A NEW PATH TO LIGHTWEIGHT SHEET METAL STRUCTURES STRENGTHENED BY IN SITU JOINED FIBRE REINFORCED THERMOPLASTIC TAPES

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Abstract
Modern lightweight design strategies provide various approaches to improve the weight-specific mechanical properties of load bearing structures. Among these possibilities, hybrid structures based on fibre reinforced plastics (FRP) and metals are particularly interesting, since advantageous material properties can be combined. Thus, the weight specific stiffness and load-bearing capacity of FRP can be coupled with the broad joining possibilities of metallic structures. In order to exploit this potential, however, a suitable process is required to combine these dissimilar materials in respect of their inherent properties.
In the present paper, a novel joining method based on a force-closed connection is examined. The necessary connection force is provided by the spring-back difference of FRP and metal resulting from a plastic deformation. For this purpose, a continuous fibre reinforced thermoplastic (CFRTP) tape is loosely wrapped around a stiffening stringer welded onto a flat sheet metal base plate. Using a tensile test setup to provide the necessary deformations, the metallic component is elongated plastically, while the FRP is stretched elastically. The resulting residual stresses in the hybrid structure can be utilised for the formation of the frictional connection. The presented experimental and numerical investigations focus on the identification of the underlying mechanisms and the evaluation of the hybrid structure's potential for lightweight design.

1. Introduction

Reducing the weight of load bearing structures is an important objective in modern industry. In order to increase the energy efficiency of cars, trucks and airplanes, sheet metal structures with a high strength and stiffness at low weight are needed. In order to achieve this goal, hybrid structures made from different types of materials are increasingly used. Especially hybrids made of fibre reinforced plastics (FRP) and steel have significant advantages. Schmidt and Lauter emphasise the low steel price and the versatile processing possibilities of the metallic material in combination with the possibility of local reinforcement by FRPs as a benefit of hybrid constructions since the stiffening effect of the FRP results in a reduced wall thickness of the metallic component [1]. Grujicic describes the advantages of polymer-metal hybrids additionally with increased bending strengths and improved acoustic damping properties [2]. To utilise these advantages, however, some challenges need to be overcome. According to Wang et al., additional complex process steps are necessary to join the foreign materials. Also new tool concepts have to be developed to meet the combined requirements of the different materials [3].

While there are several options to realise the material combination of metal and FRP, e. g. adhesive bonding, riveting, bolting, clinching or welding [4], the rigidly coupled hybrid structures often lack the necessary formability to withstand further processing by forming as well as high temperature fluctuations or deformations during their service life. This is due to the strong disparity of FRP and metals in terms of their thermal expansion coefficients as well as the tolerable strains.

To overcome these constraints, new joining technologies are needed [5]. In order to ensure the cost-effectiveness, it is advantageous to integrate the joining process into already existing processes required for the production of the load bearing structure itself. For this purpose, forming processes are especially suited, since they are used both for global shaping as well as for joining. In addition, since the difference in spring back after a conjoint forming of the components often is used to create a force-closed connection, the differences in the mechanical properties of FRP and metal can be targeted at the joining mechanism. Using stringer sheet blanks as a metallic base structure, attachment points for the FRP at the stringer ends as well as a high geometrical stiffness and strength are provided.

1.1. Joining by Forming

Plastic deformations can be utilised to join two or more components in many ways according to the geometric properties and joining mechanisms [6]. In case of force-closed joints, the parts are held in place by means of friction. The normal force necessary to provide this friction is obtained by compressing one or several surfaces in normal direction. The relative movement of the corresponding surfaces perpendicular to the normal forces is prevented by friction as long as they stay in contact and do not exceed the forces determined by sticking friction. Often, the normal loads are generated due to residual stresses by a difference in spring-back after a conjoint forming.

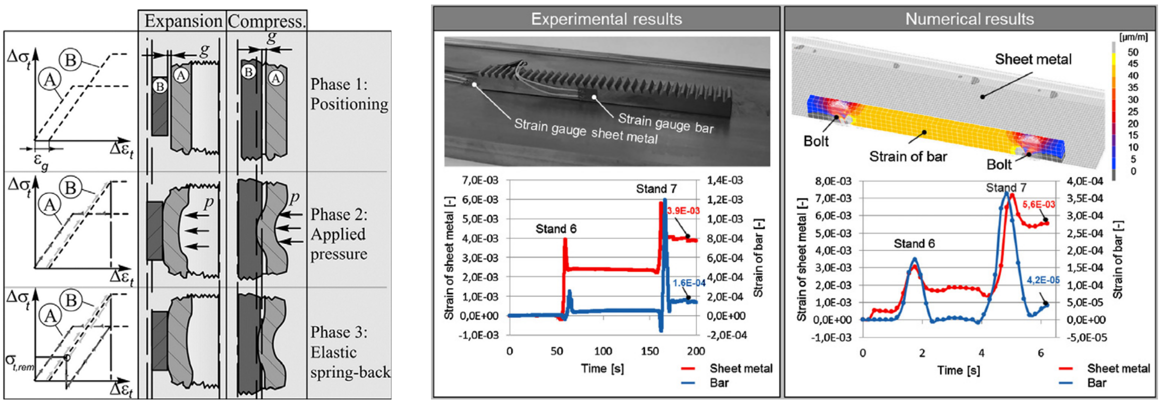

Figure 1. Force-closed joining by expansion and compression (left) [7]
and by linear flow splitting (right) [8]

Marré et al. illustrate this process for an expansion as follows (Fig. 1, left): Joining partner A is placed in joining partner B leaving an initial gap *g* between them (phase 1). A pressure *p* applied to the inner workpiece consequently deforms the inner part towards the corresponding outer part until contact occurs. Both parts precede their deformation until the inner joining partner is plastically deformed while the outer partner is solely elastically widened (phase 2). After the pressure *p* is relieved, the elastic spring-back of the outer part is stopped by the plastically deformed inner part leaving the residual stress for the frictional joint [7]. Homberg et al. show that the residual stresses can be influenced by the yield strength and the Young's modulus of the joining partners as well as the gap *g*, the outer and inner rings thickness and the expansion ε [9]. Groche et al. describe a similar mechanism for the joint formation between bifurcated sheet metal profiles and additional bar elements by using the strains inherent to the forming process of linear flow splitting (Fig. 1, right) [8]. For this purpose, a bar element with bolts attached to its bottom side is loosely inserted into boreholes drilled into the sheet metal strip. During the process of linear flow splitting, the sheet metal strip as well as the inserted bar are elongated by the strains resulting from the forming process. The higher spring-back of the sheet metal strip after forming results in a force-fit connection of the bar and the strip. Monnerjahn et al. describe the influence of geometric parameters on the resulting connection force [10]. An increase of the length as well as a decreasing cross section of the bar result in a higher elastical strain of the bar and therefore in an increasing connection force.

1.2. Stringer Sheets and Stringer Sheet Forming

Since sheet metal structures are manufactured out of flat semi finished products, their stiffness and yield strength are comparatively low when they are submitted to bending loads. To improve these properties, the structures' geometry can be optimised by the use of stiffening elements such as beads and stringers. Due to the fact that the height of a stringer increases the geometrical moment of inertia with a power of three, even small stringers can significantly increase the structures' stiffness and strength to an impressive amount making stringer sheet blanks an extraordinarily suited base structure for lightweight design. The significantly improved mechanical properties, however, come along with limited production possibilities. Due to the stringer, flat punches or dies of conventional deep drawing tools cannot be used to form the stringer sheets. In this context, Groche et al. demonstrate the possibility to form curved sheet metal structures with stiffening stringers by hydroforming [11], die bending and deep drawing with rigid tools [12, 13]. Thus, both complex and high productive forming processes are available.

2. Objectives

In the present paper, a joining technique is presented, which enables the reinforcement of a stringer sheet metal structure using continuous fibre reinforced thermoplastic tapes (CFRTP). For this purpose, a strap of CFRTP is wound around the stringer, using ring-shaped coupling elements to transmit the forces from the stringer into the CFRTP strap. An elastic-plastic deformation behaviour of these coupling elements compensates for the inadequate elongation capability of the FRP. During a forming process, the stringer sheet blank can be plastically formed whereas the CFRTP is solely elastically elongated. Due to the difference in spring back of CFRTP and metal after the forming process, a beneficial pre-stress remains in the hybrid structure, which can be utilised to form a friction based joint between FRP and metal as well as postpone the structure's failure under subsequent bending loads.

In the present paper, stringer sheet metal blanks are reinforced by CFRTP-Tapes attached to elastic-plastic ring-shaped coupling elements. The necessary strains are provided by means of tensile tests. Numerical simulations provide the process insights to comprehend the joining mechanism and the accompanying forces and strains. The investigations focus on the proof of the joining concept regarding the increase of the hybrid structure's endurable strain and strength as well as on the identification of the joining mechanisms.

3. Materials and Methods

3.1. Specimen Preparation

The specimen's geometry used for the tests is shown in Fig. 2. A laser cut tensile test specimen with a width of 15 mm in the narrow section and a laser welded stringer represents the metal structure to be reinforced. The 8 mm high stringer and the base plate are made of 1 mm thick steel DC04 (1.0338). The joining process is carried out by laser welding at 1000 W laser power and a feed of 22 mm/s using an *IPG* fibre laser system. Both ends of the stringer are attached with 1 mm thick ring-shaped coupling elements also made of DC04. The coupling elements with a height of 8 mm and an outer diameter of 16 mm are formed into their geometry by an adapted U-O die-bending of a laser-cut sheet. By slightly over-bending the limbs, a sufficient clamping force can be generated so that they are held in a centric position at the stringer ends. Lastly, a CFRTP strap with unidirectional fibre orientation and a width of 8 mm is manually wound around the coupling elements. The FRP component is designed as a non-laminated pin-loaded strap. Thus, only the outermost end of the used 0.25 mm thick glass fibre reinforced polyamide tape (*BASF Ultratape B3WG12 UD01*, glass content: 60 wt.%) is melted by hot air and bonded to the underlying layer under slight tension at its free end. The innermost layer is fixed by friction. In the experiments, CFRTP straps with 5 layers are tested. As a reference, a non-reinforced stringer sheet is used to determine the influence of the FRP strap.

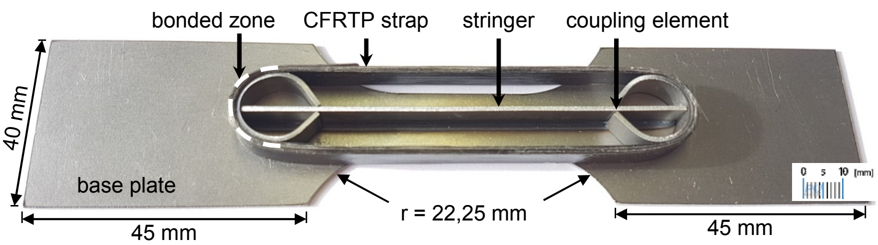

Figure 2. Geometry of the test specimen

3.2. Experimental Setups

The setup for the tensile tests is depicted on the left of Fig. 3. To provide the necessary forces, a tensile/ compression testing machine (*Zwick Allround-Line 100 kN*) with an optical strain/ displacement measurement system (*videoXtens)* is used, which records the relative displacement of two measuring marks attached to the test specimen. In the tests, two of the specimens depicted in Fig. 2 are clamped back to back to provide a symmetric force transmission and prohibit an uncontrolled out-of-plane deflection of the asymmetrically stiffened stringer sheet. The distance between the clamping jaws is set to 127 mm leaving enough space for the FRP straps as well as the measurement marks. In two test series, the marks are either placed at the narrowed section of the specimen (Fig. 3, top right) or between the stringers end and the clamping jaws (Fig. 3, bottom right).

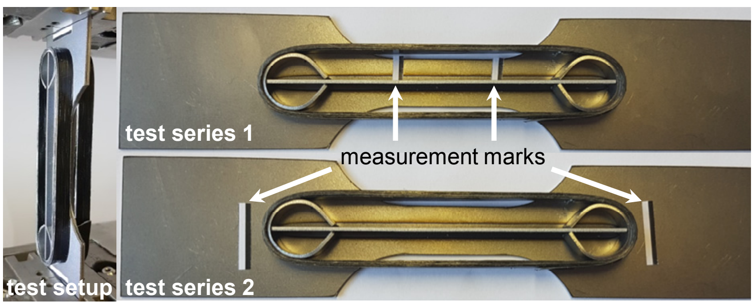

Figure 3. Test setup for the tensile tests (left) and measurement mark attachment points (right)

For the first tensile test series, the measurement marks are attached to the narrowed section. A maximum load of 15 kN is applied, ensuring the plasticisation of the metal component but avoiding the specimens' failure. In the second test series, the endurable strain is evaluated by elongating the specimen until failure of the metal or the CFRTP strap, respectively. For these tests, the marks are attached to the specimens head. All experimental tests are performed with a sample size of three.

3.3. Numerical Setup

The numerical studies are used for the investigation of the joining mechanism. For the FEM analyses, the software *Dassault Systèmes Abaqus 2017* employing an implicit solver is used. Because of the present symmetries, only a quarter of the tensile test assembly is modelled in order to shorten the computational effort (Fig. 4). To account for the second test specimen arranged at the back of the other, an analytical rigid face is arranged at the specimens back surface providing a hard contact free of friction. To further simplify the model, the clamped area of the test specimen is removed, applying the tensile force directly at the remaining cross section. After an increase to the final force as in the experiment, the load is completely released in a second step.

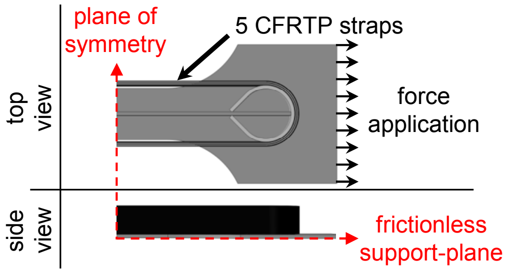

Figure 4. Numerical model of the tensile test

For the metal components (base plate, stringer and coupling element), an isotropic elastic-plastic material model is used. The flow curves are determined by tensile tests and extrapolated using the 'Ludwik' equation [14]. Due to the low plasticity of FRPs in fibre direction, the CFRTP strap is modelled fully elastic. Its anisotropy is taken into account by a material model based on engineering constants, calculated from manufacturer's specifications and data from literature. A material orientation tangent to the edge of the strap accounts for the fibre direction. Contrary to the experiments, the CFRTP is modelled as five separated seamless straps in order to reduce the complexity of the model. All contacts are modelled using the option *hard contact* in normal direction and a *penalty algorithm* with estimated friction coefficients of 0.15 (steel-steel), 0.35 (steel-FRP) and 0.4 (FRP-FRP) in tangent direction. Table 1 provides an overview of important material properties.

Table 1. Material properties of steel and CFRTP

Material	Young's Modulus [N/mm²]	Density [g/cm³]	Strain at break [%]	Yield strength [N/mm²]	Tensile strength [N/mm²]
DC04, (1.0338)	210,000	7.85	27.5	195	330
CFRTP 0° (PA6-GF)	33,000	1.72	3.4	-	770

4. Results

4.1. Validation of the Numerical Model

The numerical and experimental results of the tensile tests with a maximum load of 15 kN are shown in Fig. 5. It can be seen that the experimentally determined force-strain curves of both sample types are very well matched by the results of the numerical model. In comparison to the arithmetic mean of the experimental results (marked with a red cross) the numerically obtained elongation for a given load of 15 kN is 15.8 % higher for the reinforced specimen and 3.2 % higher for the reference specimen. Regarding the qualitative accuracy of the numerical model, a good match of the geometric deformations obtained from the numerical model and those from the experiments can be stated. In both, the deformation of the coupling element as well as an out-out-plane deformation of the base plate at the stringers end can be observed (Fig. 5, right). Due to the qualitative and quantitative accuracy, the validity of the numerical model is sufficient for the further investigations.

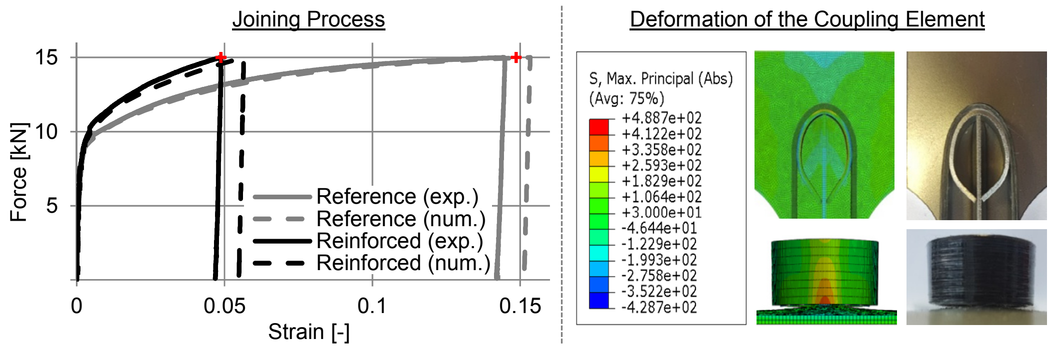

Figure 5. Comparison of the numerical and experimental results of the joining process

4.2. Joining Mechanism

In Fig. 6, the development of the forces transmitted by the CFRTP strap and the sheet metal base plate are depicted as a function of the strain during loading and subsequent unloading. As it can be seen, the major part of the total forces is transmitted by the stringer sheet. At the beginning, the tensile loads of both components rise with a linear function according to the respective components stiffness. While the stringer sheet metal plasticises early, the forces in the FRP continue to increase linearly until the coupling element connecting the stringer with the FRP plasticises as well. From this point on, the force transmitted by the strap only rises with a low gradient until the maximum force of 15 kN is applied to the hybrid specimen. During the following unloading, the energy stored elastically in the components is reduced in part, leaving a residual force of opposite direction in FRP and stringer sheet after the completed spring-back due to the major plastic strain of the metal component. This residual force of about 1.13 kN is used to form the force-closed joint between the two components.

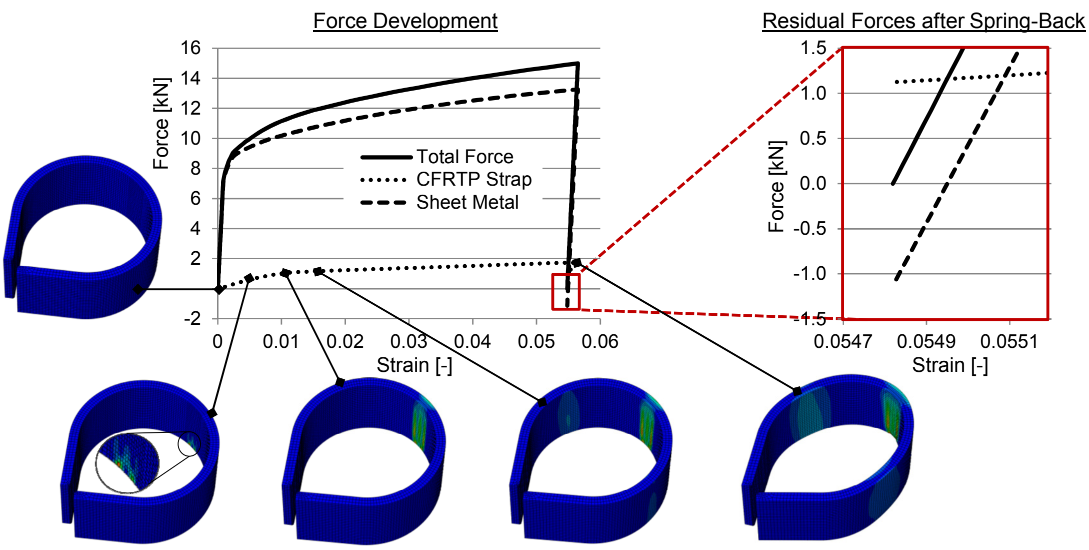

Figure 6. Development of the forces transmitted by FRP and stringer sheet during elongation (top) and the according plastically strained areas of the coupling element (bottom)

4.3. Strengthening Effect

The strengthening effect of the hybridisation can be verified by the results of the tensile tests (Fig. 5 and Fig. 7). Regarding the tensile loads, the CFRTP strap reinforces the stringer sheet structure by decreasing the strain of the most stressed area, i. e. the narrowed section of the specimen. Compared to the reinforced sample, the strain of the reference determined in the first test series is about three times higher at a load of 15 kN. The results of the second test series regarding the loading until failure show the same effect (Fig. 7). For a load of about 15.4 kN at a strain of 0.1 the yield strength of the reference is reached. Complete failure occurs later on by a ductile fracture in the narrowed section. The reinforced samples failure occurs at a maximum load of about 19.5 kN at a strain of 0.13 by fibre breakage at the most bended area around the coupling element, thus increasing the weight specific strength by about 13.1 %. A necking of the narrowed section did not occur.

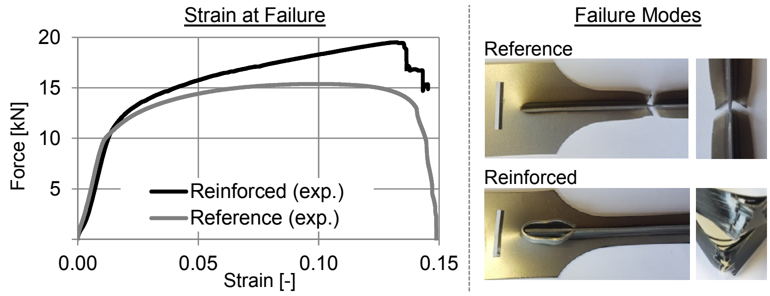

Figure 7. Comparison of the maximum endurable strain and failure modes

5. Conclusions

In this paper, a novel joining method for stringer sheet structures with reinforcing CFRTP straps is presented. Based on the results of experimental and numerical investigations, the following conclusions can be made:

- Deformable coupling elements can compensate for the inadequate elongation capability of FRP at high strains

- Stringer sheet metal blanks and CFRTP straps can be joined by the difference in spring-back subsequent to a conjoint forming

- The endurable strain as well as the strength of load bearing structures can be increased by joined CFRTP straps

Based on the identification of the joining mechanism in this paper, subsequent investigations are needed to determine the dependencies of the individual components, i. e. the stinger sheet, the coupling element and the CFRTP strap, and their influence on the properties of the entire hybrid structure. Thus, it would be possible to optimise the hybrids behaviour to the application-specific loads and strains in order to fully utilise the FRPs load bearing capacity.

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