# EFFICIENT JOINT DESIGN USING METAL HYBRIDIZATION IN FIBER REINFORCED PLASTICS

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## ABSTRACT:

Present work deals with the design of high performance bolts using the local substitution of CFRP layers with thin metal sheets. A common method to increase the overall bearing strength is a ramp-up of the CFRP layup to a thickness, which is sufficient to sustain the loads. This approach is accompanied by negative effects, like an occurring eccentricity and additional weight. The local metal hybridization substitutes the non-load carrying layers in the joining region with metal sheets of the same thickness. Using the metal's plasticity, the grade of the connection can be increased significantly, while the weight increase is low. Beside the efficient design of the joint region, a closer look is taken on the transition zone, where the metal layers end and the stresses are transferred into the pure CFRP. This drop-off zone preferably has a staggered pattern to transfer the stresses more gradually. An efficient design also includes an advantageous sequence of layer terminations and drop-off lengths. Comparison of experimental results with nonlinear finite element simulations is used to clarify the origin and propagation of occurring damages. Input parameters are determined on coupon level and followed by larger size structural level tests and simulation.

**KEYWORDS:** Fiber-Metal-Laminates, Joining Techniques, Delamination

## 1 INTRODUCTION

Composites show very good strength and stiffness to weight ratios in fibre dominated direction. Apart from the load direction fewer fibres are necessary. This effective possibility to use the material leads to the high overall material property to weight ratios. If the stress situation is very complex and fibres in many loading directions are necessary, the weight saving in comparison to a metal design is vanishing. For an efficient lightweight design it is not satisfactory to just replace metals with composites without considering the inherent merits and demerits of the materials.

Negative aspects of composites in comparison to metals are their lower damage tolerance and bearing behaviour. Especially laminates with high unidirectional strength and stiffness are very weak related to above mentioned topics.

One approach to increase the bearing strength is the addition of layers with 90° fibre direction, what lowers contradictory the strength to weight ratio in the dominated loading direction. To minimize the material effort, the 90°-layers are added locally in the load introduction region using a gently inclined ramp-up to minimize the stress peaks.

As eccentricities cannot be avoided completely, the ramp-up concept is always associated with unwanted bending moments, which have to be considered in the design process and lead to additional weight.

Obviously, it would result in a great benefit to combine the positive aspects of both material groups. Fibre-Metal-Laminates (FML) represent an approach to build hybrid materials with added strength and compensated weaknesses. One established material combination is GLARE (glass fibre epoxy composite & aluminium), which application region lies in modern airplanes in highly fatigue stressed parts, where pure metal cannot achieve the requirements.

Using the metal's plasticity locally in joining areas is one approach to overcome one weakness of composite materials, while preserving the high strength and stiffness to weight ratios in load direction as in the remaining part.

## 2 CONCEPT OF LOCAL METAL HYBRIDISATION

From the idea, which was firstly introduced by Kolesnikov in 2000 [1] the concept is increasing the grade of the joining technique without modify-

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ing the volume. This means the reinforcement is only intrinsic and hence no eccentricities are occurring. Of course, the structural mass is increasing because of the higher density of the metal, what leads to the conclusion to keep the metal volume fraction as small as possible. Therefore, the metal reinforcement is only used in the region where it is required to sustain the loads. This leads to the concept of only locally substituting specific CFRP layers with thin metal sheets of the same thickness. In the bolt region, induced loads are carried by the metal sheets and have to be transferred into the monolithic CFRP part, what is mainly accomplished by shear in the interface.
Between the ending metal sheet and the adjacent CFRP ply the stiffness gradient causes stress concentrations. This issue leads to the essential staggered drop-off of the metal sheets in the transition zone between FML and monolithic CFRP. Fig. 1 shows the concept of local metal hybridisation with a staggered transition zone.

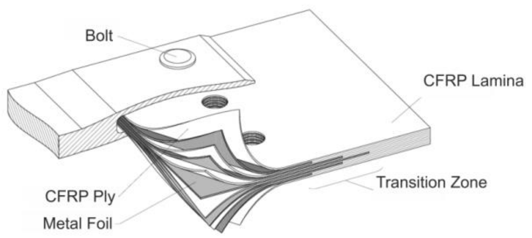


***Fig. 1*** *Concept of local metal hybridisation in joining*

# 3 DESIGN ASPECTS

Summing up, the FML has to sustain the loads, what basically means the stresses are not allowed to exceed the material strength. Composites failure has to be distinguished in different failure types related to fibre and matrix failure and the loading direction.
In contrary to the metals, ductile failure type, where initial plasticity can be calculated with the von-Mises yield criterion, the composites failure type is brittle. Under the appearance of biaxial stresses the failure can be hindered or supported. This is related to internal friction aspects. Especially matrix failure is affected by these micromechanical processes, what makes it necessary to consider complex failure criteria like Pucks Actions Plane criterion or Cuntzes Failure Mode Concept, which are both taking these internal processes into account.
Additionally to the intralaminar damage types, the separation of different layers as interlaminar damage has to be considered. Therefore, a fracture mechanical approach is used, what is discussed in detail in section 4.1. As the metals plasticity and its bearing strength is mainly responsible for the fracture volume content in the bearing region, this aspect is separately discussed in the next section 3.1.
The interlaminar strength is strongly dependent on the metal surface treatment as part of the bonding process. Furthermore, the chosen manufacturing process, especially the process temperature, is responsible for internal stresses, which are induced through the different thermal expansion coefficients of metal and CFRP.
A special topic, which has to be considered in the design process, is related to corrosion in regions with contact to environmental conditions.
This work deals only with the mechanical issues and design aspects of the local metal hybridisation. If possible, further aspects are excluded from present work.

## 3.1 BOLT REGION

At all, the FML is supposed to show first failure in the bolt region by bearing and not by net tension or shear out failure, what means the bolt and edge distances have to be chosen large enough. Hence, the load carrying capacity of a bolted joint must be limited by the maximum allowable plastic strain or hole expansion. Fig. 2 shows a hybrid bolt region with bearing failure. The efficient design of the bolt region was already scope of work in [3], [4] and [5], where some design basics were achieved and could be applied to a specific application.

***Fig. 2*** *Bearing failure [7]*

The nature of the bolt region where the bearing loads are introduced into the FML is mainly influenced by the necessary metal volume fraction. As can be taken from the plot in Fig. 3, a higher metal content leads to higher bearing strength for different types of basic layups.

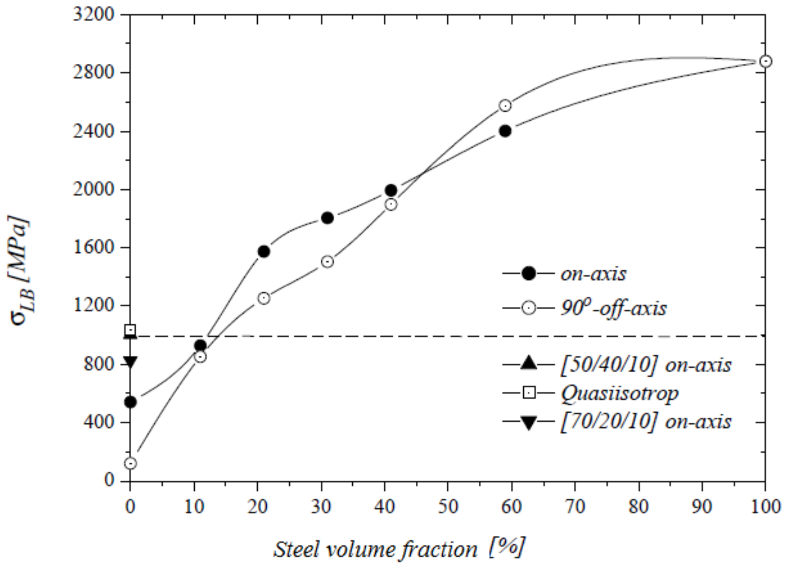


***Fig. 3*** *Bearing stress for different steel volume fractions [7]*

If the bearing strength is related to the density of the laminate, as depicted in Fig. 4, the graphs are showing maxima at 20% steel volume fraction for a 0° dominated layup and 60% for a 90° dominated layup. The specific bearing strength of the reinforced laminates is not reaching the maximum values of a quasi-isotropic or even a [50/40/10]-laminate, but it has to be kept in mind that at the same time the part's overall strength and stiffness in load direction is much higher.

have to be considered. Following above mentioned rules, the substitution of a 45°-ply, concludes also the substitution of a -45°-ply and because of the symmetry a second pair of ±45°-plies.

### 3.2 TRANSITION REGION

The loads from the full FML have to be transferred into the monolithic CFRP laminate by interlaminar shear.

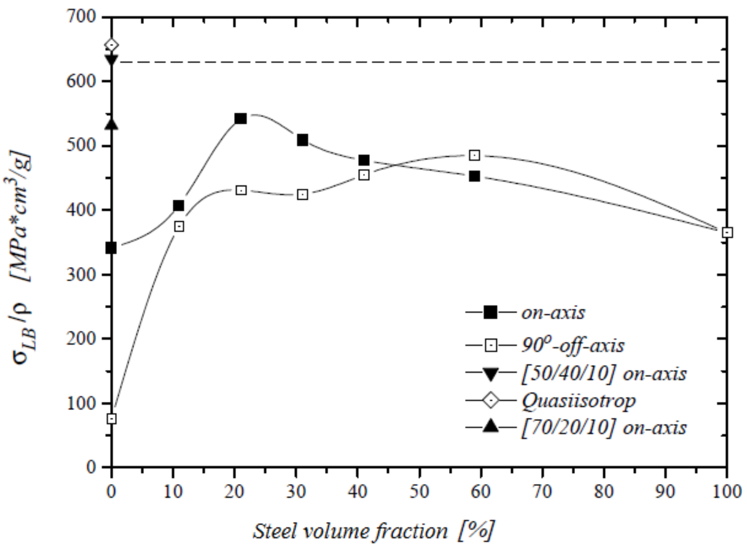


***Fig. 4*** *Bearing stress related to weight for different steel volume fractions [7]*

As known from the design process of monolithic CFRP, some requirements have to be fulfilled, when plies are substituted. Layers with a smaller contribution to the overall strength and stiffness, as 90°- or ±45°-plies are substituted first. Additionally, restrictions to a balanced and symmetrical layup

As described above, the drop-off should be arranged in a staggered manner and should be symmetrical to the laminate mid plane. Required parameters which have to be determined, are the required length of the metal sheets to transfer the loads and the distances between the single ply endings to overcome the influence of local stress concentration effects. From these stress peaks matrix failure can be induced and continue as delamination or debonding between metal and CFRP, what is shown in Fig. 5. With debonding along a metal layer, the FMLs overall stiffness decreases rapidly but still a reserve to sustain higher loads is possible accompanied by stress redistribution. Dependent on the corresponding load concept, the initial delamination stress limits the load carrying capacity or a progressive damage analysis has to be performed.

***Fig. 5*** *Transition region with occurring debonding and delamination failure type [7]*

Analytically the critical initial delamination stress for tension $\sigma_{del,t}$ and compression $\sigma_{del,c}$ between two regions, *a* and *b*, can be calculated as specified in [7]:

$$\sigma_{\mathrm{del,t,c}} = -\frac{\lambda_2}{2\lambda_1} \pm \sqrt{\left(\frac{\lambda_2}{2\lambda_1}\right)^2 + \frac{G_{\mathrm{IIc}} - \lambda_3}{\lambda_1}} \quad (1)$$

With

$$\lambda_1 = h_b \left(\frac{h_b}{h_a \hat{E}_a} - \frac{1}{\hat{E}_b}\right) - \frac{1}{2}\sum_{i=1}^{n_a}\left(\frac{h_b}{h_a \hat{E}_a}\right)^2 E_i h_i + \frac{1}{2}\sum_{i=1}^{n_b}\left(\frac{h_i E_i}{\hat{E}_b{}^2}\right)^2 \quad (2)$$

$$\lambda_2 = h_b * \Delta T(\hat{\alpha}_a - \hat{\alpha}_b) \quad (3)$$

$$\lambda_3 = -\frac{1}{2}\sum_{i=1}^{n_a}\frac{h_i}{E_i}\sigma_{t,i,a}^2 + \sum_{i=1}^{n_b}\frac{h_i}{E_i}\sigma_{t,i,b}^2 \quad (4)$$

With:
the laminate thickness $\hat{h}_a$ and $\hat{h}_b$, the laminate stiffness $\hat{E}_a$ and $\hat{E}_b$ and the thermal expansion coefficients $\hat{\alpha}_a$ and $\hat{\alpha}_b$ in region a and b, the residual thermal stress is $\sigma_t$. Required material resistance against debonding is the critical energy release rate $G_{IIc}$, which has to be determined in static tests.

The reason for the two different solutions of equation (1) is the residual thermal stress which can increase or decrease the resulting delamination stress in tension or compression.
For a more detailed solution, a numerical simulation is considered to enable a progressive damage study, but for a first design approach considering only first failure equation (1) is sufficient.

# 4 EXPERIMENTS

A test campaign is set up, which is based on coupon level tests to determine necessary input parameters. The composite layer's stiffness and strength are required. Because of the transversely-isotropic material behaviour the parameters in direction parallel und perpendicular to the fibre under tension, compression and shear have to be determined in static tests. Because of the metals isotropy a single tension test can be used to obtain the required stiffness, the yield point and following plasticity behaviour.
Additionally the interface fracture toughness between CFRP layers or CFRP and metal has to be investigated. On a higher level, tests with different transition zones under tension and bending will be conducted to exploit information about the damage propagation. These tests will be conducted in the near future.

## 4.1 FRACTURE TOUGHNESS TESTS

Under the aspect of fracture mechanics the issue of interface bonding is investigated. Fig. 6 depicts the possible fracture modes, where the shear mode II is the most important for the current field of investigation.

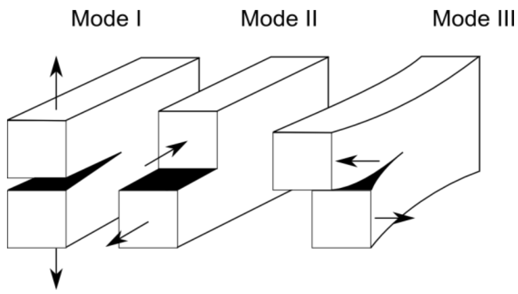


***Fig. 6*** *Fracture Modes*

According to tests for monolithic composites, fracture mechanical tests with metal to CFRP interfaces are conducted to determine the bonding strength as the critical energy release rate $G_c$. The test concept is based upon the principle of conservation of energy as depicted in Fig. 7. The potential energy under the curve *U= Pδ/2* is calculated in dependency of the crack length *a*. An increasing crack length *a* leads to a stiffness reduction and as the crack grows the potential energy for a specific load level *P* is decreasing. The loss of energy or the energy difference $\Delta E$ between *a* and *a+da* is set equal to the energy required to open the crack and hence as material resistance against fracture. This means crack opening is occurring when the potential energy reaches the material inherent value of $\Delta E = G_c$.

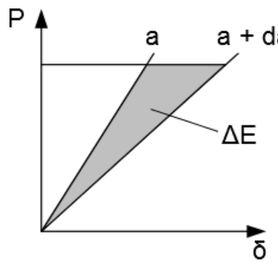


***Fig. 7*** *Scheme of stored potential energy*

The common test setup for composites for above described principle is based on beam type specimen with an artificial starter crack as shown in Fig. 8.

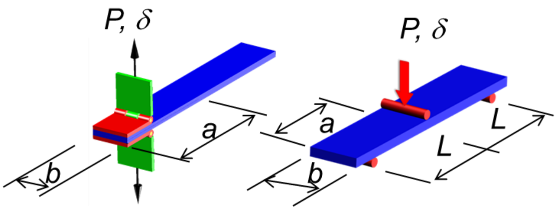


***Fig. 8*** *Beam type specimens with required parameters*

Equation (5) is used to calculate the peel mode I critical energy release rate $G_{Ic}$, where equation (6) can be used to obtain $G_{IIc}$ for the sliding shear mode II. Additionally a compliance calibration method is used to compensate nonlinearities, therefore the crack growth has to be traced for several load level.

$$G_{Ic} = \frac{3 * P\delta}{2ba} \quad (5)$$

$$G_{IIc} = \frac{9 * Pa^2\delta}{2b * (2L^3 + 3a^3)} \quad (6)$$

Above specimens are commonly used to investigate the fracture toughness between different layers of monolithic composites. It can easily be adapted to FMLs using an interface with metal and CFRP. Small occurring asymmetries at the interface can be neglected.

### 4.2 TRANSITION ZONE TESTS

As essential as the bearing strength is the debonding resistance of the transition region. Different layers exhibit different stiffness, what leads to a discontinuous stress distribution over the laminate thickness. For the ply drop-offs this results in different positions of the initial debonding failure. For example the abutting points of 90° layer are very sensitive to matrix cracks, but the load carrying capacity of the whole transition region lies much higher. Therefore, a progressive damage characterization has to be realized.

An experimental design approach with thin additional titanium films to reinforce the bolt region was investigated by Nekoshima et. al in 2012 [2]. Different transition regions were investigated and compared under the aspect of tension and bending strength. According to the approach by Nekoshima, tests to determine the progressive damage behavior of different composition of the transition region will be conducted. Layups with 16 plies are required to exhibit sufficient possibilities for the ply substitution. Tested as reference are specimens with monolithic CFRP layup and complete substituted layers (full FML). Different transition zone patterns will be tested as depicted in Fig. 9. To investigate homogenous and asymmetrical load situations tension and bending tests will be conducted.

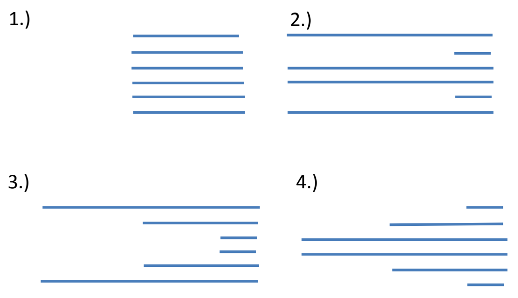


***Fig. 9*** *Considered metal drop-offs in the transition zone*

The static tests will be accompanied with digital image correlation recording the strains along the longitudinal edge especially around the abutting points. The recorded maximum strain at failure level is on the one hand an adequate indicator for the predictive capability of occurring delamination, on the other hand the measured strains can be taken into comparison with numerical results to validate the simulation.

## 5 SIMULATION

The obtained values from the experimental testing are used as input for the simulation including the damage processes.

Critical energy release rates are basic input for numerical fracture calculation methods like the Virtual Crack Closure Technique (VCCT) or the Cohesive Zone Method (CZM), which are used to simulate separation processes. The VCCT is based on the assumption, the energy required to close a crack must equal the energy required to open it.

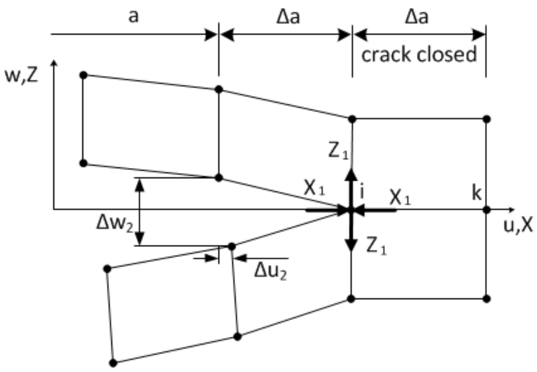


***Fig. 10*** *Scheme of VCCT*

The deformation energy at the crack front is calculated with the nodal forces at the crack front and the displacement before the crack front:

$$G_I = \frac{1}{2\Delta a}[X_1 \Delta u_2], \quad (7)$$

respectively

$$G_{II} = \frac{1}{2\Delta a}[Z_1 \Delta w_2]. \quad (8)$$

Where separation without mode interaction takes place at:

$$G_i / G_{ic} = 1. \quad (9)$$

As the scheme behind the VCCT, see Fig. 10 and equation (7-9), is relatively easy to apply, it is chosen as method for the coupon test benchmark. From the comparison of simulation and test results using only the $G_c$-values as input, the tests their self and the gained parameters can be validated and used for higher level simulation.
A nonlinear simulation including progressive failure propagation in the bolt region was performed by Kolks et. al in 2014 [6], showing a good reproducibility of the bearing behaviour.
The numerical simulation of the transition region must focus on a fracture mechanical model to calculate the separation between the layers.
Fink [7] already simulated parts of the transition zone of titanium-CFRP-laminates using the CZM. Fig. 11 shows the stress concentration around the edges of an abutting point between metal and a 45° layer. As can be seen, the stress peaks influence the adjacent 0° plies and also the interface between 0° and 90° plies. A separation starting from the abutting point can continue as a delamination and even propagate over the thickness into arbitrary interfaces. The nonlinear simulation shows the damage propagation path, which leads to the information where to change substituted plies or drop-off lengths to reduce or stop the material damage process.

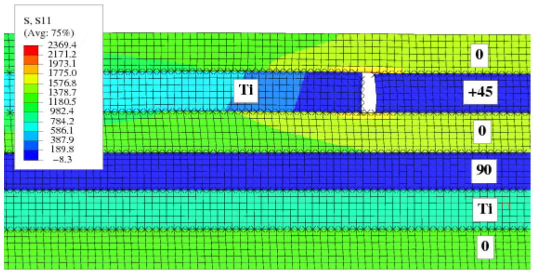


***Fig. 11*** *FE model of transition zone [7]*

## 6 RESULTS AND DISCUSSION

As the experimental results are not yet available generic input parameter for the finite element simulation are used allowing only a direct comparison of the FE results. Considered are 16 ply layups with a pure 0° or a quasi-isotropic stacking including the transition zones depicted in Fig. 9. In the following simulations only the pattern of the transition zone is investigated. Required metal content to prevent bearing failure is neglected.
For the 0° dominated layup (see Fig. 1) stress peaks occur at the abutting points leading to local failure, which is the origin for overall fibre failure and hence, the limit state of the load carrying capacity. Several ply drop-offs at the same position leads to superposition of the stresses and hence, higher failure indices, especially for pattern 1 and 2.
For the quasi-isotropic layup failure in the 90° and ±45° CFRP plies takes place at an applied load effecting an overall elongation of $\varepsilon$ = 0.008 for all patterns. Stiffness degradation and consecutively debonding occurs and limits the load carrying capacity. As the value for the debonding resistance is not yet known the results have to be proved.
One have to keep in mind, the FMLs behaviour is dependent on the specific circumstances as layup, load case and the chosen plies for hybridisation. For example the 0° dominated layup, exhibits a higher strength in tension than the corresponding hybrid-steel-laminate A quasi isotropic layup instead becomes strengthened in tension through the hybridisation, because in loading direction the steel plies show a larger resistance than the 90° or ±45° plies. Instead the stiffness jumping between the

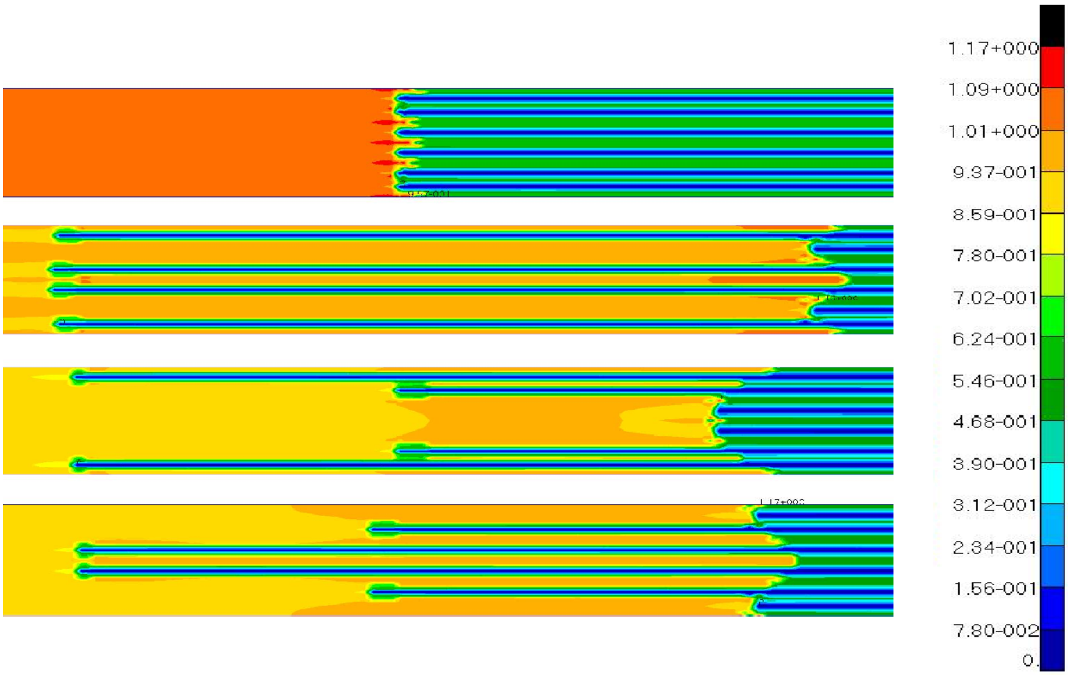


***Fig. 1*** *Failure index for transition zone 1-4, at $\varepsilon$ = 0.018, 0° dominated layup*

CFRP plies and the metal sheets lead to higher stress peaks and initial debonding, what limits the load carrying capacity drastically.
Hence, especially for a quasi-isotropic layup the transition zone pattern should be chosen carefully with a slightly increase of laminate stiffness between monolithic CFRP region and full FML region to minimize the stress peaks.

## 7 CONCLUSIONS

This work presents an approach to design fibre metal laminates for the application in joining techniques, including the transition region. As basic methods and investigations can be found in the literature the herein presented approach is according to validated information and additionally considering aspects about the transition zone. Especially the ply drop-off has not been in the focus of research and is supposed to exhibit a great weight saving potential.
More detailed statements are possible after testing and comparison with the simulation has been conducted.

## 8 ACKNOWLEDGEMENT

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