mechanical joint, adhesive joint, composite material, load transfer, FEA

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ANALYSIS OF LOAD TRANSFER INTO COMPOSITE STRUCTURE

Abstract

The paper presents advantages and disadvantages of metal foils insertion between composite layers. Composites are complex materials of anisotropic structure leading to various failure mechanisms. Mechanism of compressive load transfer into composite laminates by shear of the matrix is analysed. The method of improvement compressive strength of laminates is presented according to literature and analysed for a selected case. Simplified models of a laminate structure modified using various metal foils configurations are analysed with MSC.Marc code. Axial stress in prepreg layers and shear stress in adhesive layers are studied.

1. INTRODUCTION

The usage of different materials in aircraft structures results in the necessity of joining composite and metallic components. The never-ending attempt to obtain the lowest possible mass is the reason for using material of high specific strength in the aerospace industry. High strength titanium or aluminium alloys and composite laminates (e.g. CFRP) are the examples of such materials.

The main advantages of composite materials are: high specific strength, corrosion resistance, vibration damping ability and 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 prediction of strength (load carrying capacity) of composite materials. However, the attempt to obtain the lightest

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possible structures 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 [1-4].

1.1. Composite material

Laminates consist of several layers (plies). Each layer is usually a unidirectional or woven fibre reinforced composite (fig. 1b). It means that it has a specific fibre orientation (angle between fibre and load direction – fig. 1a).

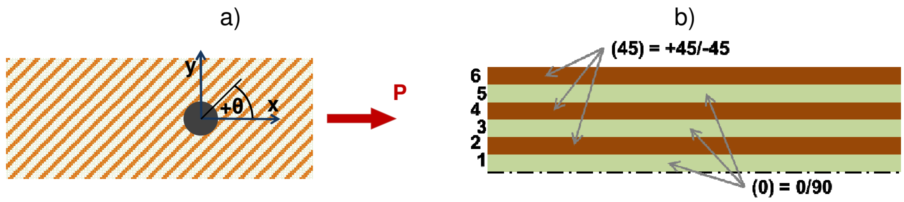

Fig. 1. Composite: a) definition of fibre orientation, b) woven laminate layers of different fibre orientation [source: own study]

A unidirectional composite layer indicates substantially different mechanical properties in all directions as its strength is mostly determined by fibre, whereas a woven ply has the same properties in two fibre directions. Strength of composite laminates is considerably influenced by laminate lay-up [1, 5].

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

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. 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. 2).

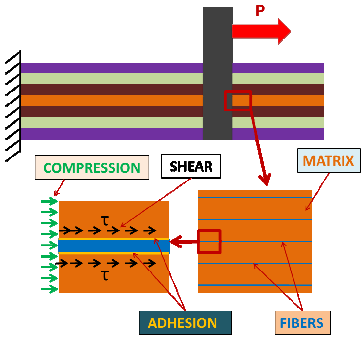

Fig. 2. Load transfer in mechanical joint of fibre reinforced composite [source: own study]

The fact that the matrix deforms more than the fibres causes adhesion failure. An unsupported fibre of a minor diameter (200 Å) has a tendency to local buckling and cracking. The whole load is transferred by the compressed matrix which fails suddenly [1, 4]. The above problems were considered by many authors [6, 7, 8].

Compression in composites can lead to damage. Taking these facts into account, the improvement of load transfer into composite panels seems to be reasonable. Exemplary methods of bearing strength improvement in composite laminates are as follows: matrix reinforcement by Al_2O_3 particles [9], fibre steering and z-pins [10] or bonding an aluminium alloy insert in the hole [11]. Another attempt to achieve this aim (one of the most promising solutions) is presented in papers [2, 3]. Sheets made of titanium alloy are bonded between composite layers in some distance from the edge of the composite panel in a way that causes gradual load transfer into the composite structure (fig. 3).

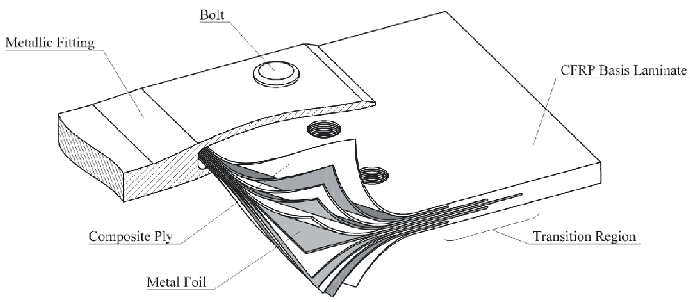

Fig. 3. Titanium foils bonded between laminate layers [2]

2. NUMERICAL SIMULATION OF LOAD TRANSFER INTO LAMINATE STRUCTURE

Selected laminate consists of twelve HTA/6376 woven prepreg layers (configuration $[(45)/(0)/(45)/(0)/(45)/(0)]_S$). A material orthotropic model of the prepreg ply is as follows: $E_1 = E_2 = 75.4$ GPa; $E_3 = 12.6$ GPa; $G_{12} = 4.55$ GPa; $\nu_{12} = 0.04$, $\nu_{13} = \nu_{23} = 0.46$ (based on literature data [12] and the classical lamination theory). Parameters of a resin elasto-plastic model with Mises plasticity criterion are E_a = 3.6 GPa; ν_a = 0.4; R_e = 35.2 MPa; R_m = 44.9 MPa [13]. Metal foils are made of titanium alloy (isotropic model: E=115 GPa; ν = 0.3).

Exemplary methods of modelling adhesive joints are presented in papers [13-15]. A simplified plane strain model of load transferring into laminate structure (between laminate layers) using metal foils is analysed with MSC.Marc code [16]. One edge of the model is fixed and the opposite one is pulled (fig. 4). The model is 6.32 mm long and 1.5 mm high (it means half a total laminate thickness). Single prepreg ply thickness is 0.25 mm (including adhesive of 0.01 mm). Prepreg and adhesive plies are described/labelled by p1-p6 and a1-a5, respectively.

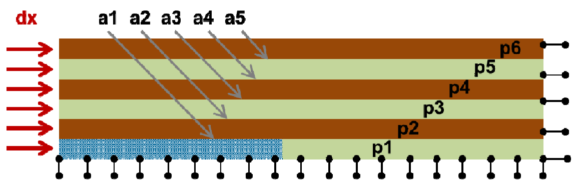

Fig. 4. Laminate model: load and boundary conditions and notation [source: own study]

One half of the laminate thickness is modelled due to plane symmetry with respect to its middle surface. Four-node, isoparametric quad elements with a bilinear interpolation function and two translational degrees of freedom at corner nodes are used. Mesh density is adapted to adhesive layer thickness (consisting of 4 finite elements) a bit further from the adhesive region element dimensions gradually increase (fig. 5).

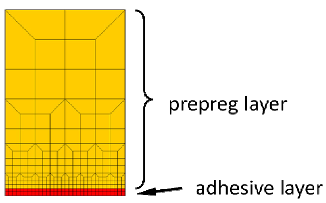

Fig. 5. Mesh density [source: own study]

Four insert configurations (where a part of selected prepreg layer is replaced with a metal foil) are taken into account (fig. 6).

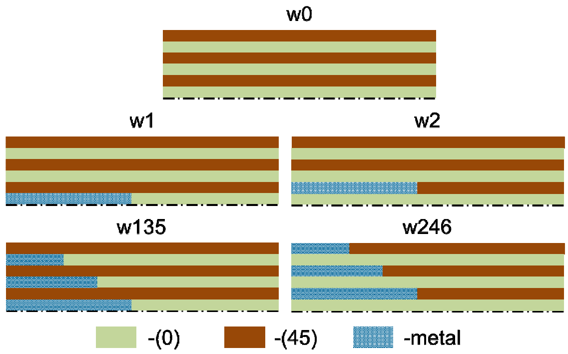

Fig. 6. Laminate configurations [source: own study]

Laminate deformation for various configurations of metal inserts are shown in fig. 7.

Selected results for cases w1 and w2 as well as w135 and w246 are presented in fig. 8-9 and fig. 10-11, respectively.

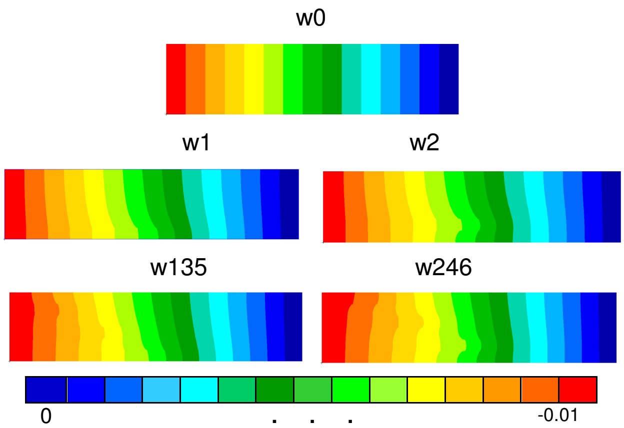

Fig. 7. Laminate deformations: X displacement component [source: own study]

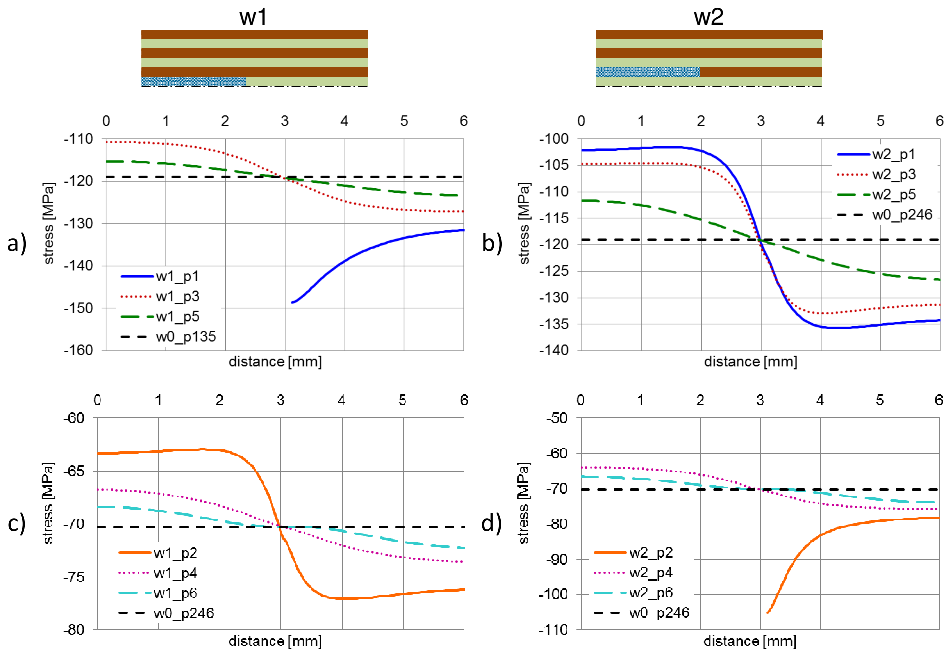

Fig. 8. Normal stress (axial component) in laminate layers – cases w1 and w2: a)-b) layers p1,p3,p5; c)-d) layers p2,p4,p6 [source: own study]

The applied load is carried into a laminate structure mainly by metal foils (fig. 7), then it is gradually transferred between the foil and the prepreg layer, due to adhesion (fig. 9 and fig. 11). Normal stresses (axial components) are larger in prepreg plies which follow the metal foils, however they are smaller at the pulled edge of the laminate (fig. 8 and fig. 10). In the insert area, stress values in prepreg layers are lower than mean stress (corresponding to model w0 – without metal inserts). Beyond this region, stress values exceed the mean ones.

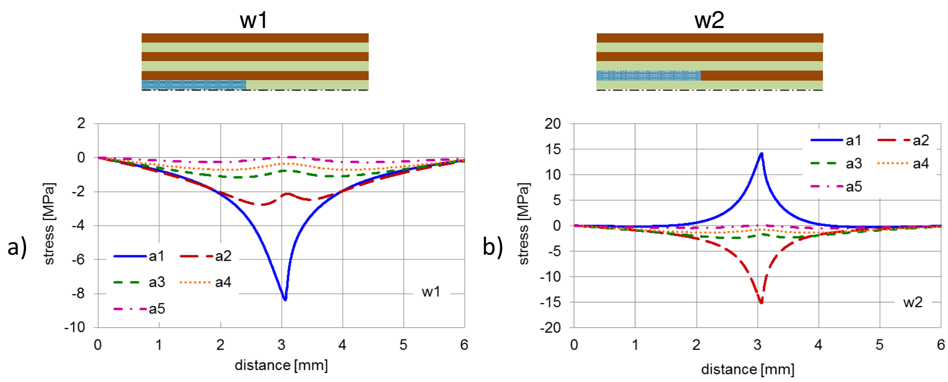

Fig. 9. Shear stress in adhesive layers – cases w1 and w2 [source: own study]

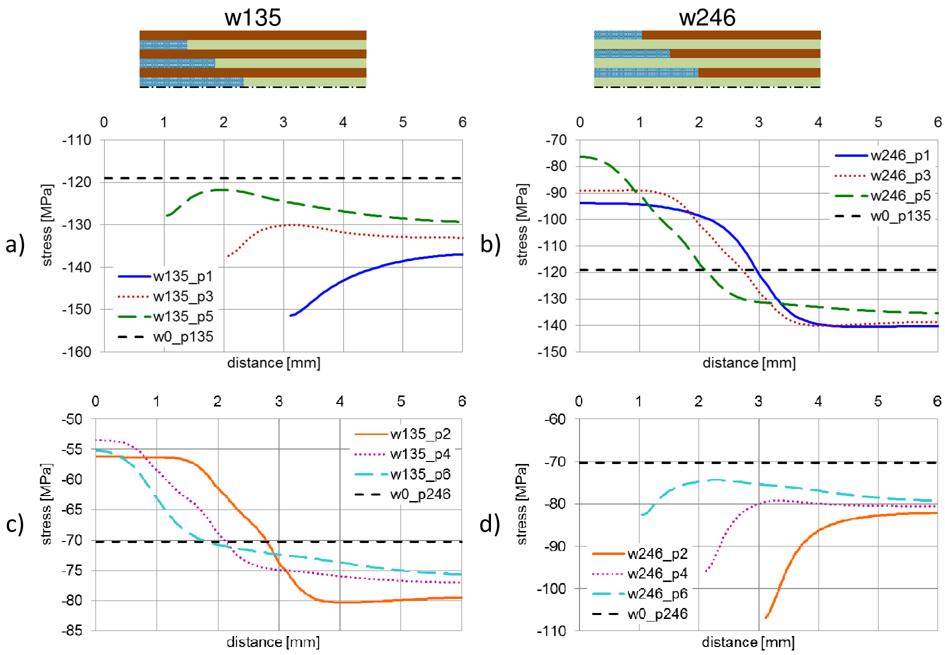

Fig. 10. Normal stress (axial component) in laminate layers – cases w135 and w246: a)-b) layers p1,p3,p5; c)-d) layers p2,p4,p6 [source: own study]

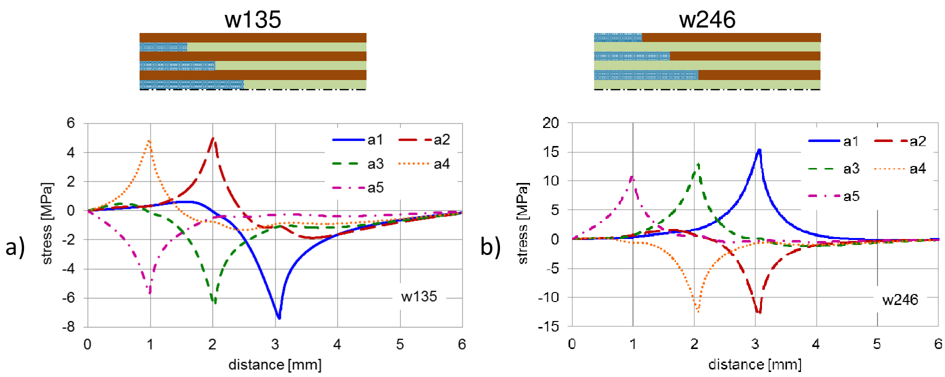

Fig. 11. Shear stress in adhesive layers – cases w135 and w246 [source: own study]

The largest axial stresses are observed in the prepreg ply which follows the longest metal insert. Those values are about 33 MPa greater than mean values regardless of insert configuration (compare fig. 8a, 8d, 10a and 10d). However, this increase in the stress value is significantly influenced by insert stiffness (twice as great as a composite one) and boundary conditions (due to a relatively short specimen). Maximum shear stress in the adhesive layers is about 7.5 MPa for cases w1 and w135 (where (0) prepreg plies are replaced with metal foils), while it is about 15 MPa for cases w2 and w246 (where (45) plies are modified). In the latter cases, the load transferred by means of shear stress is two times greater than in the former ones.

3. 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. Bonding of titanium foils between laminate layers [2] is the most advantageous solution (since the load transfer becomes more gradual), however, it is the most expensive one as well.

The authors effort is concentrated on searching for an optimal solution that would create a possibility of transferring the compressive load into the composite material in a gradual way.

A proper solution of load transferring into the composite structure using shear stress in the resin matrix between metal and composite layers can improve bearing capacity of mechanically fastened joints.

The research has been funded from the Polish-Norwegian Research Programme coordinated by the National Centre for Research and Development under the Norwegian Financial Mechanism 2009-2014 within Project Contract Pol-Nor/210974/44/2013.

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