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Production-based design of a hybrid load introduction element for thin-walled CFRP Structures

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Abstract
The project “Multi-Layer Inserts” (MLI) proposes a new design for inserts used in thin-walled CFRP structures. The proposed inserts consist of multiple thin metal sheets and are build up simultaneously with the laminate in an intrinsic hybridization process, eliminating time-consuming post-processing steps. Furthermore, at equal weight, such inserts greatly increase the bonding area between metal and CFRP in comparison to conventional inserts. This results in a significant increase of the loads that can be transmitted into the CFRP. The present work discusses how the shape of the metal sheets which the proposed inserts consist of influences the mechanical properties of the surrounding laminate. This influence is investigated by measuring the strain distribution during tensile tests by means of digital image correlation. The strain distributions around the following three different MLI design approaches are compared: An elliptical metal sheet, which is expected to be ideal in terms of mechanical performance of the overall structure; a cross-shape metal sheet representing a production-driven simplification which only requires the ability to perform cuts in individual tows perpendicular to the laying direction and can be performed by state-of-the-art AFP systems; and lastly, a compromise between manufacturability and achieved mechanical performance, a decagonal metal sheet design, which requires angled cuts of the fiber tows. It is shown, that the decagon is able to evenly spread the strain over a larger area and is therefore able to significantly reduce the maximum strain values compared to a cross-shape metal sheet, while still being automatable.

Keywords Fiber-metal laminate · Automated fiber placement · Automation · Insert · CFRP · Embedded load introduction element

1 Introduction
The choice of a suitable joining element for thin-walled carbon-fiber-reinforced plastic (CFRP) structures plays an essential role in lightweight design processes. In most commercially available joining techniques, a metal element coupled with a common joining element (such as a bolt) is placed into the CFRP. Such an attachment element creates a detachable joint, simplifies the joining of several parts and allows for the inspection of the joint. An additional manufacturing step, the additional structural weight and in most cases a thickening of the laminate are typical disadvantages in comparison to adhesive joints [1]. A further drawback is the limited bonding surface between a monolithic insert and the surrounding CFRP. The solution presented in this work—an intrinsically build, layered insert—resolves these disadvantages by creating a local fiber metal hybrid as shown in Fig. 1b. The hybrid is built by locally replacing CFRP layers with metal sheets. In conventional insert solutions as shown in Fig. 1a, the fibers are placed around the insert resulting in fiber undulation that weakens the structure [2, 3]. The amplitude of the undulation can be considered proportional to the thickening of the CFRP. In the proposed approach, fiber undulation is mitigated due to the cutting of the fibers.
and replacement of individual layers. Furthermore, the structural loads are fully transmitted as shear forces between the involved layers. In contrast to prior hybridization approaches improving the bearing strength of CFRP by Fink et al. [4] the proposed layered insert contains a (pure) metal laminate in its center instead of a CFRP-metal-hybrid. This center metal area allows the use of screw connections as there is no loss of clamping force. In a conventional hybrid laminate with alternating CFRP and metal layers, the clamping force reduces over time due to creep phenomena in the CFRP layer under compression forces of the screw connection.

Because of the simultaneous assembly of the insert and the laminate, the whole process can be fully automated and the impact on the productivity of the automated process is minimized. However, an automated process leads to some restrictions regarding the design of the insert. This paper investigates the effect of layered inserts (Multilayer Insert—MLI) on the structural integrity of the laminate by means of tensile tests. The investigated shapes of the metal sheets are the result from production driven adjustments.

2 Integrated production process

Due to the high achievable fiber volume fraction, commonly pre-impregnated fiber tows (prepregs) are used in automated fiber placement (AFP) or automated tape laying (ATL) processes to build thin-walled CFRP structures. An integration into an existing AFP process is only possible if either the insert is built simultaneously to the surrounding CFRP or if the process allows for placing the prepreg tows around the already placed insert.

The research group HP CFK at CFK Nord in Stade is currently developing such a fully automated production process to realize the simultaneous building of the insert. Both, the placement process of the single metal sheets and the corresponding cutting process to form the cutout in the prepreg layer are integrated into an AFP process. Figure 2 gives an overview of the proposed process chain.

The process starts with the AFP head cutting the prepreg tows at laying speed to create a cutout with the desired contour. Subsequently, the contour is measured by means of a laser line scanner to verify that the dimensions of the cutout are within specified tolerances. A dedicated unit, which is integrated into the AFP system, then places one metal sheet into the cutout. When placing the next layer of the laminate, the position of the metal layer is verified using an infrared camera. This process is repeated until the laminate is completed. This approach allows for the integration of the insert placement into the AFP process while maintaining high laying speeds. However, it also restricts the design of the metal sheets as well as their orientation.

To meet production-based restrictions as well as for mechanical reasons, the insert is integrated into a double-layer laminate (see Fig. 3). This means, that the laminate is built up of pairs of layers with the same orientation. Such layup ensures that the bonding surface is independent of the
By placing the metal sheets into the CFRP a hybrid composite is formed, where the connection between a metal sheet and the encasing CFRP can be simplified as a double shear lap connection and in case of the top and bottom layer a single shear lap connection. An analytical description of single and double shear lap tests of the bonding between two elastic parts can be found in [7]. The proposed solution is based on the research performed by Volkersen [8] and describes the stress by a hyperbolical function. Several assumptions are made which limit the applicability to CFRP materials and the presented load case. In case of the double shear lap connection, the stiffness of the upper and lower joining partners are assumed to be the same. In addition to these assumptions the surface contour of the connection is neglected due to the two-dimensional modeling approach. Therefore, the results can only be used as general guidelines in the design process of the metal sheets and as an estimate of a reasonable bonding length. Misseroni et al. [9] present a model that describes the stress concentration at stiff inclusions under Mode I loading which is validated experimentally by means of photoelasticity. The results show that blunt inclusion angles in the range of $\left[\frac{1}{2} \pi, \frac{3}{4} \pi\right]$ lead to a significant reduction of stress concentrations, which is considered in the metals sheet design.

In the present investigation, two locations in each double layer are expected to exhibit strain concentrations, each located where the CFRP adjoins the metal in the respective layer (material transitions A and B in Fig. 4). Because of the small frontal surface area of the layers and the mechanical properties of the adhesive, the load has to be transmitted through the layer above and below the material transition B resulting in the already mentioned strain concentration in these adjacent layers. The strain at transition A in the top and bottom layers is expected to be higher than in the inner layers, since the outer layers are only enclosed from one side. A detailed description of the strain distribution at these butt joints can be found in [10].
In contrast to the material transition A, the strain in the material transition B is transferred through another layer of CFRP instead of a metal sheet. Therefore, the strain peak in transition B is expected to be the sizing quantity. The stress distribution around an elliptic-shape metal sheet is expected to be optimal for load transmission and the prevention of crack initiation because of the steady slope and absence of corners. However, it cannot be realized using the automated layup within an AFP process, as a conventional AFP head, such as the one available at the research group HPCFK, is not able to create a cutout featuring an elliptical contour. The current cutting unit only allows for cutting tows perpendicularly to the laying (and thus fiber) direction, which—along with the simultaneous placement of four ¼" tows—limits the possible contour to an incremental approximation. Therefore, two different stages of approximation of the elliptical shape for a production-based design are considered and benchmarked against a layup with inserts made up of elliptical metal sheets. The three resulting designs are shown in Fig. 5.

The design of the simplest stage of approximation for the implementation in an enhanced AFP system (see Fig. 6a) constitutes a cross-shape metal sheet (see Fig. 5c). An equivalent cutout in the laminate is realized by cutting the four tows to individual lengths (see Fig. 6b).

A decagon-shape metal sheet (see Fig. 5b) constitutes a compromise between the mechanically optimized elliptical design and the production-optimized cross-shape design. This approximation requires an AFP system which allows angular cutting of prepreg tows, such as the system described in [11].

As the metal sheet consists of two areas with different thicknesses, not only the outer contour has to be designed according to restrictions of the chosen production method, but the inner contour has to be shaped accordingly as well. Furthermore, the inner contour defines the area available for mounting a joining element such as a screw or a rivet.

The design of the inner contour also defines the size and distribution of the bonding surface for load transmission between metal and CFRP and therefore has a high impact on the strain distribution. By using an elliptical shape or an elliptic approximation in the form of a decagon, the available surface area can be increased and distributed more evenly. Figure 7 shows location of the bonding surfaces resulting from the different design approaches.

All three designs have a fixed width of 25.4 mm, matching the track gauge of the AFP system. The step width for incremental approximation of the ellipse for both the cross-shape as well as the decagon shape is given by the width of a ¼" prepreg tow. The corners of the respective shapes are
based on the required bonding length and the intersection point of the tow edges with the ellipse. Depending on the area of the metal sheet, the amount of CFRP replaced by the denser metal sheet varies. This in turn influences the overall weight of the structure. The current designs of the single metal sheets result in weights of 258 mg for the decagon, 267 mg for the ellipse and 373 mg for the cross-shape design.

4 Experimental setup

For evaluating joining elements, two important mechanical load cases have to be assessed: The transmission of structural loads through the region disturbed by the insert and the load introduction from the insert into the laminate. In the presented work, the load transmission behavior is investigated and the insert can be considered an inclusion. The tensile tests are performed on a 25 kN universal testing machine (Instron) at room temperature along the 0° fiber axis while measuring the surface strain by means of a digital image correlation system (GOM Aramis 12M). Since the strain can only be measured on the surface (transition A), the strain in the deeper layers (transition B) is extenuated by the overlaying layers. To examine the strain in transition B directly and not through layer 1 as it is the case in this investigation, it would be necessary to conduct the experiment with an alternate layup. However, the results of such tests would not be comparable, as a different layup also changes the boundary conditions of the single shear lap. These boundary conditions have a large influence on the stress distribution in the connection [12].

Figure 8 shows the dimensions of the specimens with the centrally placed metal sheets. A summary of the three investigated specimen configurations is given in Table 1.

Each specimen of the conducted investigation consists of eight layers of Cycom 977-2-35-12KHTS-134-300 prepreg with a thickness of 0.1 mm and a [0_1, 90_2] stacking. The

![Diagram of specimen with centrally placed metal sheets]

Fig. 8 Detailed geometry of the specimen with centrally placed metal sheets

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Table 1 Specimen configurations

<table>
<thead>
<tr>
<th>Specimen type</th>
<th>Dimensions in mm</th>
<th>Insert orientation</th>
<th>Specimen count</th>
</tr>
</thead>
<tbody>
<tr>
<td>cross (C)</td>
<td>110×170</td>
<td>90°</td>
<td>5</td>
</tr>
<tr>
<td>decagon (D)</td>
<td>110×170</td>
<td>90°</td>
<td>5</td>
</tr>
<tr>
<td>ellipse (E)</td>
<td>110×170</td>
<td>90°</td>
<td>5</td>
</tr>
</tbody>
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Therefore, equally good results are expected in cycling testing which are subject of further research.

Figure 10 shows the major strain, measured by digital image correlation, on the specimen surface for the differently shaped inserts at a load of 23 kN. The displayed values of the strain tensors are calculated from the displacements of 5×5 facets (1.2×1.2 mm²). As expected, the highest strain is measured at the transition between the top CFRP layer, the adhesive and the MLI metal core (Fig. 4, transition A).

![Graphs showing load displacement curves](image)

Fig. 9 Load displacement curves of the specimen C1, D1 and E1. The specimens were loaded up to a load of 23 kN with a cross head velocity of 1 mm/min. After the load limit was reached, the specimen was unloaded. This process was repeated seven times while keeping the clamps closed (dotted line: first repetition).

Laminates are produced by hand layup to ensure manufacturability and comparability between all specimens. The used metal sheets are made of stainless steel, 1.4028Mo, with a total thickness of 0.2 mm and an etched bonding area with a thickness of 0.1 mm as described above. Since an etching process is used the sheets are free of any burrs at the circumference. An adhesive film of 3M Scotch Weld AF 163-2 covers the etched bonding surface of the metal sheet. Subsequently, the specimens are cured in an autoclave process at a temperature of 180 °C and a pressure of 10 bar for 2 h.

5 Results and discussion

Figure 9 shows exemplary load displacement curves of the three specimen configurations. The specimens were loaded seven times up to a load of 23 kN. Between load cycle 1 and load cycle 2–7, an increase in stiffness is observed caused by initial settlement of the clamps. For load cycles 2–7, the load increases linearly with head travel whereas the stiffness is nearly constant for all cycles of one specimen configuration. This linear behavior suggests that the specimens were loaded within linear elasticity range without any obvious damages.

Material transitions in load and fiber direction cause a local strain concentration, whereas material transitions perpendicular to the fiber and load direction show no increased strain. The strain in transition B located in layer 2 is still visible but extenuated by layer 1. Since the strain concentrations coincide with the edges of the metal sheets, the shape of the metal sheet can easily be deduced from the strain distribution.

The actual strain values along the displayed lines of interest (LOIs) are shown in Fig. 11. The route of the LOIs is chosen to contain both, the maximum strain of the inner and that of the outer circumference respectively.

The cross specimen shows the highest strain concentration in both, the material transition A in layer 1 with approximately 3.25% and in transition B with about 0.75% of strain. This exceeds the limit of the adhesive which is 3% according to the datasheet [13]. The unequally distributed strains

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1 The strain computation of one facet within the digital image correlation is based on the change of distance to the surrounding facets. To be independent of axis misalignments, e.g. of the camera and specimen axes, the strain tensor is computed. The direction of maximal strain is defined as major strain.
suggest that in the displayed specimen either the specimen itself or the metal sheets were mounted under an angle of about 2°.

The decagon specimen also exhibits a concentrated strain at transition A, but only with a maximum of 1.8%. The strain in transition B is on the same level as in the cross configuration but much more equally distributed. The reduction of strain peaks in transition A from 3.25% (cross shape) down to 1.8% (decagon shape) is caused by the use of blunt angles in the relevant material transition zones with an angle of 148.5° and thus confirms the results described by Missironi et al. [9].

The maximum strain value of 2.5% for the elliptic metal sheet in transition A is above that of the decagon, whereas
the strain in transition B is only 0.6% and is even more equally distributed then in the decagon specimen. The increased strain in transition A results from mismatching dimensions of the inner and outer ellipse. With the chosen parameters, the semi-major axis of the inner ellipse is bigger than the semi-minor axis of the outer ellipse. At the four intersection points, transition B in layer 1 (Fig. 10, black line) and transition A in layer 4 (Fig. 10, grey dashed line), overlap resulting in the measured strain peaks. This shows that the strain peaks in an overlap of transition A and B influence each other even if two CFRP layers are placed between the overlapping metal sheets.

Strain peaks constitute a potential cause for failure initiation in the laminate. Therefore, the ratio of the maximum to the mean strain of each specimen is used as a figure to correlate the influence of metal sheet design with the observed strain peaks. As described above, transition B is considered to be the sizing factor, therefore the strain peaks in transition A (adhesive) are excluded. Thus, only the strain values in transition B are taken into account.

Table 2 shows the mean strain ratio with the respective standard deviation depending on metal sheet design. This factor allows the estimation of the maximum strain peaks caused by the insert from the strain distribution of an undisturbed laminate without inserts. This result shows that the elliptical shaped as well as the decagon shaped design reduce the strain peaks compared to the production driven cross shaped design.

### 6 Conclusion and outlook

It has been shown, that the contour of the metal sheets has a significant impact on the strain distribution in the transition zone between metal and CFRP of a hybrid laminate. Apart from the overlapping points, the elliptical shape shows a reduction of the strain in the transition zones. However, the production of such a complex-shaped insert cannot be integrated in to a state-of-the-art automated process such as AFP. On the other hand, a production driven cross-shape insert leads to high strain concentrations, which are likely to cause damage initiation under cyclic loading. By approximating the elliptical shape with a decagon, the maximum values of the strain peaks can be clearly reduced, while reducing the additional metal weight compared to the cross-shape configuration. The manufacturing of inserts of such design can be integrated into an AFP system, which features angular cutting of the prepreg tows. Therefore, the design and integration of a cutting unit that allows for angular cutting of the prepreg tows is subject of ongoing research.

An additional investigation on the influence of the adhesive thickness with an improved elliptical shape will be performed in which strain concentrations resulting from the overlap will be prevented to further improve the strain distribution and decrease the additional weight.

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### References