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Experimental investigation of load carrying mechanisms and failure phenomena in the transition zone of locally metal reinforced joining areas

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ABSTRACT

In modern lightweight structures the use of fasteners is preferred to other joining techniques due to the simple disassembly. Because of the low bearing strength of carbon fibre reinforced plastics often a local increase of the thickness is necessary, what is accompanied by eccentricities. A different approach is the local metal hybridisation, where CFRP layers are substituted locally by metal sheets of the same thickness. The local replacement leads to a transition zone between the hybrid region and the pure CFRP region. The present work deals with an experimental investigation of different transition zone patterns and especially the damage behaviour of CFRP-steel hybrid specimens in static tension and bending tests. Digital image correlation is used to measure the strain state during the testing. It is revealed that a staggered pattern with centre endings leads to a high load carrying capacity and a robust transition zone.

1. Introduction

For aerospace applications it is common practice to use fastener based joining techniques like bolting or riveting as parts can easily be detached. The increased use of modern lightweight materials as carbon fibre reinforced plastics (CFRP) is not in compliance with these techniques. Composites in general show very good strength and stiffness to weight ratios in fibre dominated direction, but a low bearing strength and a high notch sensitivity [17,13,4]. Layers which are aligned in loading direction (x-direction, 0°) contribute with a high amount to the global stiffness and strength. However, a high fraction of uniaxially orientated fibers decreases the bearing strength. Therefore, the joining strength of a bolted connection in a composite structure shows some deficiencies in comparison to bolted joints in metallic structures [1].

Some attempts can be found to increase the bearing strength, e.g. by the local use of fibre material aligned around the hole [8,25] or inserting patches, which can be made of different materials [5]. Other possibilities are the use of z-pinning around the hole [26] or the use of doublers. A widely used approach to compensate the low bearing strength is the local addition of layers with 90° fibre direction with a gently inclined ramp-up. This technique is especially used, if very high loads have to be transferred. Hereby, eccentricities often cannot be avoided, as in general the outer surface must keep its contour. The ramp-up concept is always associated with unwanted secondary bending moments, which have to be considered in the design process and lead to additional weight [11,12,16].

One different approach to deal with the challenge of low bearing strength in composites is the local metal hybridisation. It is based on the use of metal foils to substitute CFRP layers locally in the load introduction region. The metals stiffness and bearing strength yields to a high bearing strength of the fibre metal laminate (FML) [32,24]. In general metal alloys allow smaller ratios of width to diameter or edge distance to diameter than composites. Hence, adding metal plies to a CFRP laminate decreases the possible ratios and less fasteners are required, while still bearing is the occurring failure type.

The metal foils and the CFRP layers have the same thickness in the technology regarded here, hence, the volume is kept equal and the bearing strength is increased. Therefore, the unwanted eccentricities and following side effects can be avoided. Fig. 1 shows the scheme of the local metal hybridisation.

In the vicinity of the load introduction, there is a full hybrid laminate with continuous metal layers. These metal layers end in a certain distance of the bolt, thereby the good specific properties of the CFRP material can be exploited in the remaining structure.

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Nomenclature

Abbreviations

AP	abutting point
CFRP	carbon fibre reinforced plastics
COM	compression
CoV	coefficient of variation
DIC	digital image correlation
FML	fibre metal laminate
MEAN	mean value
MVF	metal volume fraction
QI	quasi-isotropic
TEN	tension
TZ	transition zone
UD	unidirectional

Symbols

A	cross section area (mm^2)
E	elasticity, Young's modulus (GPa)
F	applied force (N)
$G_{\perp\parallel}$	in plane shear modulus (GPa)
G_{IIc}	critical energy release rate in mode II (kJ/m^2)
h	height (mm)
M	bending moment (N mm)
n	number of interfaces between layers (–)
R	strength (N/mm^2)
W	elastic section modulus (mm^3)
α	thermal expansion coefficient (1/°K)
ΔT	temperature difference between manufacturing and testing (°K)
ϵ	strain [%]
$\lambda_{1,2,3}$	terms in the equation for delamination threshold (–)
σ_t	residual thermal stress (N/mm^2)
$\sigma_{x,del}^{t/c}$	delamination threshold under tension or compression load (N/mm^2)

Indices

a, b	properties of sublaminates
i	properties of single plies
LT, RT	in or transverse to rolling direction of the metal foil
max	maximum value
$p0.2$	limit of 0.2% plastic strain
t, c	under tension or compression loading
v	elastic limit
x	Cartesian coordinates, laminate length direction
$\parallel, \perp$	parallel or perpendicular to fibre direction

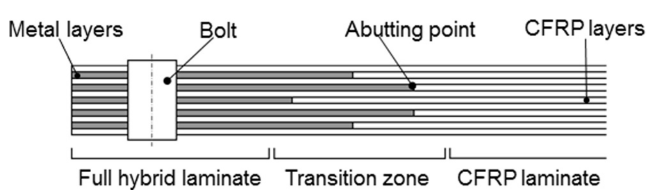

Fig. 1. Scheme of local metal hybridisation.

As here implied, the metal layer endings are arranged in a staggered pattern to realize a gradual decrease of the stiffness and the metal volume fraction (MVF). This can be realized in different patterns in the transition zone (TZ).

The technology of the local metal hybridisation was first introduced by Kolesnikov in a patent in 2000 [20]. Comprehensive investigations were conducted, e.g. by Kolesnikov and Fink [21,15] and applied to a spacecraft payload adapter [14]. Investigations focussing on the load introduction region were conducted, where especially the load redistribution after plasticity, delamination and matrix failure were described in numerical models [6,22].

Fewer attention has been paid to the TZ, although it exhibits a high potential for weight reduction. Because of the higher density of the metal, intentionally the metal layers length is kept as short as possible increasing the load carrying capacity per weight of the complete structure. It should be guaranteed that the TZ does not become the weak spot of the joint to enable the full exploitation of the metal reinforcement in the load introduction region. An analytical method developed by Fink [15] is available to calculate the normal stress causing a delamination between metal and CFRP. By investigating different laminate configurations, Kolesnikov showed that the strength of the monolithic reference specimens is achievable by titanium TZ in the majority of regarded configurations [21]. The reinforcing effect of different titanium foil patterns placed additionally into CFRP laminates was investigated by Nekoshima [27].

At the metal ply endings the difference in elastic compliance of the adjacent materials lead to a distortion of the stress state, which size can be approximated [15]. To obtain information about matrix failure and load transmission Camanho used Cohesive Zone Elements to model separations at the metal ply endings [6]. Further, numerical investigations by Petersen already showed a higher failure index in the vicinity of closely positioned metal ply endings [29]. The resulting initial resin failures propagate as delaminations and lead to a decreased load carrying capacity. Therefore, it is important to investigate the strain distribution in the TZ and to identify the metal layer attributes leading to the highest distortion.

The aim of this publication is the identification of the influence of the TZ pattern on the load carrying capacity. Therefore, static tests are conducted and the maximum occurring stresses are identified for different TZ patterns. To prove the practicality of an analytical method the predicted failure stresses are compared to the test results. The related failure types are investigated subsequent the tests and before total failure. Further, some tests are accompanied by digital image correlation (DIC) to record the strain state in the TZ allowing the identification of highly loaded ply ending and the load redistribution caused by occurring damage types. At all, the test data and the information about failure types and strain distribution are taken into account to identify, which failure mechanisms in the TZ lead to the achieved failure stresses.

2. Methodology

2.1. Specimen design

The required metal volume content takes the main influence on the hybrid design. It is derived from the necessary bearing strength. The estimation of the bearing strength of a CFRP laminate is quite complex and takes into account many circumstances. The impact of the laminate thickness and layup, as well as the clamping pressure and area have to be investigated [13,28,7]. Especially the nature of the damage behaviour leading to hole elongation is