRP 14 % metal

For the composite areas (yellow), a glass fiber reinforced epoxy resin was used. The fiber material is a glass fiber roving of the type PulStrand4100 with 4,800 tex from the manufacturer Owens Corning. The epoxy resin used is a pultrusion resin, which consists of 5 components. Table 2 shows the components of the anhydride epoxy resin system. The composite areas of the hybrid profiles are characterized by a fiber volume content of 70 %.

Table 2: Components of the epoxy resin system

Component	Designation	Supplier
Resin	Araldite LY 3585 CH	Huntsman
Curing Agent	Aradur 917-1 CH	Huntsman
Catalyst	Accelerator DY080	Huntsman
Internal Mold Release	IC25	ChemTrend
Filler	ASP 600 (0,6 µm)	BASF

A cold-rolled unalloyed steel sheet of quality DC01/S235JR was chosen for the metallic inserts. The inserts are mechanical blasted with aluminum oxide (high class corundum) and pre-treated with zinc phosphate leading to a fine crystalline layer. The metal gets a good corrosion protection. As previous investigations have shown, this treatment is also necessary in order to achieve the highest possible adhesion in the later hybrid structure [10]. The powder coating materials consist of a two-step curable powder coating based on commercially available uretdione (internally blocked isocyanates) crosslinkers, OH-functionalized polyester resins and a specific catalyst system which was developed at the IPF in former research projects. The curing mechanism is shown in Figure 1. The primary focus of the coating formulation is the variation of the OH-group number of the polyester resins to investigate their influence on the adhesive strength to the epoxy-matrix of the link. Additionally, the post formability of the coating system, as well as the surface appearance should be maintained at a high level.
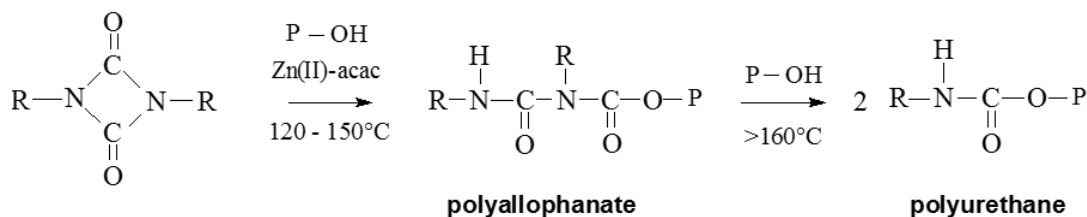

Figure 1: Two step curing mechanism of the used uretdione powder-coating

The powder coating is applied to the metal sheets in the form of dry powder by corona discharge. This technology uses a spray gun with an integrated high voltage cascade that charges an electrode and the powder, and also generate an electric field between the gun and the grounded steel sheet. The powder particles moves along this field lines to the metal sheet. At last, the powder coated sheets are cured at temperatures of 150 °C for 15 min. This process step completes the first reaction step of the powder coating material resulting in a polyallophanate network and simultaneously creates a strong bonding to the metal.

In previous research work, the IPF determined a bond strength of up to 16 MPa between the epoxy composite components and the powder-coated steel components. The samples were produced in an RTM process. The strengths were determined using a tensile shear test according to DIN 65148 [11].

2.2   Manufacturing by pultrusion

The pultrusion process, which is focused for the later application, is one of the few manufacturing processes for continuous FRP profiles that is suitable for large-scale production. Figure 2 shows the basic features of the process: Semi-finished fiber products (1) are pulled from bobbins by alternately moving pulling devices (4) and pass through a resin bath (2). Afterwards, the impregnated fibers are pulled through a heated die (3), in which the liquid thermoset plastic cures completely within seconds. A saw (5) cuts the profiles to the desired length. The pultrusion process is characterized by a high degree of automation and high material utilization paired with low process forces by a high level of economic efficiency. In addition to the pure unidirectional fiber reinforcement, there is also the option of flexibly adjusting the fiber orientations by processing flat semi-finished products. In this way, multi-axially fiber reinforced lightweight structural components can be manufactured efficiently [12].
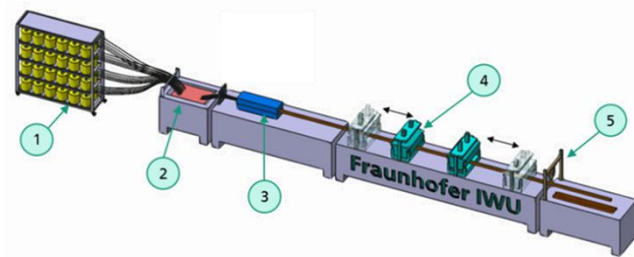
Figure 2: Pultrusion line (1: Semi-finished fiber products; 2: Resin bath; 3: Pultrusion die; 4: Pulling system; 5: Cut-off saw)

The processing of metallic inserts in the pultrusion process for the production of hybrid profiles entails various challenges. Metallic semi-finished products are characterized by significantly higher flexural rigidity compared to fiber semi-finished products. This primarily complicates the feeding and positioning of the inserts in the process or in the pultrusion die. The reason for this is that it is not possible to redirect the inserts in any way. The inserts should be integrated into the material flow from the start in this position, in which they will later be intended in the pultrusion die and thus also in the profile. The deformation of the inserts is thus prevented during the feeding and draping process. Especially in the production of variants C and D, this leads to challenges in filling the composite areas located between the inserts. This required the elaborate design of guide elements to ensure that all composite areas are characterized by a homogeneous fiber volume content. Inserts with a length of 500 mm were used for the pultrusions tests. In contrast to feeding the inserts as coil material, this solution has the advantage that coating with the special powder coating technology is possible. The coating with the special powder coating is currently not yet transferable to a coil coating process. In addition, defined distances can be implemented between the hybrid sections of the endless profile produced, so that the hybrid profiles canbe separated by cutting the pure composite sections. Figure 3 shows the manufacture of the hybrid profiles using the pultrusion process.
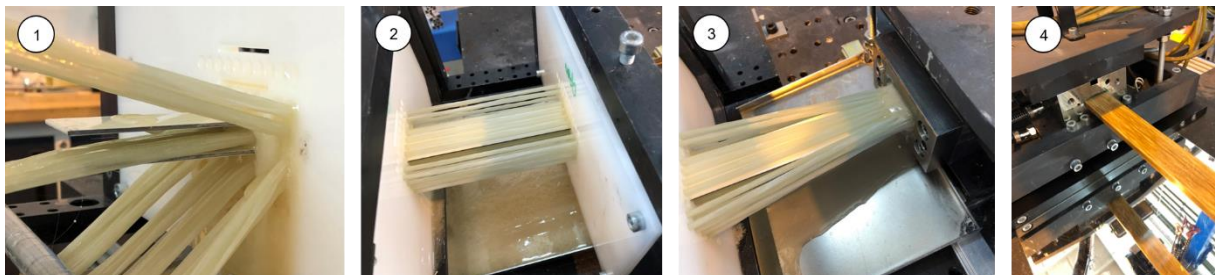

Figure 3: Manufacturing of hybrid profile structures (1: Integration of the inserts in the material flow; 2: Positioning of the materials; 3: Pass through the pultrusion die; 4: Exit of the hybrid profile)

The production of variant C can be seen in the illustrations. In (1) the integration of the two inserts into the material flow of the impregnated glass fibers is shown. The straight alignment and the feeding of the impregnated fibers between the inserts is recognizable. The number of fibers between the inserts is selected so that the composite area between the inserts has the same fiber volume content as the surrounding composite area und so that both inserts have a defined distance between them. In (2) the alignment of all materials takes place. A second guide plate is also required to ensure that the inserts are supported. This means that the inserts cannot move and retain their defined position. The entry of all materials into the pultrusion die is shown in (3). It can be seen that the inserts, which are completely enclosed by fibers, are just entering the pultrusion die and are thus consistently in their target position. The surrounding fibers run conically into the pultrusion die and condense in the entrance area to the target cross-sectional area. When passing through the heated pultrusion die (4), the curing of the epoxy resin matrix takes place. In the course of this, the materials consolidate into a shaped profile. During the curing reaction, the covalent bonding between the inserts and the matrix also takes place via the previously applied powder coating.

The integration of metallic inserts in the pultrusion process significantly influences the curing of the epoxy resin matrix. Due to the high thermal conductivity of steel compared to fiber and matrix material, the curing process is slower. As a result of the dissipation of both the externally supplied heat via the

pultrusion die and the internal heat generated during the exothermic curing reaction, which additionally accelerates the curing, the temperatures in the gel zone are lower in hybrid profiles than in a pure composite profile. For this purpose, the process parameters had to be adjusted. Table 3 gives an overview of the process conditions for the different profile variants.

Table 3: Process conditions for the pultrusions processes depending on the profile variants

Process conditions	A	B	C	D
Process speed [mm/min]	250	150	100	150
Pultrusion die	400 mm die length with 4 heating zones			
Temperature profile [°C]	145 – 175 – 190 – 160			

The same pultrusion die was used to manufacture the different profile variants. The length of the die is 400 mm and thus largely determines the processing speed. It is possible to set any temperature profile along the length of the four heating zones. In preliminary tests, an optimal temperature profile, which is dependent on the matrix material, the profile cross-section and the die length, was determined. The aim was to keep the temperature profile constant for the different profile variants. This ensures that the maximum temperature acting on the inserts during processing is always constant for the various variants. The purpose of this is to ensure that the internal thermal stresses within the hybrid profiles due to the different coefficients of thermal expansion of the matrix and the inserts, are as equal as possible for the different variants and do not lead to a falsification of the mechanical parameters. In order to counteract the changed curing behavior due to the heat dissipation in the hybrid profiles, only the process speed is adjusted. As can be seen in Table 3, the process speed for the hybrid variants (B to D) had to be selected lower compared to the pure composite variant A. The speed of variant C even had to be selected at 100 mm/min even lower than that of variants B and D. This is because of the higher metal content in variant C, which is associated with higher heat dissipation. With the selected parameters, reproducible hybrid pultrusion profiles could be produced, which were characterized by complete curing and a high-quality surface.

3   Results

3.1   Optical and non-destructive analysis

Figure 4 shows microscopic images of grinding patterns of the hybrid specimens manufactured by pultrusion. The left picture shows a direct bonding of metal to powder coating and powder coating to FRP. The right picture shows a hybrid specimen without powder coating. It can be clearly seen that there is no connection between metal and FRP as embedding material has deposited in the space between the two materials.
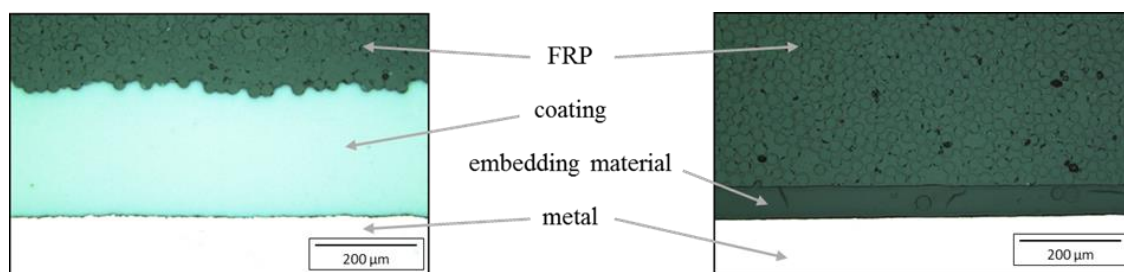

Figure 2: Microscopic images of boundary layers (left: hybrids with powder coating; right: hybrids without powder coating)

3.2 Specimen preparation and test method

In order to be able to evaluate the mechanical properties such as the energy absorption capacity of the hybrid profiles, 4-point bending tests according to DIN 53293 were carried out. The test setup and the specimen dimensions are shown in Figure 5. All dimensions are selected depending on the specimen thickness [13]. For this purpose, the hybrid profiles were cut into 240 mm long samples. Processing in width and thickness direction was not carried out. The specimen is supported at its ends and stressed with a bending punch at two points between the supports. As a result, a constant bending moment acts under the bending punch. The test speed is chosen so that failure occurs within 1 to 3 minutes [13]. A test speed of 5 mm/min was determined in preliminary tests.
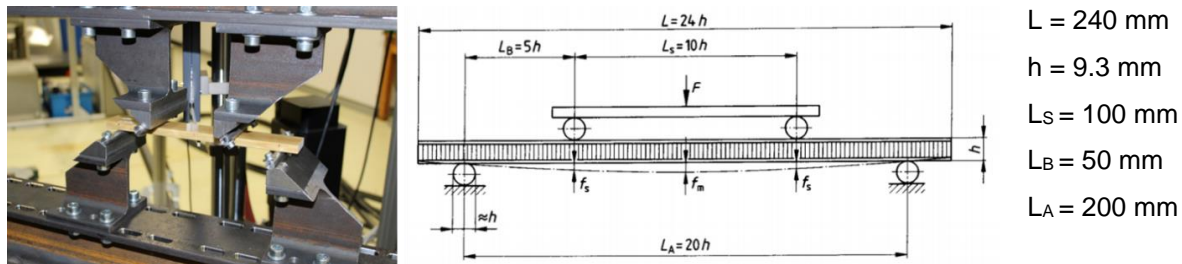

L = 240 mm

h = 9.3 mm

L_S = 100 mm

L_B = 50 mm

L_A = 200 mm

Figure 3: 4-point-bending test according to DIN 53293 [15]

3.3 Experimental results

Five specimens were tested for each profile variant. Figure 6 shows the force curves of all specimens during the bending test. The curves of variants A, B and C are characterized by an abrupt drop in force after the maximum force has been reached. The maximum forces of the hybrid variants B and C are lower than those of the pure composite variant A.
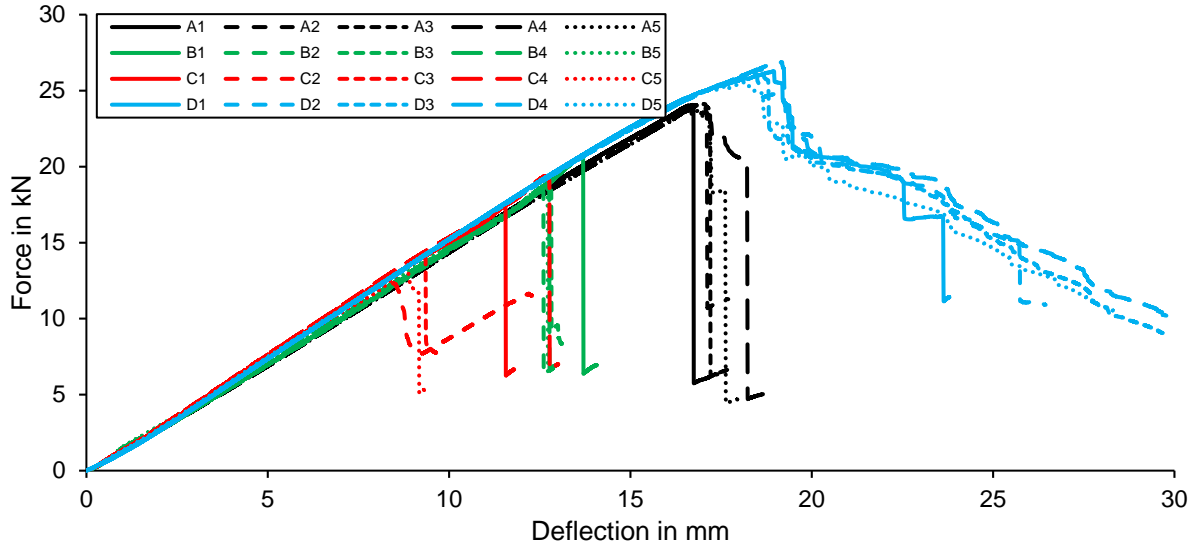

Figure 4: Force-deflection curves of the 4-point-bending tests

This means that as a result of the hybridization of the pultrusion profiles through inserts lying across to the test direction, causes a deterioration in the mechanical properties. When looking at the failure patterns in Figure 7, the causes become apparent. The pure composite variant A is characterized by an intermediate fiber failure. The failure thus takes place in the matrix material and the potential of the fibers cannot be fully exploited with this type of stress. The matrix failure takes place in the strechted area. Some curves of the A variants are identified by two failures. The first failures here is the pressure failure when the stamp penetrates the specimen. The second failure is the total failure of the specimen. The failure behavior can be seen very well in Figure 7 (A). The variant B is characterized by an interface failure. The insert in variant B is arranged exactly in the middle of the cross-section. As can be seen in

Figure 7 (B), the interface fails in the stretched area. The bonding between the insert and the matrix material is therefore too low before the ductile behavior of the metal insert can come into play. The bond forces at this type of load are also below the matrix strength, so that variant B is characterized by a lower maximum force than variant A. Surprisingly, variant C is characterized by a mix of intermediate fiber and interface failure. However, the maximum forces are below those of variant B. The failure takes place between the inserts on the top of the lower insert. This behavior can be seen in Figure 7 (C). The integration of a second transverse insert thus causes a further weakening of the structure.

Variant D is characterized by a completely different failure behavior than the previous variants. As can be seen in the course of the curve, a gradual decrease in force takes place after the maximum force has been reached. In addition, an increase in the maximum force compared to pure composite variant A could be achieved. When looking at the failure pattern in Figure 5 (D), it becomes clear that in variant D, unlike in all other variants, a failure of the fibers was caused. The curves of D are initially due to a sudden drop in force down to a level which is roughly that of the maximum forces of variant B. After that, the fibers gradually begin to break and the force slowly decreases with increasing deflection.
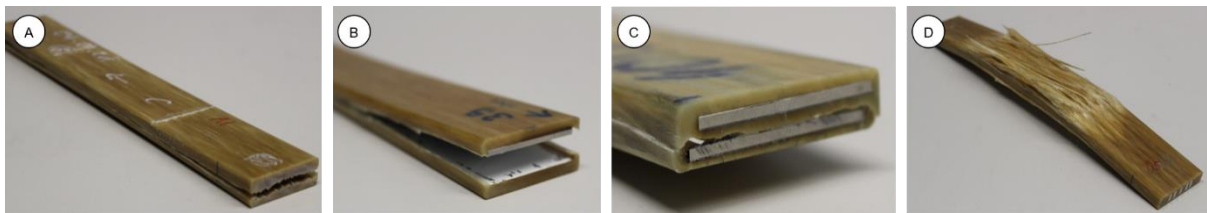

Figure 5: Typical failure patterns depending on the cross-sectional design of the hybrid profiles

In addition to the averaged maximum forces of the different variants, Figure 8 also shows the absorbed energy. The energy absorption capacity was calculated as the area under the curves in the force-deflection diagram. It is therefore obvious that variant D has by far the highest energy absorption capacity. The reason is to be found in the successive force reduction in the form of fiber failures. For this reason, with increasing load at the start of component failure, there is always residual stiffness. That means that energy can still be absorbed, in contrast to variants A, B and C in which there is no residual stiffness after the sudden component failure. With an energy absorption of an average of 401 J, an increase in the energy absorption capacity of 77 % could be achieved with the hybrid variant D compared to the pure composite variant A, in which the energy absorption is only an average of 226 J. The increase in mass due to the metallic inserts compared to variant A is only 33 %. When looking at the specific energy absorption capacity, the advantage of the hybrid variant becomes more clear. The specific energy absorption capacity of variant D is 1,76 J/g, while that of variant A is 1,32 J/g. This corresponds to an improvement of 33 %. The hybridization of the pultrusion profiles with vertically oriented inserts has thus led to a significant improvement in the mechanical failure behavior. In further development work, based on these results, optimized design methods must be determined in order to achieve additional mass savings to operate effective hybrid lightweight design.
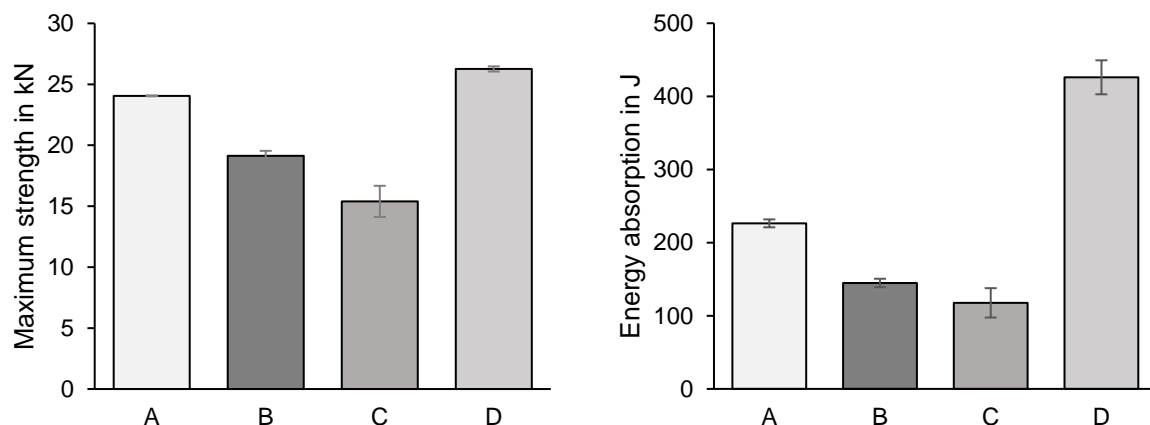

Figure 6: Maximum strength and energy absorption depending on the construction design

4   Discussion and conclusion

The investigations have shown that the hybrid pultrusion profiles exhibit very different failure behaviors under the 4-point bending load, depending on the inner metallic core structure. A significant improvement in the mechanical properties could be achieved by vertically oriented inserts. This construction prevented a sudden matrix failure, as would occur with pure composite specimen under the bending load. It was possible to achieve successive component failure in the form of fiber failures. On the one hand, this leads to an increase in maximum strength and on the other hand to a significant increase in energy absorption capacity. The vertical metal inserts act as a crack barrier to prevent the matrix failure and also cause ductile material behavior, so that there is residual rigidity even with high deflection. In addition, such an arrangement ensures that the load on the interface is a shear load. Adhesive composites usually have their highest strength under shear loads. The results of the investigations should provide clues for the design of hybrid pulrusion profiles for use as highly stressed structural components. In further development work, optimized construction concepts must be worked out on the basis of the results achieved in order to be able to operate effective hybrid lightweight design. First and foremost, a further reduction in the mass of the overall components must be aimed for. For this purpose, wall thickness reduction or the use of aluminum inserts can be investigated. A finer division of the vertical inserts would also be conceivable. In summary, it should be said that hybrid pultrusion profiles do not replace previous hybrid structural components, which are manufactured, for example, by gluing or injection molding. Much more, they represent a further new possibility to operate economical hybrid lightweight design and should therefore open up new application possibilities for pultruded components.

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