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ABOUT MECHANICAL JOINTS DESIGN IN METAL-COMPOSITE STRUCTURE

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Abstract

Riveting is still one of the main joining methods of thin-walled aircraft structures. Such features as simplicity of implementation, possibility of two different material connection (e.g. metallic with non-metallic ones) and the fact that is it a well-known (reliable) method causes popularity of riveting. The never-ending attempt to obtain as low mass as possible (mainly to reduce fuel consumption) is the reason for using material of high specific strength in the aerospace industry. High strength titanium or aluminium alloys (e.g. 2024T3) and composite laminates (e.g. CFRP or Glare) are examples of such materials.

The article deals with methods of connecting various materials. The paper presents advantages and disadvantages of different/selected connection types. Strength prediction and failure modes of mechanical joints are described for metallic as well as for composite components. Composites are complex materials having an anisotropic structure (and anisotropic mechanical properties) leading to various failure mechanisms. Main principles for appropriate joint design of composite laminate panels (laminate configuration and typical/specific geometrical dimensions) are indicated/specified. The bearing failure mechanism is accepted to be a safe progressive one. Mechanism of bearing (generally compressive) load transfer into composite laminates by shear of the matrix is analysed.

Some examples of improvement bearing strength of laminates are presented according to literature. On the base of presented examples and bearing load transfer analysis, some conclusions for an appropriate solution of this problem are drawn.

Keywords: *mechanical joint, adhesive joint, FEA, aviation*

1. Introduction

The usage of different materials in aircraft structures results in the necessity of joining composite and metallic components.

Main advantages of composite materials are high specific strength, corrosion resistance, vibration damping ability, possibility of property tailoring for any specific case. Their main disadvantages are anisotropy, lower deformation ability, higher notch sensitivity and higher dependence on temperature. These factors lead to difficulties in strength (load carrying capacity) prediction of composite materials. However, the attempt to obtain as light aircrafts as possible forces constructors to search for new solutions for composite structures. Despite a large number of composite types, fibre reinforced composites in the form of laminates are commonly used in aircraft structures.

1.1. Connection types

There are three connection types concerning joining method:

- mechanical e.g. riveting, bolting or pinning (Fig. 1),

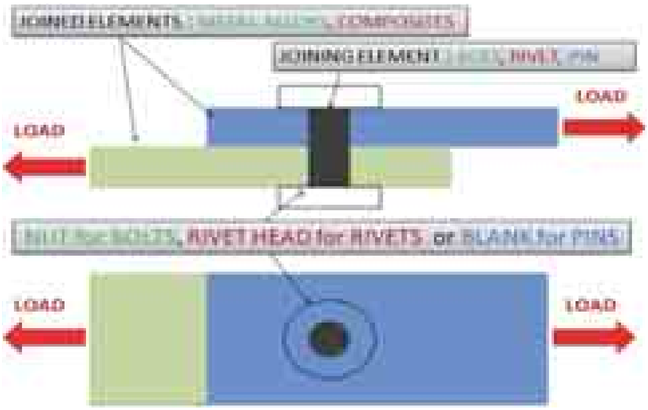

Fig. 1. Mechanical joint

– adhesive e.g. bonding, welding (Fig. 2),

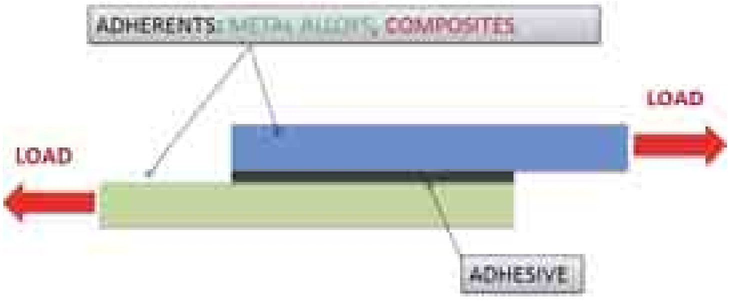

Fig. 2. Adhesive joint

– hybrid where both above mentioned method are used.

1.2. Advantages and disadvantages of connection methods

Riveting is the oldest and the most popular method of joining metal parts of aircraft structures. It is used in large airliners, freight aircrafts (in which number of rivets is counted in millions and their weight may attain a few tons), light fighter-trainers and cargo planes as well as in helicopters in which riveting is the basic method of joining metal components.

If one of the components is made of composite material, bolted or bonded joints are more preferable. Making holes is a necessity for mechanical joints. These holes are the areas of high stress concentrations and determine load capability of the whole structure. In bonded joints, the load is distributed in a more uniform way. Additionally, the application of bonded joints leads to weight reduction. Main disadvantage of bonded joints is higher cost determined by more rigorous assembly conditions, i.e. surface treating, moisture and temperature as well as the unfavourable tendency to voids nucleation between adhesive and adherent. Service conditions (atmosphere, service fluids) determine the strength of such joints. The ageing phenomenon is also important. Mechanical joints used for decades are proved to be reliable. They can be assembled and applied in very rough conditions since they are less sensitive to environmental effects.

2. Strength assessment of mechanical joints

2.1. Metallic components.

There are three major conditions that a properly designed mechanical joint made of metallic components must fulfil (Fig. 3), namely:

1. Bearing stress condition: $\sigma_b = \frac{P}{D \cdot t} \le \sigma_{b\max}$, where: σ_b - bearing stress, P – applied load, D – hole diameter, t – sheet thickness, $\sigma_{b\max}$ - allowable sheet bearing stress.
2. Shear stress condition: $\tau = \frac{P}{\frac{\pi \cdot d}{4}} \le \tau_{\max}$, where: τ - bearing stress, d – rivet diameter [mm], $\tau_{\max}$ - allowable rivet shear stress.
3. Tensile stress condition: $\sigma_t = \frac{P}{(w - D) \cdot t} \le \sigma_{t\max}$, where: σ_t, w – sheet width, b – sheet thickness, $\sigma_{t\max}$ - allowable sheet tensile stress.

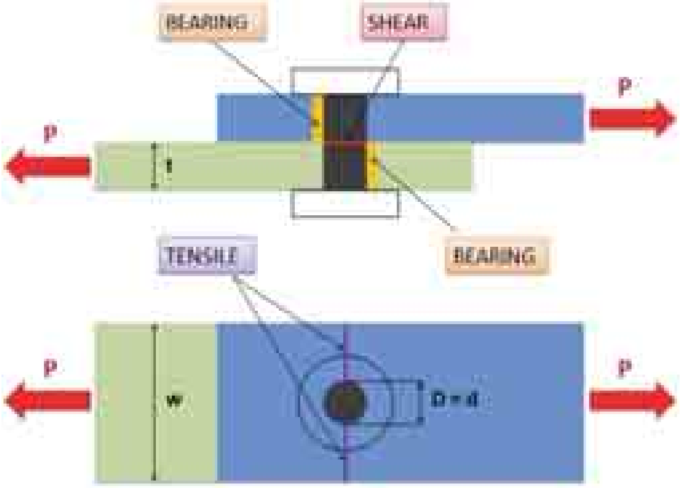

Fig. 3. Failure modes of mechanical joint of metallic components

Metallic alloys are assumed to be isotropic. For such materials, bearing strength (which in motionless joints corresponds to compression strength - R_c) and shear strength R_t can be expressed in relation to ultimate tensile strength R_m (or yield strength R_{02}) obtained from a unidirectional tensile test. Compression (bearing) strength can vary from 1.2 to 1.7 of ultimate tensile strength (R_c = 1.3 R_m is recommended). Shear strength is assumed at range from 0.55 to 1.0 of ultimate tensile strength (R_t = 0.6-0.65R_m for aluminium alloys) [1].

Allowable tensile stress $\sigma_{t\max}$ is calculated by dividing yield strength R_{02} (or ultimate tensile strength R_m) by safe factor – k_t. Allowable bearing stress $\sigma_{b\max}$ and maximum shear stress $\tau_{\max}$ are obtained in the same way using bearing strength R_b tensile strength R_t and corresponding safe factors.

Strength assessment of mechanically fastened parts made of metallic alloys is therefore not a very complex matter since it is mainly dependent on the joint geometry. In case of composite materials, the strength prediction is far more complex. The authors pay attention on mechanical joints of composite panels. Strength of bolt or rivet material is assumed to be much higher than strength of a composite one.

2.2. Composite components.

Laminates consist of several layers. Each layer is usually a unidirectional fibre reinforced composite (Fig. 4b). It means that it has a specific fibre orientation (angle between fibre and load direction – Fig. 4a). A unidirectional composite layer has substantially different mechanical properties in all directions as its strength is mostly determined by fibre (Tab. 1).

Tab. 1. Comparison of mechanical properties of exemplary unidirectional carbon fibre reinforced composite [2]

Parameter	Fibre direction	Transverse direction
E – Young modulus [GPa]	88	8,8
Tensile strength [MPa]	811	47.3
Compressive strength [MPa]	457.7	109.5
Shear modulus [GPa]	2.8	
Shear strength [MPa]	132	

Strength of composite laminates is dependent on joint geometry, however, it is strongly influenced by laminate configuration.

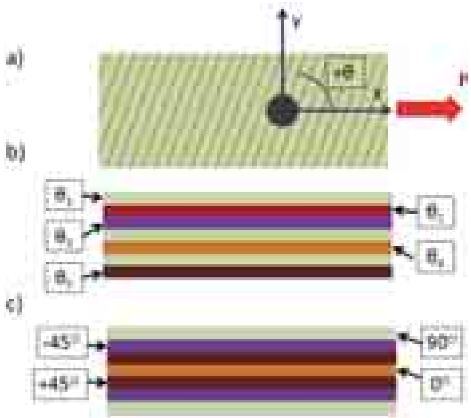

Fig. 4. Composite : a) definition of fibre orientation, b) laminate layers of different fibre orientation, c) example of quasi – isotropic laminate

There are five global failure modes for mechanically fastened composite laminates: tension, bearing, shear – out, cleavage and pull-through (Fig. 5). The bearing failure mechanism is a safe progressive mechanism not leading to catastrophic failure and therefore it is acceptable.

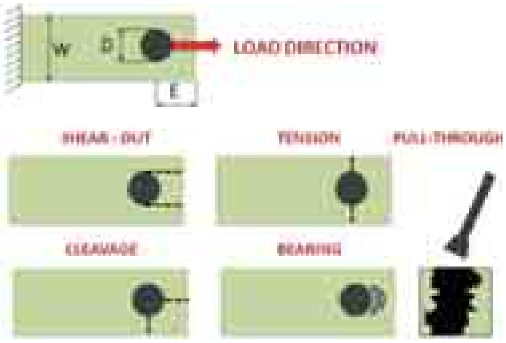

Fig. 5. Failure mechanism in bolted composites [3]

There are some hints for correct design of mechanical joint of composite panels [3]:

- Appropriate geometry: Sheet width to hole diameter ratio W/d and edge distance to hole diameter ratio E/D should reach a high enough value specific to given material. The tensile failure is likely to happen for low W/D. Low E/D leads to shear-out.
- Proper layer orientation: Composite should be quasi-isotropic (Fig. 4c) that means 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 there are too many fibres in 0 direction and too few in 90 one, the shear-out is likely to occur. Composites with a small number of fibres in 90 direction and low E/D ratio are prone to cleavage.

If the above conditions are fulfilled, the occurrence of bearing failure mode is highly probable. In composite materials, it 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 slightly lower than the tensile one, moreover, the resin matrix has much lower strength than the fibres (Tab. 2). Initially, the compressive load is transferred mostly by the matrix. After some matrix deformation, the load is also transferred by the fibres due to shear stress between the matrix and fibres (Fig. 6). The fact that the matrix deforms more than the fibres causes adhesion failure. Not supported fibre of a minor diameter (200 Å) has a tendency to local buckling and cracking (Fig. 6). The whole load is transferred by the compressed matrix, which fails suddenly.

Tab. 2. Comparison of exemplary fibre and matrix strength [4]

Parameter	Carbon fibres T300	Epoxy resin R50
Compressive Strength [MPa]	2000	93
Tensile Strength [MPa]	2500	64.5

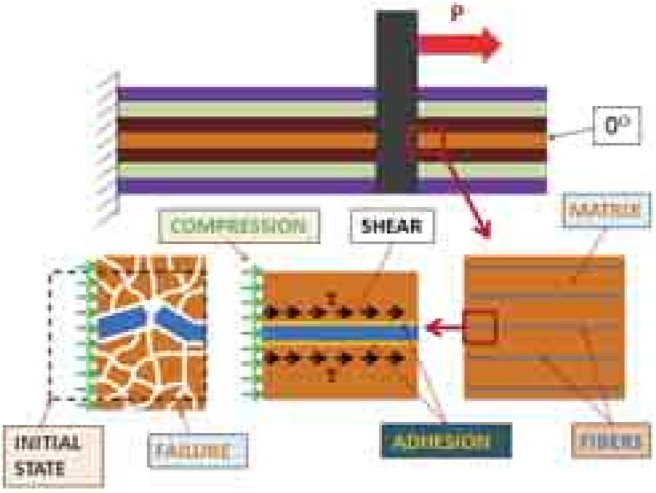

Fig. 6. Failure of mechanically joined fibre reinforced composite

During riveting the rivet shank is squeezed and, as a result, a residual stress state occurs. In metallic alloys (i.e. aluminium alloy) residual stresses cause local strengthening [5]. In composites, however, they can lead to damage. Taking these facts into account, the improvement of load transfer into composite panels seems to be reasonable. Some attempts to achieve this aim will be presented in the following part.

3. Examples of strength improvement according to literature

The influence of Al_2O_3 particles of an average size of 48 μm on bearing strength of epoxy resin reinforced by glass fibre fabric is examined in paper [6]. Series of tests were performed for specimens of various geometrical parameters (E/D and W/D ratios) and various particle contents. Exemplary results are shown in Fig. 7.

The increase of weight particle content to 10% causes an increase in bearing strength by about 18%. However, a further growth of particle ratio decreases specimen strength.

Two methods of bearing strength improvement in composite laminates, namely: fibre steering and z-pins usage are examined/presented in the paper [7].

The fibre steering is obtained in two ways: along the trajectories defined by the maximum (σ_I) and minimum (σ_{II}) principal stresses close to the hole in 2D model (Fig. 8) as well as along the load path trajectories describing the way a structure carries the applied load (Fig. 9).

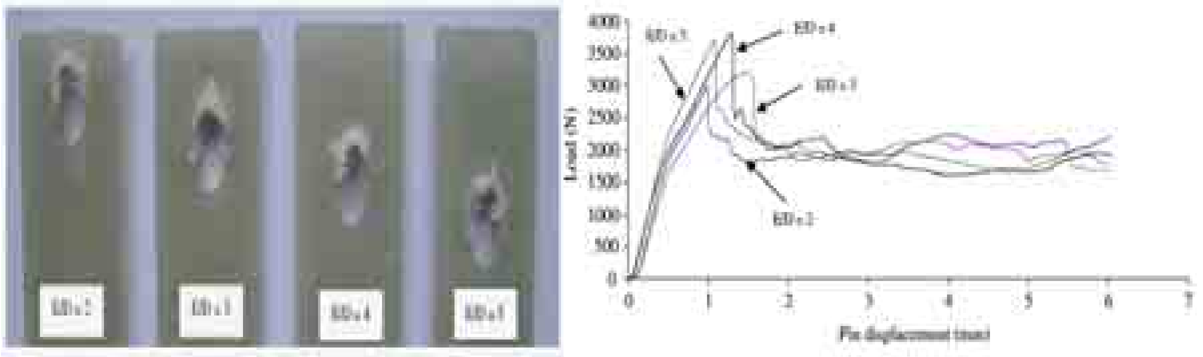

Fig. 7. Failure of exemplary specimens reinforced by Al_2O_3 particles and corresponding bearing curves [6]

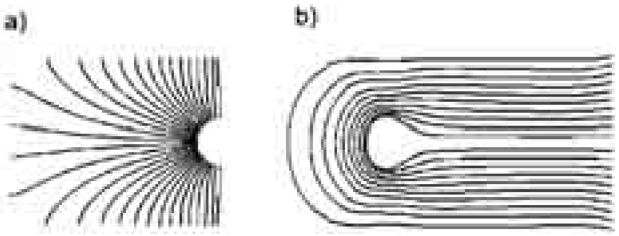

Fig. 8. Fibre steering : a) maximum principal stress trajectories, b) minimum principal stress trajectories [7]

The former fibre steering solution (Fig. 8), obtained by proper processing of FEM results, was verified experimentally and compared with the results of samples without steered fibres. Bearing strength improvement by 36% was obtained.

The later solution with the use of load path trajectories (Fig. 9) cause a strength improvement by 33%, however, for this case less fibres were used what makes this method more effective.

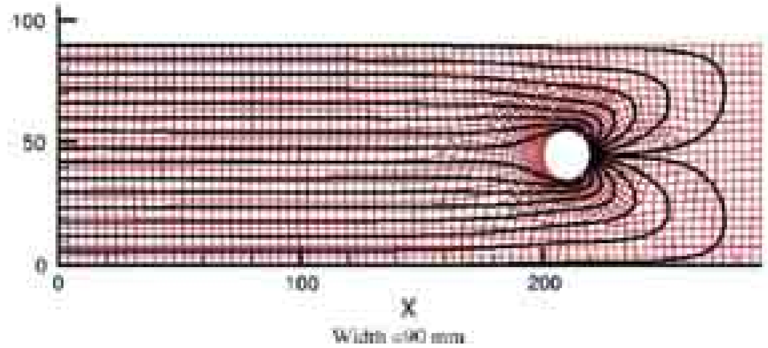

Fig. 9. Load path trajectories for exemplary sample [7]

Another method is based on using z-pins. The process of introducing z-pins into laminate is presented in Fig. 10 [7].

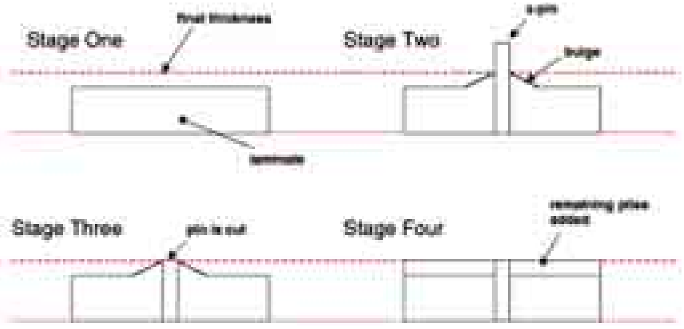

Fig. 10. Z – pins reinforcement process [7]

Although the maximum load transferred by laminate with z-pins was greater than for samples without them the bearing strength was not improved. Cross-sections without and with z-pins are shown in Fig. 11.

It can be noticed that damage for a sample with z-pins does not propagate as far as for a not reinforced one. Authors claim that this method will be perspective if the possibility of deformation in thickness direction is limited.

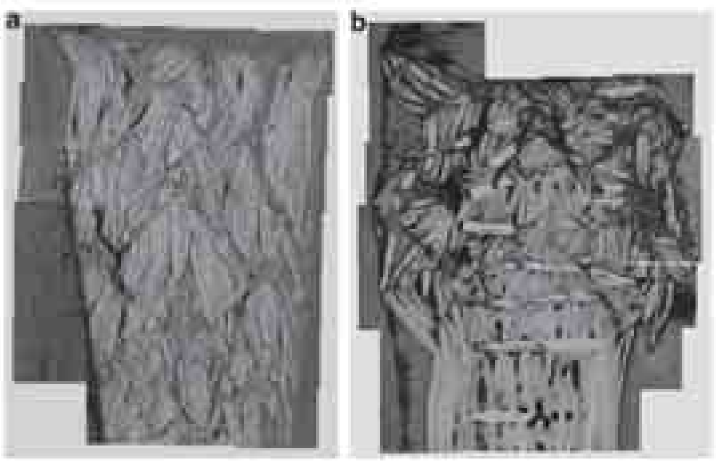

Fig. 11. Cross section showing failure of : a) specimen without z-pins, b) with z-pins reinforcement [7]

The next solution of bearing strength improvement by bonding an aluminium alloy insert in the hole (Fig. 12) is presented in paper [8]. If the insert is bonded the hole surface takes part in load transfer.

In a single-shear joint not only the hole surface but also the composite surface can contribute to the load transfer. Three insert types were tested: with tapered end (Fig. 12a), with straight end (Fig. 12b) and with no ends (Fig. 12c).

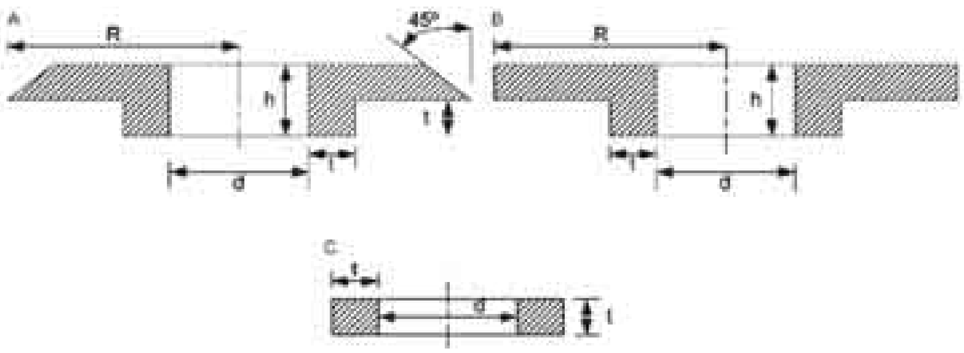

Fig. 12. Analysed inserts: a) with tapered end, b) with straight end, c) without end [8]

Although this method seems to be perspective, during the tests for single-shear joint no strength improvement was obtained. After the maximum load is reached the bond connection between the composite and the fibre fails.

One of the most promising solutions, is presented in paper [9]. 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. 13).

Various laminate configuration and bolt bearing curve are shown in Fig. 14.

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

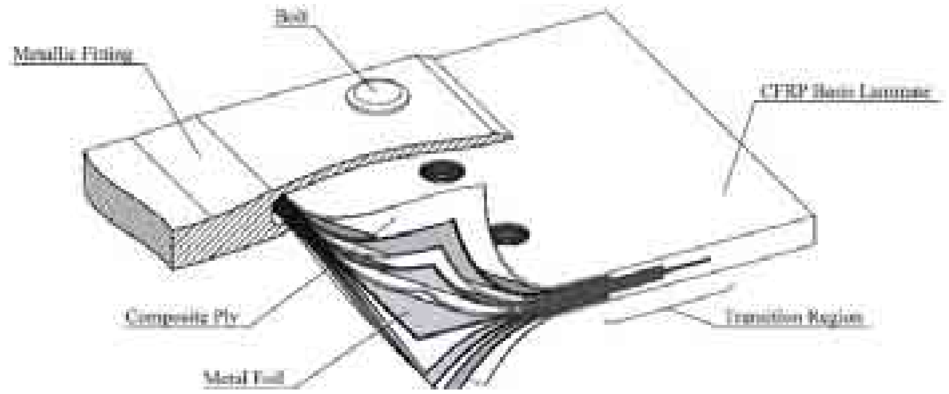

Fig. 13. Sample with titanium foils bonded between laminate layers [9]

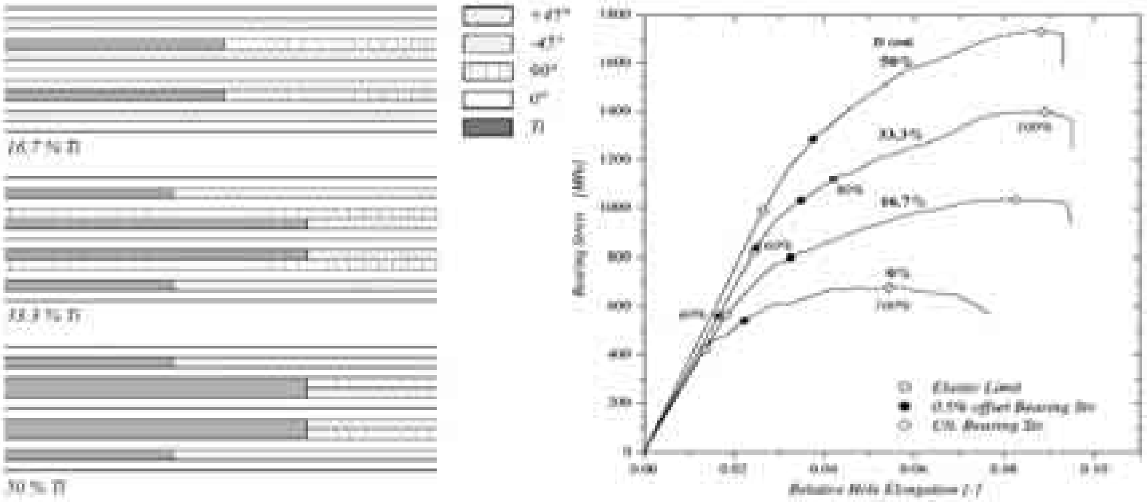

Fig. 14. Hybrid (titanium –CFRP) laminate configuration and bearing strength curves [9]

4. Numerical simulation of bearing test

The analysis is performed for a CFRP laminate used in a bearing test according to ASTM D953 standard (Fig. 15a).

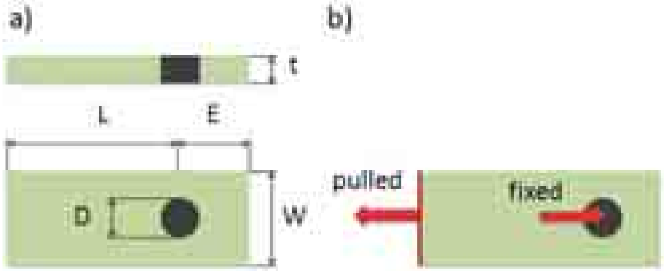

Fig. 15. Analysed sample: a) dimensions, b) load conditions [2]

The hole diameter D is 6.35 mm. Distance between the hole centre and the grip edge L is 80 mm. In paper [2] samples with different E/D and W/D ratio were examined and the best results were obtained for following dimensions: E/D = W/D = 4. Therefore, width W equals 25.4 mm and edge distance E equals 25.4 mm.

A single lamina is described by means of 2D orthographic material. Mechanical properties of single lamina are presented in Tab. 1. The laminate is composed of eight layers of 0.33 thickness. The laminate configuration is $[90/45/-45/0]_s$. Total laminate thickness t equals 2.64 mm.

Maximum stress failure criterion with progressive failure option is used. Failure occurs when stresses equal or exceed maximal values specified in Tab. 1.

Element type 72 is used, as it is preferable for composite materials. It is an eight-node thin shell element with bilinear interpolation functions having three translational degrees of freedom at corner nodes and one rotational degree of freedom at edge midside nodes. The bolt is modelled as a rigid element (RBE2) and is motionless. The grip edge is pulled and the pin is fixed (Fig. 15b).

Contact between the hole laminate and the bolt is realised by GAP elements. Nonlinear analysis is performed using Newton – Raphson method with MSC.Marc code.

Experimental [2] and numerical results, bearing load curves, are shown in Fig. 16.

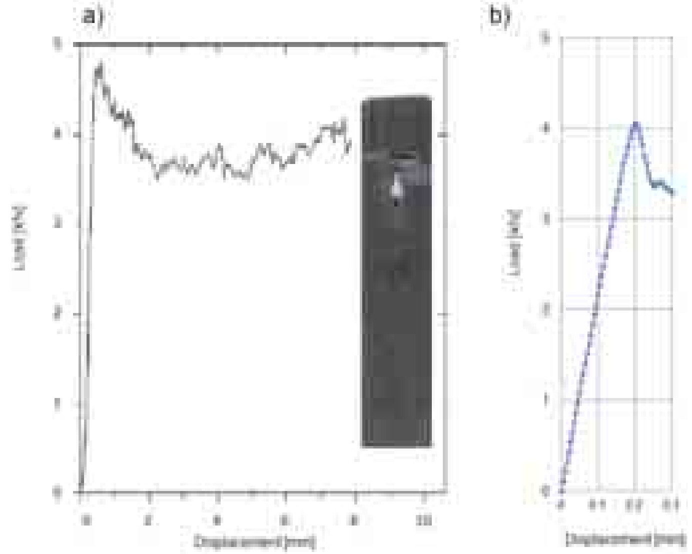

Fig. 16. Bearing load curves: a) experimental [2], b) numerical

5. Conclusions and future work direction

Although fibre reinforced composites have high tensile strength, the load transfer in mechanical joints of such components is limited. In this type of connection the load is transferred by bearing (local compression) determined by matrix strength. Using metal elements in the hole vicinity is therefore likely to be the most reasonable solution since the stress distribution becomes more uniform. Metallic inserts improve bearing strength only if both the hole and the composite surface contribute to the load transfer. It limits their usage to single-shear joints. Bonding of titanium foils between laminate layers is the most advantageous off all quoted solutions, however, it is the most expensive one as well.

A proper solution of load transfer into the composite structure using shear stress in the resin matrix between metal and composite layers can improve bearing capacity of mechanically fastened joints. It can be profitable for bolted joints. It will also make a possibility of using traditional rivets instead of special ones or a special riveting technique.

The authors' future effort will be put on searching optimal solution for mechanical joint of composite panels that makes a possibility of transfer the bearing load into the composite material in a gradual way and will be economically reasonable.

Numerical analysis of the composite structure require the usage of a 3D model.

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