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Investigation of asymmetrical fiber metal hybrids used as load introduction element for thin-walled CFRP structures

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Abstract

Due to the industrial success of fiber reinforced plastic (FRP) light-weight components, the demand for joining methods suitable for FRP increases as well. Conventional joining elements like rivets and screws or simple clamping are designed for an application in conventional isotropic materials such as steel or aluminum. Therefore, by design these joining elements do not consider characteristic FRP properties such as the orthotropic (fiber) or the setting behavior of matrix materials that are subjected to a constant load. Thus, without any FRP specific adjustments, conventional joining elements will, in most cases, lead to poor results and an inferior joint. Hence, this investigation presents the concept of a layered local metal-hybrid area that can be used as a load introduction element, the "Multilayer-Insert". The design aspects of the hybrid area are discussed for several stacking options. Furthermore, the sensitivity to geometrical design variables and asymmetrical stackings are investigated by a simplified two-dimensional finite element model. The deduced parameter relations are discussed in the context of an application in an automated fiber placement process in order to formulate recommendations for the geometrical parameters.

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Keywords: Fiber-metal laminate; Insert; Embedded load introduction; Joints

1 Introduction

The continuing success of fiber reinforced plastics (FRP) in most industry branches like the automotive or aviation industry also increases the necessity to design joints between FRP and conventional metallic parts [1, 2]. Typically, these joints are realized as an adhesive joint or by additionally inserted metallic elements (inserts); but riveting or screw connections are also still quite common. The maintenance of an adhesive joint is still very difficult since the joint quality can hardly be assessed, whereas insert, screw and rivet joints disturb or damage the fiber path, while additionally suffering from the poor hole bearing capability of FRP laminates. Thus, leading to a reduction in the transferable load. In order to improve the hole bearing behavior using bolted joints Camanho et al. (2009) [3] propose a local hybridization by intermittently replacing FRP layers with thin titanium sheets whose thickness can span one or several FRP layers. In the presented shear load case the prevalent failure always occurs in the interface between the bolt and the (hybrid-) FRP laminate. Also, several concepts describing the strain field surrounding inhomogeneities such as

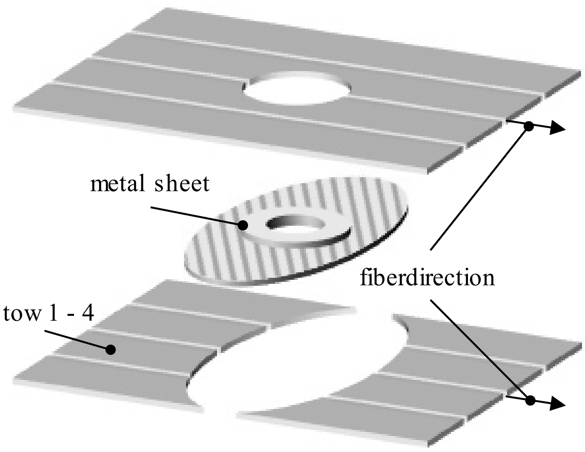

Fig. 1: Schematic view of the integration of a (MLI-) metal sheet into a double-layer laminate.

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the analytical description of ellipsoidal inclusions by Eshelby (1957) [4] or the more recent validation of the linear elastic solution for stress concentrations near (simply shaped) rigid polygonal inclusions by means of photoelasticity presented by Misseroni et al. (2014) [5] are available.

The project "Multi-Layer Inserts" (MLI) proposes a new design for inserts used in thin-walled structures made of carbon fiber reinforced plastic (CFRP). The proposed insert consists of multiple thin metal sheets and is built up simultaneously with the laminate in a fully automated intrinsic hybridization process: Thus, eliminating time-consuming post-processing steps [6]. Furthermore, such inserts significantly increase the bonding area between metal and CFRP in comparison to conventional inserts at equal weight. This results in a significant increase of the loads that can be transferred into the CFRP. The detailed positioning of the metal sheets within the laminate layers is shown in Fig. 1.

The MLI is designed to introduce loads into thin-walled (shell) structures, since these are the most common lightweight structure. These thin-walled structures are mainly exposed to

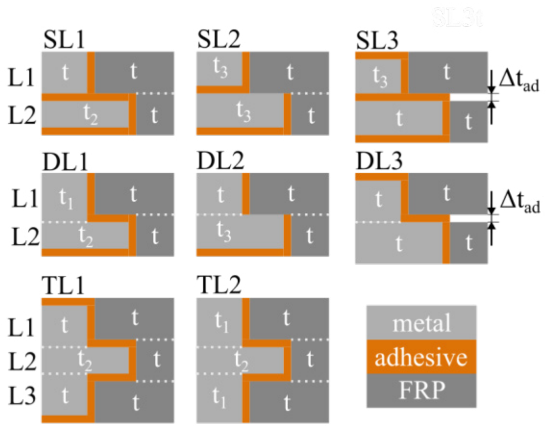

Fig. 2: Several stacking concepts for the hybrid-area for metal sheets with a single-, double- and triple-layer thickness.

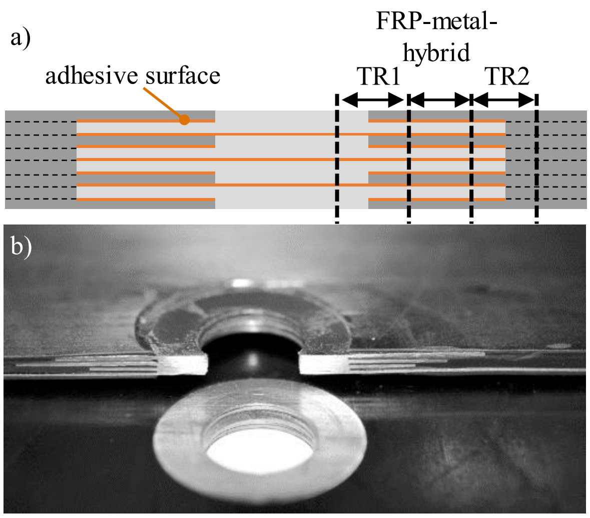

Fig. 3: a) Simplified model of the adhesive connection formed by the MLI with sectioning for further investigations. b) cross section of a MLI with centre hole.

(shear) loads perpendicular to the thickness direction. Therefore, the in-plane shear is also chosen as the reference load case during this investigation.

The individual material layers of the local CFRP-metal-hybrid (CFRP, metal, adhesive) are very thin, i.e. 0.1 mm up to 1.34 mm and form a multitude of adhesive connections, see Fig. 3. The complexity of their interaction prevents the application of analytical calculation methods. However, when modelling thin layers in a finite element analysis, the recommended aspect ratio of the elements significantly increases the numerical effort.

An investigation of a load introduction element has to differentiate two scenarios: The introduction of external loads into the element and the transmission of structural loads through the element. The present work considers the MLI as an inclusion, which is obstructing the load transition within the structure and discusses its sensitivity to design parameters.

2 Design

In addition to limitations in the actual hybridization process, the selection of a suitable topology for the local hybrid area depends on the chosen aim and its application as well as the used FRP material, the adhesive, the metal sheet, their production processes and especially the (layer) thickness of each component. In addition, deliberate choices resulting from design restrictions such as the prohibition of a local thickening, also limit the available designs.

The design process of the metallic sheets can be divided into three subdomains with their own characteristic design requirements: On a microscopic level a sufficient roughness of the bonding surfaces has to be ensured. The height profile has to match the layer thicknesses in order to avoid a local thickening, while the circumferential shape influences the strain concentration in the material transitions TR1 and TR2. A first study investigating metallic sheets with a different circumferential shape was performed in [7]. It could be shown, that the circumferential shape of the metal sheets strongly influences the strain field surrounding the hybrid area as well as the transferrable loads. The main scope of this investigation will be the influence of the height profile and stacking parameters in a two-dimensional cut-view.

Stacking sequence

Several stacking variations can be used to build up the hybrid area. Fig. 2 shows models of several stacking concepts assuming a fixed layer-thickness. In the following sections the influence of design parameters will be exemplary discussed for concept TL2. Consolidation effects will be neglected during this discussion. The relation between the depicted layer thicknesses are the following:

$$t_1 = t + t_{ad} \quad (1)$$

$$t_2 = t - t_{ad1} - t_{ad2} \quad (2)$$

$$t_3 = t - t_{ad} \quad (3)$$

Where, $t = 0.1$ mm, $t_{ad} = 0.04$ mm are typical thicknesses used in the experimental setup of an automated fiber placement process, see Table 2.

The concepts are suited for metallic sheets with a constant thickness (SL), sheets with a locally reduced thickness (DL)

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and sheets with a symmetrically reduced thickness (TL). The metal sheets depicted in the DL and TL stackings are one connected piece. The joining of the metal sheets can either be done by adhesive layers or an adapted resistance welding process.
The simplest stacking concept is the single layer approaches with a constant thickness (SL1-SL3). The required metal sheets can e. g. be laser-cut, while an etching process is suitable to produce the required metal sheets for DL and TL. For each adhesive surface the thickness of the metal sheet in the second layer transmitting the loads into the FRP has to be reduced by the adhesive thickness in order to prevent local thickening. This is true for all depicted stackings. Thus, due to the restriction of no thickening, the only possibility to increase the thickness of the second metallic layer transmitting the loads into the laminate is to increase the layer thickness of the FRP or to only use an adhesive on one side (SL2, DL2). A significant advantage using thicker and more complex DL and TL metal sheets over the single layer variant is the reduction of joints between the metal layers, the reduced number of metal sheets and the simpler placement during the production process.

3 Model

In a prior investigation it could be shown, that in case of an in-plane shear load, the material transition TR2 (Fig. 1) can be simplified to a lap joint [7]. It was also shown that for a sufficient adhesive length the strain along a material transition with a constant transition angle is also constant. This behavior is consistent with prior findings of a hyperbolic strain distribution in adhesive (lap) joints originating from investigations by Volkersen (1963) [8] and Bruyne (1944) [9]. The analytical models were extended by Tsai et al. (1999) [10] in order to better describe FRP lap-joints by allowing a shear deformation in the adherents. The elevated strain due to the hyperbolic fraction in the strain distribution can be reduced by an increase of the adhesive length above a characteristic adhesive length, the effective adhesive length [11]. While these finding, as long as the effective adhesive length is smaller than the actual adhesive length, allow a general investigation of the design parameters by two a dimensional model, it cannot be assumed that the strain in corner of the circumferential shape is described accurately.
The model used for the investigation is shown in Fig. 4 and its initial parameters are given by Table 1 in Appendix A. The right edge is displaced in x-direction by ΔU_1, while the left edge is fixed in x-direction. The linear elastic computation is performed with Abaqus/standard. The step size is fixed to 1 % thus also resulting in a measurement error of 1 % for both the load and displacement in the linear elastic section of the load-displacement curve (before the first failure). The parameters of the used materials are given by Table 1 in Appendix B. The damage initiation is computed using an Abaqus user subroutine by Kodagali [12] for the Puck damage criterion and the constant stress exposure method for material degradation.
The first failing element in the FRP-layer is located in the transition region TR2 between the adhesive and FRP layer, develops a V-shape, see Fig 5. While this displacement-controlled approach leads to a faster convergence during the damage evolution, it also results in variable step sizes for the reaction forces in the non-linear section after the first element failed. The geometrical dimensions of the specimen are

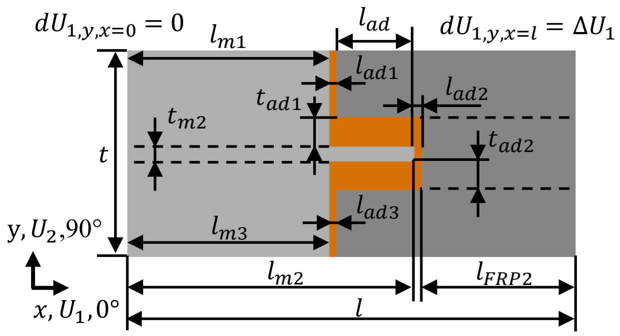

Fig. 4: Model geometry and parameters of the investigated TL2-stacking.

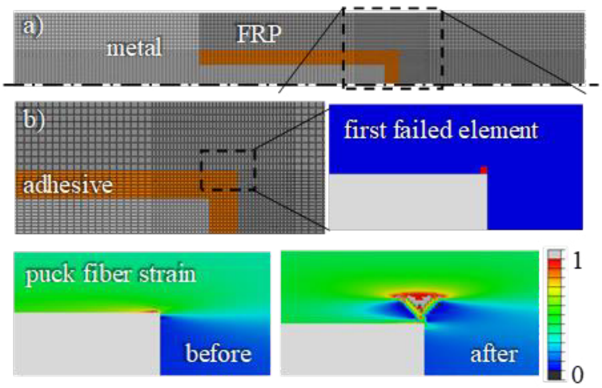

Fig 5: a) Upper half of the symmetrical TL2-stacking model b) enhanced critical area with the first failed element and the Puk fiber strain before any damage and at a later failed stage.

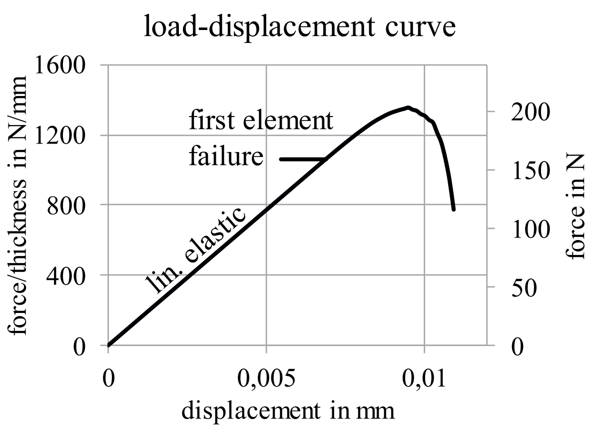

Fig. 6: FEA result of a typical load displacement curve for TL2-stacking with model parameters according to Table 2.

calculated from the input parameters of the individual layers. Due to the prohibition of local thickening, the total thickness equals the thickness of three FRP-layers for the whole specimen. Therefore, the thickness in the central metal sheet t_{m2} needs to be reduced by t_{ad1} and t_{ad2} according to the model sketch in Fig. 4. In order to capture local strain concentrations, the element size of 0.01 mm for the coarse meshing areas and 0.001 mm at both material transitions (TR1, TR2) was chosen. The deliberate choice of these small elements and the measurement directly in the strain concentrations greatly influences the failure load of the first

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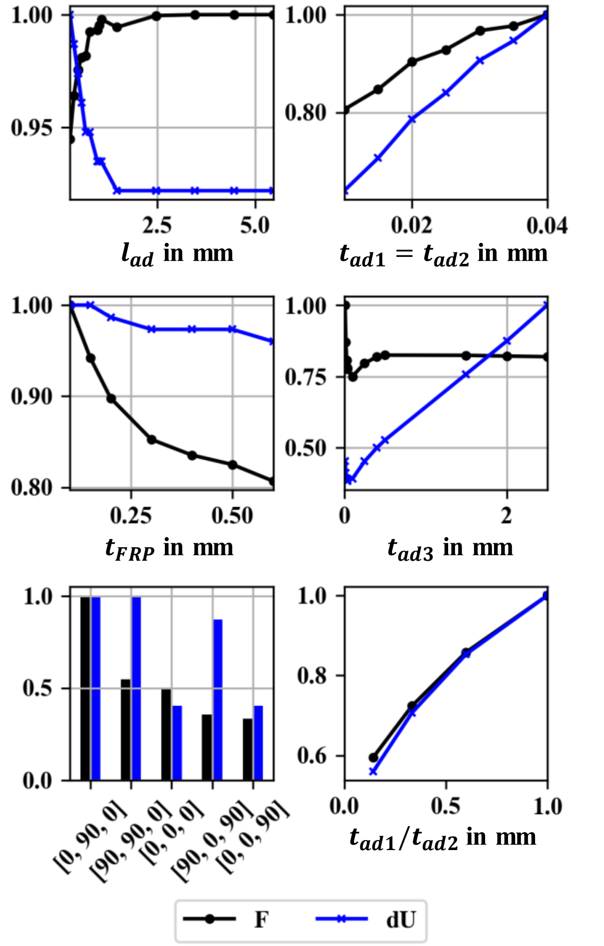

Fig. 7: Graphs showing the influence of the design variables on the first element failure.

element. This effect can also be seen in the load-displacement curve depicted in Fig. 6. Due to the small element size the slope at the first failing elements failure stays linear until a considerable number of additional elements have also failed. While the criterion is not suited to determine the failure load of a real specimen in a tensile test, it can be used to perform a qualitative comparison of the design parameters. Also, in order to get comparable results for the first element failure using different set of geometric parameters, the element size needs to be kept constant.

4 Design Parameter Sensitivity

Fig. 7 shows the normed load per thickness at the first element failure. All parameters are kept constant at the values given by Table 1 except for the varied parameter. For short adhesive lengths, in this case $l_{ad} < 2.5$ mm, the failure load is reduced and stays constant afterwards. Its assumed that this occurs due to the hyperbolic component in the shear stress distribution, which can be neglected for increased lengths. While a simultaneous increase of the adhesive thickness t_{ad1} and t_{ad2} will lead to an increased failure load in the investigated FRP section, the increase will also have a negative impact on the total transferrable load of the specimen. This decrease is a direct consequence of the prohibited “local thickening”. As a consequence, any increase of the adhesive thickness will result in a decreased thickness in the metallic layer t_{m2}, which will therefore fail earlier. By increasing the FRP layer thickness t_{FRP}, the thickness of the metal sheet t_{m2} can be increased while keeping the adhesive thickness constant, thus increasing the failure load in the metal area, but overall an increased FRP layer thickness still results in a decreased failure load per thickness. Therefore, a combination of parameters resulting in an equal strain in the central metal sheet and the FRP layer is preferable and needs to be determined. Also, very small adhesive gaps (t_{ad3}) lead to a very stiff joint and an increased failure load; but in an actual production process these small gaps typically cannot be realized. It is also important to notice that any unwanted increase of the adhesive gap during the production process reduces the actual available adhesive length l_{ad} and therefore needs to be avoided.
In case of a uniform 0° laminate the material transition TR2 is considerably less stiff than the hybrid and the surrounding FRP, thus resulting in a high local strain concentration and a fiber failure in the outer layers due to the localized load transfer in the transition. If the stiffness of the second layer is reduced by a change in the orientation, the FRP laminate becomes less stiff, thus allowing the load transfer in the outer layers over an extended the range. Thus, by reducing the concentration of strain, the [0,90,0] specimen acquires in the highest relative failure load in this investigation, while also changing the prevalent failure to mode II. In the specimen the mode II Puck strain at failure is about 10 % higher than the mode I strain. By changing the orientation of an outer 0° layer to a 90° orientation only one (stiff) layer is left, which reduces the failure loads by 38%. Compared to the uniform 0°stacking.

5 Discussion

A suitable adhesive length cannot be chosen by only relying on the ideal model and its parameters. Parameters defined by the production process such as the positional and repetitive accuracy, in case of AFP process, also need to be considered. If the minimal adhesive length without a visible reduction of the failure load is chosen without any margin for errors, any deviation away from the hybrid center will result in a shorter adhesive length, thus reducing the failure load. Also, any deviation towards the hybrid center will result in an overlap of the FRP layer and the central metal area that will cause a local thickening and prevent the desired (pure) metallic central area. Also, the insertion of FRP in the central part will limit the available machining processes, since now additional measures due to the machining of FRP have to be taken. Therefore, an early consideration of the desired production process as well as its capabilities during an early design phase can prevent the introduction of additional high process requirements by adding specific margins in the geometrical design. Therefore, this first sensitivity study can give a first general guideline in the build-up of local fiber-metal hybrid area. In order to get a more detailed understanding of local effects and interactions with the production process further investigations need to be performed.

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Appendix A. Material data

Table 1: Material and puck parameter for IM7-8551-7 [13], steel and epoxy. t: tension, c: compression.

IM7-855-7	
$E_{\parallel}$	165 GPa
$E_{\perp}$	8.4 GPa
$G_{\parallel\perp}$	5.6 GPa
$\nu_{\parallel\perp}$	0.34
$\nu_{\perp\perp}$	0.5
Φ	0.6
$E_{\parallel,Faser}$	276 GPa
$R_{\parallel}^{t}/R_{\parallel}^{c}$	2560 MPa / 1590 MPa
$R_{\perp}^{t}/R_{\perp}^{c}$	73 MPa / 185 MPa
$S_{\parallel\perp}$	90 MPa
$p_{\perp\parallel}^{c}$	0.25
$p_{\perp\parallel}^{t}$	0.3
$p_{\perp\perp}^{t,c}$	0.3
Steel	
E_{Steel}	210 GPa
ν_{Steel}	0.33
Epoxy	
E_{Epoxy}	3.5 GPa
ν_{Epoxy}	0.3

Appendix B. Material data

Table 2: Initial model parameters for the TL2-stacking.

Parameter name	initial value
t_{FRP}	0.1 mm
$t_{ad,1} = t_{ad,2} = l_{ad,1} = l_{ad,2}$	0.04 mm
$\alpha_1 = \alpha_2 = \alpha_3$	0°
$l_{m1} = l_{m3}$	1.5 mm
l_{m2}	2 mm
$l = l_{m2} + l_{ad2} + l_{FRP2}$	3.04 mm
$t = 3 \cdot t_{FRP}$	0.3 mm
$t_{m2} = t_{FRP} - t_{ad1} - t_{ad2}$	0.02 mm
Element size	0.01 / 0.001 mm

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