FEM design of composite – metal joint for bearing failure analysis

An airframe structure is a thin wall structure in the form of a skeleton consisting of longitudinal stiffeners known as stringers and transverse stiffeners generally flat frames or ribs. The skeleton is covered with thin metal or laminate sheets called panels (Fig. 1).

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The newest Boeing and Airbus aircrafts are built, in approximately fifty percent, of composite materials (e.g. 787 – Fig. 2). The fuselage and wing skins, together with the stiffeners are almost in the whole made of composites (Fig. 3).

In the case of Boeing 787, the stringers and the skin are co-cured [6]. However, in the case of Airbus A350 XWB, the stringers are bonded to the skin whereas frames are connected with the skin using special rivets. The usage of special rivets in the composite panel is presented in Fig. 4.

Most of the hitherto built aircraft structures are mainly made of aluminium alloys. Owing to a tendency to use composite materials (Fig. 2), the modernizations of existing structures are highly probable, i.e., gradual substitution of metallic components with composite ones.

The process of structure development with the application of composite materials can be implemented in many ways, e.g.:

- Metallic parts of a structure are partly replaced with composite ones. It can be performed at design or modification stage. For example, replacing metallic panels with composite ones according to stiffness criteria (with appropriate strength) or according to strength criteria (with appropriate stiffness). In such case, the airframe skeleton stiffening the structure

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Fig. 1. Exemplary aircraft structures [1, 2]

Fig. 2. Usage of composite materials over time [4]

Fig. 3. Materials used in temporary aircraft structures [5]

Fig. 4. Mechanical joints in composite structures [6]
usually remains metallic. Therefore, there is a necessity of metallic and composite material connecting (panels with panels and panels with skeleton). It is worth mentioning that in such hybrid structures, aluminium elements are often replaced with titanic ones.

- A new, mainly composite, structure is designed. Some metallic parts are used for various types of fittings and strengthening elements. Component dimensions and chosen metal alloy depend on the selected composite, applied stress, etc. The most highly loaded frames in Airbus A350 WXB are made of titanium alloy (e.g. door frames) [4].

- Some parts of new or modified structures are made of special types of laminates – FML (fibre metal laminates). These types of materials coalesce advantageous properties of fibre reinforced plastics and metals (to improve fatigue strength and fracture resistance).

Strength of composite laminates is dependent on the joint geometry, however, it is strongly influenced by the laminate lay-up. There are five global failure modes for mechanically fastened composite laminates: net-tension, bearing, shear-out, cleavage and pull-through (Fig. 5). The bearing failure is a safe progressive mechanism not leading to catastrophic failure and therefore it is acceptable [7].

There are some hints for correct design of a mechanical joint of composite panels [7]:

- appropriate geometry (sheet width to hole diameter ratio \( W/D \) and edge distance to hole diameter ratio \( E/D \) should reach a sufficiently high value specific for the given material),

- proper laminate configuration (composite should be quasi-isotropic, i.e., that they should have at least \( 1/8 \) fibres but no more than \( 3/8 \) fibres in one of basic directions: 0, \( +/–45 \), 90).

If the above conditions fulfilled, the occurrence of a bearing failure mode is highly probable [7]. Analysis of bearing strength in composite materials is more complex than in metal alloys due to the following reasons. Material in the vicinity of the hole is compressed. Fibres compressive strength is lower than the tensile one, additionally, the resin matrix presents much lower strength than the fibres [6]. Initially, the compressive load is transferred mostly by the matrix. After a specific matrix deformation, the load is also transferred by the fibres due to shear stress between the matrix and fibres. The fact that the matrix deforms more than the fibres causes adhesion failure. An unsupported fibre of a minor diameter has a tendency to local buckling and cracking. Then, the whole load is transferred by the compressed matrix which fails suddenly. The above problems were considered by many authors [8 – 13]. Some attempts to improve bearing performance in composite parts are analysed in [14].

One of the most promising solution is presented in paper [15]. Sheets made of titanium alloy are bonded between composite layers in some distance from the edge of the composite panel in the way that causes gradual load transfer into the composite structure (Fig. 6).

Ultimate bearing stress increases about 3 times with the increase of the titanium content to 50%. With the use of this solution it is possible to reduce the overlap joint dimensions, what causes mass reduction. The major disadvantage of this method is its high cost, making this solution acceptable only in very demanding constructions [15].

The goal of the work is to design a mechanical metal-composite joint and failure analysis of the composite part. The results of presented analysis will be
used in development of an improved alternative mechanical metal-composite connection.

### Mechanical joint design

Modern aircraft composite skins are mainly made of carbon fibre reinforced plastics (CFRP). The analysis of metal and composite large aircraft panels is presented, e.g., in [4]. The analysis is performed for the specimen in the form of a double-shear bolted joint with four steel fasteners (Fig. 7). Overall dimensions and composite laminate lay-up are chosen according to [4] and aircraft requirements [16]. The outer elements are made of 2024T3 aluminium alloy and the inner element is made of quasi-isotropic CFRP laminate consisting of HTA/6376 UD prepreg layers. The stacking sequence is \([0/45/90/-45/0/45/90/-45]\). The joint length \(L\) is 300 mm. The bolt diameter \(d\) and hole diameter \(D\) are assumed to be 6 mm. A selected pitch length is \(5d\), which results in joint width \(w\) of 60 mm.

Fig. 7. Double lap joint

The assumed composite lay-up provides its thickness of about 3 mm \((t_c = 3\) mm). The remaining dimensions are calculated according to typical mechanical joint conditions which require the absence of plastic strains within the limit load range (limit load is the maximum load expected in service):

- Aluminium/composite sheet and bolt (bolt to composite) bearing condition:

\[
P \frac{1}{4 \cdot n \cdot D \cdot t_c} \leq S_{br}^i
\]  

- Aluminium/composite sheet net-tension condition:

\[
P \frac{1}{n \cdot (w - 2 \cdot D) \cdot t_c} \leq S_i^t
\]

- Bolt shear condition:

\[
P \frac{1}{8 \cdot \pi \cdot d^2} \leq S_{st}^i
\]

where:
- \(P\) – applied force, N,
- \(D\) – hole diameter, mm,
- \(t_c\) – element thickness, mm, \((i = AL – aluminium alloy sheet, ST – steel (bolt), C – composite laminate)),
- \(n = \begin{cases} 1 & \text{for single composite element} \\ 2 & \text{for two composite elements} \end{cases}\)
- \(w\) – joint width, mm,
- \(d\) – fastener diameter, mm,
- \(S_{br}^i\) – bearing yield strength, MPa, \((i = AL – aluminium alloy, ST – steel, C – composite),
- \(S_i^t\) – tensile yield strength, MPa, \((i = AL – aluminium alloy, ST – steel, C – composite),
- \(S_{st}^i\) – bolt shear yield strength, MPa.

Metallic alloys are assumed to be isotropic. For such materials, bearing strength \(S_{br}\) (which in motionless joints corresponds to compression strength \(S_t\)) and shear strength \(S_{st}\) can be expressed in relation to tensile yield strength \(S_{t}\) (or ultimate tensile strength) obtained from an unidirectional tensile test \((S_{t}^{AL} = 360\) MPa, \(S_{t}^{ST} = 700\) MPa, AL – aluminium, ST – steel [17]).

Compression (bearing) strength for aluminium alloys can vary from 1.2 to 1.7 of tensile strength: for 2024T3 \(S_{t}^{AL} = 1.46S_{t}^{AL} = 524\) MPa and for steel \(S_{t}^{ST} = 1.4S_{t}^{ST} = 980\) MPa is assumed according to [17]. Shear strength is assumed within the range from 0.55 to 1.0 of tensile strength [18]. For steel bolt \(S_{st}^{ST} = 0.56S_{t}^{ST} = 405\) MPa is assumed [17]. The local stress state is a function of applied load \((\sigma = \alpha(P))\). For the applied load (sum of all forces acting on the structure) lower than limit load, the local stress cannot exceed yield strength and ultimate strength divided by proper safety factor \(k\) \((\sigma < S_{yield}, \sigma < S_{ult}/k)\). The focus of attention are local phenomena. Therefore, only yield strength criterion is taken into account \((1 - 3)\) (and yield index is omitted).

In the case of metallic alloys (elasto-plastic materials), yield strengths are clearly defined. For the composite materials the situation is more complicated. The yield stress determination can be performed in many ways. The exemplary definitions of the bearing yield stress are as follows:

1. global bearing failure
   - the stress corresponding to 2% permanent hole elongation;
   - the stress corresponding to 30% stiffness loss;
2. local (and micro local bearing failure)
   - the stress corresponding to first peak load on the stress-strain graph;
   - the stress corresponding to initial matrix fractures determined, e.g., with the use of acoustic methods.

The bearing yield stress (corresponding to 2% permanent hole elongation) is assumed at the level of 520 MPa according to [19]. A similar problem occurs for tensile strength determination. Composite materials are notch-sensitive. For material similar to that taken into consideration unnotched tensile strength equals 710 MPa, but open hole tensile strength is 456 MPa [20]. In the mentioned paper, the author claims that no damage occurs up to 75% of open hole
tensile strength. As the damage was monitored at a selected load level, the damage probably occurred between 65 – 75% of open hole tensile strength. In the paper, a 65% load level is taken into account, what results in yield strength equal to 300 MPa, which is in agreement with [19].

The yield stresses used in analytical calculations are presented in table I.

Comparing all the aforementioned strength conditions (1 – 3) (with assumption that the value of the lowest failure force corresponds to bearing of the composite part) results in aluminium sheet thickness of 2 mm ($t_{al} = 2$ mm). For a selected pitch, the bearing and tensile strength of the composite element is comparable. Additionally, the bearing by-pass diagram presented in [19] shows that there is a possibility of a composite tension failure mode. Therefore, the joint width $w$ is increased to 70 mm. For such dimensions, the joint fails in the composite bearing mode. The failure load equals 37 kN.

Comparing all the aforementioned strength conditions (1 – 3) (with assumption that the value of the lowest failure force corresponds to bearing of the composite part) results in aluminium sheet thickness of 2 mm ($t_{al} = 2$ mm). For a selected pitch, the bearing and tensile strength of the composite element is comparable. Additionally, the bearing by-pass diagram presented in [19] shows that there is a possibility of a composite tension failure mode. Therefore, the joint width $w$ is increased to 70 mm. For such dimensions, the joint fails in the composite bearing mode. The failure load equals 37 kN.

The lowest force ($F_{IA} = 1,34$) corresponds to bearing failure of the composite part (which is in agreement with the assumption), the next one ($F_{IA} = 1,00$) corresponds to bearing failure of the aluminium sheet and then force corresponding to net-tension failure of the composite part is almost at the same level ($F_{IA} = 0,96$).

**Numerical analysis**

A solid element is used to model all the components (aluminium and composite sheets and bolt). It is an eight-node element with linear interpolation functions and three translational degrees of freedom per node. Due to symmetry, only a quarter of the joint is modelled. The boundary and symmetry conditions are presented in Fig. 8. The left grip edge is fixed and the right grip edge is pulled.

Node to segment contact [21] is applied between the contacting surfaces. Nonlinear analysis is performed using Newton – Raphson method with MSC.Marc code. The properties of metallic alloys used in analysis are shown in table III.

A single lamina is described by means of one layer of 3D orthographic material (HTA/6376 UD prepreg) the properties of which are presented in Tab. IV.

![Fig. 8. Numerical model of the joint, iso view, load, boundary and symmetry conditions](image_url)

**TABLE I. Yield stresses used in analytical calculations**

<table>
<thead>
<tr>
<th>Material</th>
<th>$S_{y_1}$</th>
<th>$S_{y_2}$</th>
<th>$S_{y_3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2024 T3 ($i = AL$) [17]</td>
<td>524</td>
<td>360</td>
<td>-</td>
</tr>
<tr>
<td>Composite ($i = C$) [19, 20]</td>
<td>520</td>
<td>300</td>
<td>-</td>
</tr>
<tr>
<td>Steel bolt ($i = ST$) [17]</td>
<td>980</td>
<td>700</td>
<td>405</td>
</tr>
</tbody>
</table>

**TABLE II. Calculated stresses for load equal to 50 kN**

<table>
<thead>
<tr>
<th>Strength condition</th>
<th>Area, mm²</th>
<th>Stress $\sigma_i$, MPa</th>
<th>Analytical failure index $F_{IA} = \sigma_i/S_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bearing of composite part</td>
<td>72</td>
<td>699</td>
<td>1,34</td>
</tr>
<tr>
<td>Net-tension of composite part</td>
<td>174</td>
<td>289</td>
<td>0,96</td>
</tr>
<tr>
<td>Bearing of aluminium sheet</td>
<td>96</td>
<td>524</td>
<td>1,00</td>
</tr>
<tr>
<td>Net-tension of aluminium sheet</td>
<td>232</td>
<td>217</td>
<td>0,60</td>
</tr>
<tr>
<td>Shear of bolt (in composite part)</td>
<td>226.1</td>
<td>223</td>
<td>0,55</td>
</tr>
<tr>
<td>Bearing of bolt</td>
<td>72</td>
<td>699</td>
<td>0,71</td>
</tr>
</tbody>
</table>

The analytical failure indices ($F_{IA} = \sigma_i/S_i$) for each considered failure condition at the load level of 50 kN (corresponding to bearing failure of aluminium sheets) are presented in table II. It is assumed that bearing failure index of the aluminium sheet is equal to unity. This statement will be appropriate to compare analytical and numerical results.

![Fig. 8. Numerical model of the joint, iso view, load, boundary and symmetry conditions](image_url)
Failure criteria compare the appropriate components of the stress tensor in the material coordinate system ($\sigma_1$, $\sigma_2$, $\sigma_3$, $\sigma_{12}$, $\sigma_{23}$, $\sigma_{13}$) or their combination with the corresponding strengths values.

According to the maximum stress criterion, the failure indices are calculated as follows [21]:

1. First index:

\[
F_{Mx1} = \begin{cases} 
\frac{\sigma_1}{S_{1}} & \text{for } \sigma_1 > 0 \\
\frac{\sigma_3}{S_{3}} & \text{for } \sigma_3 < 0
\end{cases}
\]

(5)

2. Second index:

\[
F_{Mx2} = \begin{cases} 
\frac{\sigma_2}{S_{2}} & \text{for } \sigma_2 > 0 \\
\frac{\sigma_3}{S_{3}} & \text{for } \sigma_3 < 0
\end{cases}
\]

(6)

3. Third index:

\[
F_{Mx3} = \begin{cases} 
\frac{\sigma_3}{S_{3}} & \text{for } \sigma_3 > 0 \\
-\frac{\sigma_3}{S_{3}} & \text{for } \sigma_3 < 0
\end{cases}
\]

(7)

4. Fourth index:

\[
F_{Mx4} = \frac{\sigma_{12}}{S_{12}}
\]

(8)

5. Fifth index:

\[
F_{Mx5} = \frac{\sigma_{23}}{S_{23}}
\]

(9)

6. Sixth index:

\[
F_{Mx6} = \frac{\sigma_{13}}{S_{13}}
\]

(10)

The Hashin failure criterion distinguishes between fibre failure and matrix failure [24]:

1. First index, fibre tension mode:

\[
(F_{H1})^2 = \left( \frac{\sigma_1}{S_1} \right)^2 + \frac{1}{S_{12}^2} (\sigma_{12}^2 + \sigma_{13}^2)
\]

\[
\text{or } F_{H1} = \frac{\sigma_1}{S_1} \text{ for } \sigma_1 > 0
\]

(11)

2. Second index, fibre compression mode:

\[
F_{H2} = \frac{\sigma_3}{S_3} \text{ for } \sigma_3 < 0
\]

(12)

3. Third index, matrix tension mode:

\[
(F_{H3})^2 = \frac{1}{S_{23}^2} (\sigma_2 + \sigma_3)^2 + \frac{1}{S_{12}^2} (\sigma_{12}^2 - \sigma_{13}^2) + \frac{1}{S_{13}^2} (\sigma_{13}^2 + \sigma_{12}^2)
\]

\[
\text{for } \sigma_2 + \sigma_3 > 0
\]

(13)

4. Fourth index, matrix compression mode:

\[
F_{H4} = \frac{1}{S_{23}^2} \left( \frac{S_{23}^2}{S_{23}} - 1 \right) (\sigma_2 + \sigma_3)
\]

\[
+ \frac{1}{4S_{23}^2} (\sigma_{12}^2 + \sigma_{13}^2)
\]

\[
\text{for } \sigma_2 + \sigma_3 < 0
\]

(14)

TABLE V. Strengths of HTA/6367 lamina [23]

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength 1, MPa</td>
<td>2250</td>
</tr>
<tr>
<td>Compressive strength 1, MPa</td>
<td>1600</td>
</tr>
<tr>
<td>Tensile strength 2, MPa</td>
<td>64</td>
</tr>
<tr>
<td>Compressive strength 2, MPa</td>
<td>290</td>
</tr>
<tr>
<td>Tensile strength 3, MPa</td>
<td>94</td>
</tr>
<tr>
<td>Compressive strength 3, MPa</td>
<td>290</td>
</tr>
<tr>
<td>Shear strength 1-2, MPa</td>
<td>98</td>
</tr>
<tr>
<td>Shear strength 1-3, MPa</td>
<td>98</td>
</tr>
<tr>
<td>Shear strength 2-3, MPa</td>
<td>30</td>
</tr>
</tbody>
</table>

Failure criteria compare the appropriate components of the stress tensor in the material coordinate system ($\sigma_1$, $\sigma_2$, $\sigma_3$, $\sigma_{12}$, $\sigma_{23}$, $\sigma_{13}$) or their combination with the corresponding strengths values.

According to the maximum stress criterion, the failure indices are calculated as follows [21]:

For applied stress of 80 MPa (and corresponding load of 22.4 kN), the maximum stress value in aluminium alloy sheets is equal to yield strength (360 MPa) and failure index $F_{Mx1}$ reaches unity. The von Mises failure index distribution in the aluminium sheet is presented in Fig. 9.

For the same load level as in the case of aluminium sheet failure, failure indices according to max stress and Hashin failure criterion were observed in the composite part. Table V shows the values of the laminate layer strengths, used for calculating the failure indices.

Fig. 9. Von Mises failure index distribution in aluminium part (applied stress level 80 MPa)
Fig. 10. Mechanical joint failure forms and corresponding failure indices maps

**TABLE VI. Maximum stress failure indices**

<table>
<thead>
<tr>
<th>Laminate Layer</th>
<th>angle, $\theta$</th>
<th>$F_{IMX}^1$</th>
<th>$F_{IMX}^2$</th>
<th>$F_{IMX}^3$</th>
<th>$F_{IMX}^4$</th>
<th>$F_{IMX}^5$</th>
<th>$F_{IMX}^6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>0</td>
<td>0.614</td>
<td>1.239</td>
<td>0.368</td>
<td>1.198</td>
<td>2.725</td>
<td>5.540</td>
</tr>
<tr>
<td>L2</td>
<td>45</td>
<td>0.589</td>
<td>1.380</td>
<td>0.350</td>
<td>1.014</td>
<td>1.269</td>
<td>2.005</td>
</tr>
<tr>
<td>L3</td>
<td>90</td>
<td>0.535</td>
<td>1.006</td>
<td>0.338</td>
<td>0.900</td>
<td>1.179</td>
<td>0.811</td>
</tr>
<tr>
<td>L4</td>
<td>-45</td>
<td>0.708</td>
<td>1.043</td>
<td>0.225</td>
<td>0.864</td>
<td>1.664</td>
<td>0.529</td>
</tr>
<tr>
<td>L5</td>
<td>0</td>
<td>0.649</td>
<td>0.407</td>
<td>0.266</td>
<td>0.942</td>
<td>1.929</td>
<td>0.442</td>
</tr>
<tr>
<td>L6</td>
<td>45</td>
<td>0.983</td>
<td>1.354</td>
<td>0.207</td>
<td>0.967</td>
<td>1.107</td>
<td>0.778</td>
</tr>
<tr>
<td>L7</td>
<td>90</td>
<td>0.481</td>
<td>1.744</td>
<td>0.108</td>
<td>1.141</td>
<td>1.879</td>
<td>0.338</td>
</tr>
<tr>
<td>L8</td>
<td>-45</td>
<td>0.992</td>
<td>1.380</td>
<td>0.528</td>
<td>1.218</td>
<td>1.405</td>
<td>2.037</td>
</tr>
</tbody>
</table>

According to the maximum stress criterion, the highest indices values are those corresponding to the tension/compression in direction 2 – $F_{IMX}^2$ (determined by the properties of the matrix), the shear in 2-3 plane – $F_{IMX}^5$ and the shear 1-2 plane – $F_{IMX}^4$.

**TABLE VII. Hashin failure indices**

<table>
<thead>
<tr>
<th>Laminate Layer</th>
<th>angle, $\theta$</th>
<th>$F_{IH}^1$</th>
<th>$F_{IH}^2$</th>
<th>$F_{IH}^3$</th>
<th>$F_{IH}^4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>0</td>
<td>0.993</td>
<td>0.580</td>
<td>2.627</td>
<td>7.518</td>
</tr>
<tr>
<td>L2</td>
<td>45</td>
<td>1.028</td>
<td>0.589</td>
<td>1.483</td>
<td>10.901</td>
</tr>
<tr>
<td>L3</td>
<td>90</td>
<td>0.996</td>
<td>0.535</td>
<td>2.127</td>
<td>10.901</td>
</tr>
<tr>
<td>L4</td>
<td>-45</td>
<td>0.910</td>
<td>0.708</td>
<td>1.679</td>
<td>8.385</td>
</tr>
<tr>
<td>L5</td>
<td>0</td>
<td>0.917</td>
<td>0.639</td>
<td>1.832</td>
<td>5.317</td>
</tr>
<tr>
<td>L6</td>
<td>45</td>
<td>0.986</td>
<td>0.563</td>
<td>1.406</td>
<td>15.574</td>
</tr>
<tr>
<td>L7</td>
<td>90</td>
<td>1.198</td>
<td>0.481</td>
<td>2.225</td>
<td>27.259</td>
</tr>
<tr>
<td>L8</td>
<td>-45</td>
<td>1.329</td>
<td>0.991</td>
<td>2.158</td>
<td>6.813</td>
</tr>
</tbody>
</table>

Hashin failure indices are presented in Tab. VII. If fourth Hashin failure index is equal to unity ($F_{IH}^4 = 1$), a load level is found. Then, the applied load (corresponding to aluminium alloy sheet failure) is divided by the former one (consistent with a matrix compression failure mode).

Large values of the index $F_{IMX}^5$ are significantly influenced by low shear strength in 2-3 plane as well as the vicinity of the hole edge.
The analysis of the Hashin criterion indices shows that at the beginning the resin fails by compression and next by tension (in each layer). The high values of fibre tension indices are probably overestimated, as resulted from a literature review [20].

In mechanical joints, bearing is accompanied by tension in a net section. Failure forms obtained during the joint loading can be divided into the ones typical for the bearing and the ones specific for open hole tension [17].

The typical mechanical joints failure forms of quasi-isotropic CFRP laminates and failure indices maps are presented in Fig. 10.

The bearing failure initiation occurs due to matrix compression. The matrix compression failure index \( F_{IL} \) for layer L7 \( (90^\circ) \) is equal to 27.259 (Fig. 10a). Fig. 10b presents the form of failure specific for a quasi-isotropic CFRP laminate open hole tensile test and a corresponding failure index map. For layer L7 \( (90^\circ) \), value of the second failure index according to maximum stress criterion \( F_{IMX} \) equals 1.744.

The index corresponding to the fibre compression failure \( F_{IC} \) for layer L5 \( (0^\circ) \) equals 0.639 (Fig. 11).

Although the presented data gives insights into the behaviour of a particular layer, the failure indices are valid only to first failure occurrence. Therefore, the progressive failure analysis is performed. The results of the progressive failure analysis are presented in Fig. 12. NF denotes quasi-linear analysis without failure, H\textunderscore imme and MX\textunderscore imme stands for immediate stiffness reduction to 1% according to Hashin and maximum stress failure criterion, respectively. The gradual stiffness reduction is marked by H\textunderscore grad for Hashin and MX\textunderscore grad for the maximum stress failure criterion.

The analytically calculated failure force \( P_a \) equals 37 kN. According to the Hashin failure criterion \( F_{N\textunderscore HAS} \) matrix fails in the compression mode for the force \( P_{N\textunderscore HAS} = 0.82 \) kN (Tab. 7, layer L7). Taking into account the maximum stress failure criterion \( F_{N\textunderscore MX} \), shear failure in 2-3 plane occurs for the load level of \( P_{N\textunderscore MX} = 8.22 \) kN (Tab. VI, layer L1).

During numerical analysis without failure (NF), the force increases almost linearly with displacement. However, during the progressive failure analysis, nonlinear behaviour is observed before failure. The maximum forces obtained, for immediate stiffness reduction analysis, according to Hashin \( P_{HAS\textunderscore imme} \) and maximum stress failure criterion \( P_{MX\textunderscore imme} \) are 22.28 kN and 25.63 kN, respectively. Forces \( P_{HAS\textunderscore grad} = 31.10 \) kN and \( P_{MX\textunderscore grad} = 40.80 \) kN are obtained in Hashin and maximum stress gradual stiffness reduction analysis. The safety factors \( P_a / P_f \) where \( N = NF\_HAS, ... ,MX\_grad \) for all cases of analysis are compared in Tab. VIII.

### TABLE VIII. Comparison of safety factors

<table>
<thead>
<tr>
<th>Failure analysis case</th>
<th>Type of failure</th>
<th>Safety factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>NF_HAS</td>
<td>micro\ local</td>
<td>45.03</td>
</tr>
<tr>
<td>NF_MX</td>
<td>micro\ local</td>
<td>4.50</td>
</tr>
<tr>
<td>HAS_imme</td>
<td>local/global</td>
<td>1.66</td>
</tr>
<tr>
<td>MX_imme</td>
<td>global</td>
<td>1.44</td>
</tr>
<tr>
<td>HAS_grad</td>
<td>global</td>
<td>1.19</td>
</tr>
<tr>
<td>MX_grad</td>
<td>global</td>
<td>0.91</td>
</tr>
</tbody>
</table>

The gradual stiffness reduction analysis with maximum stress failure criterion results in upper load capacity estimation (safety factor lower than 1). However, the analysis without failure according to
Hashin criterion results in lower load capacity (safety factor 45.03). Although, the analytical conditions and gradual stiffness reduction analysis allow for estimation of global failure load of the specimen, the immediate stiffness reduction analysis provides estimation of local failure load level. The analysis of failure indices (quasi-linear cases) creates a possibility to evaluate load level corresponding to micro local phenomena.

Conclusions

Analytical and numerical strength assessments were carried out for a mechanical metal-composite joint. According to the analytical calculation, global failure of the composite element occurs at the load level equal to 74% (37 kN) in relation to failure load of an aluminium alloy sheet (50 kN). The analytical calculations are based, however, on the equivalent, (experimentally determined) laminate properties. The numerical results are based on lamina determined properties, therefore, the behaviour of each lamina is considered separately. According to the numerical calculation, micro local failure of the composite element occurs at the load level equal to 37% (8.22 kN) and 3.7% (0.82 kN) in relation to failure load of an aluminium alloy sheet (22.4 kN) for maximum stress and Hashin no failure analysis, respectively. In numerical analysis, the composite element failure can be estimated with the usage of failure criteria and progressive analysis properties. The numerical analyses were carried out without failure of laminate (quasi-linear case), with immediate stiffness reduction and with gradual stiffness reduction (nonlinear cases). The assumed criterion and failure progressive analysis properties strongly influence the results. The numerically estimated safety factors vary from 0.91 to 45.03. However, all the results of numerical and analytical analyses indicate that the failure of composite element occurs before aluminium sheet failure. The load level selected in numerical calculations is comparable to the operating load of the aircraft. The gradual stiffness reduction analysis with maximum stress failure criterion results in the underestimated safety factor, which provides the upper estimation of the specimen load capacity. However, quasi-linear analysis with Hashin failure results in lower load capacity estimation.

REFERENCES