# Gradient material model in analysis of mechanical joints of CFRP laminate

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Abstract

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. Therefore, they are still employed in aircraft design. High specific stiffness and strength of composite materials (especially CFRP) cause a continuous increase in their usage in aircraft structures. In general, composites are brittle materials and more notch sensitive than metal alloys. Hole drilling is a (necessary) stage in manufacturing of a mechanical joint. Holes vicinities are the areas of high stress concentrations and determine load capability of the whole structure. Therefore, mechanical joints of composite parts require a special attention to be focused during both a designing and manufacturing process. The aim of the paper is analysis of local material weakness/deterioration caused by a drilling process and its influence on the features of a mechanical joint. The specimen in the form of a double-shear joint was analysed. The weakened areas were identified on the basis of NDT analysis. A simple gradient material model was proposed to describe the hole vicinity. Numerical simulations were performed and compared with experimental results.

*Keywords: Mechanical joints, CFRP, gradient material model, FEA*

## 1. Introduction

The constant attempt to obtain as low aircraft mass as possible is the reason for using material of high specific strength and stiffness in the aerospace industry [1]. High strength steels, titanium or aluminium alloys (e.g. 2024T3) and composite laminates (e.g. CFRP or Glare) are the examples of such materials. Hole drilling is a (necessary) stage in manufacturing of a mechanical joint. Hole vicinities are the areas of high stress concentrations and they determine load capability of the whole structure. Therefore, mechanical joints of composite parts require a special attention to be focused during both the designing and manufacturing process. The aim of the paper is analysis of local material weakness/deterioration caused by a drilling process and its influence on the features of a mechanical joint. A simple gradient material model was proposed to describe the hole vicinity.

## 2. Object of analysis

The analysis is performed on the specimen in the form of a double-shear bolted joint with four steel fasteners (Fig. 1). The outer elements are made of 2024T3 aluminium alloy sheet and the inner element is made of quasi-isotropic CFRP laminate consisting of UD laminate layers (HTA/913) and external fabric layers (TR30S twill woven) with $[(0)/0/45/90/45/0/45/90/45/0/90]_S$ stacking sequence. The joint length L is 300 mm. The bolt diameter d is 6mm. A selected pitch length is 5d and the joint width is 70 mm (w = 70 mm). The aluminium alloy sheet thickness is 2 mm and the laminate thickness is 3.1 mm.

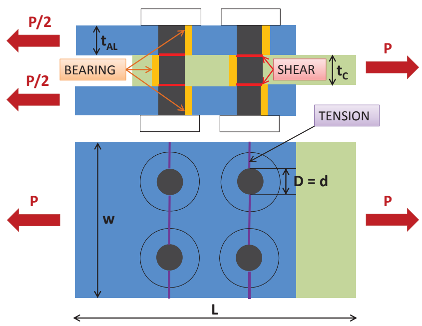


Figure 1: Analysed double-shear bolted joint

## 3. Numerical model of mechanical joint

A solid element was used to model all the components (aluminium sheet, composite and bolt). It is an eight-node element with linear interpolation functions, with three translational degrees of freedom in a node. Each prepreg lamina was modelled using one layer of finite elements. Connections of laminate plies were described using a cohesive model (zero thickness cohesive elements). It created a possibility to perform analysis of the interlaminar shear stress state around the hole and simulation of the delamination process.

Due to its symmetry, only a quarter of the joint was modelled. The mesh, boundary and symmetry conditions are presented in Fig. 2. The left grip edge is fixed and the right grip edge is pulled.

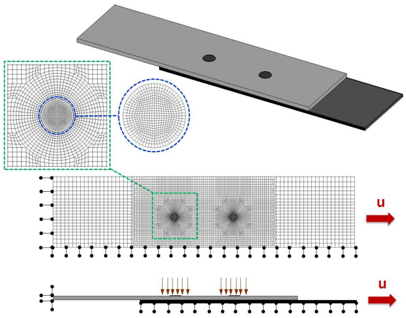


Figure 2: FE model

The area around the hole covered by the washer was subjected to pressure corresponding to the value of the fastener torque.

Segment to segment contact formulation was applied to matting surfaces of the specimen. Nonlinear analyses were carried out using Newton-Raphson method with Marc code.

Simulation of a joint tension test was controlled with damage and failure criteria. The indices according to Hashin failure criterion were used to gradually reduce stiffness of the composite part [2]. Aluminium alloy, used for outer sheets, and steel, used for the bolt, are elasto-plastic materials. The equivalent stress for the multiaxial state was calculated using the von Mises criterion. Interface delamination was employed using an exponential cohesive model.

## 4. NDT analysis and gradient material model employment

Defects of the laminate coupon around the hole, caused by drilling process, constitute an area of weakened/deteriorated material (ADM). It was identified using NDT method. The average diameter of those areas in analysed laminate coupon equals about 11 mm. The exemplary results of the NDT tests and corresponding ADM in finite element model are presented in Fig. 3.

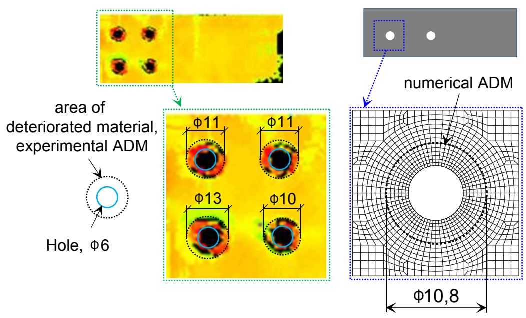


Figure 3: NDT results and corresponding area of deteriorated material in finite element model

The changes of material observed in the NDT images are surely a result of delamination. However, consideration of initial delamination only between prepreg layers (without any changes of prepreg/lamina properties) does not sufficiently affect the results. This leads to the conclusion that the drilling process has caused a significant deterioration of prepreg/lamina properties around the hole. Lamina properties are thought to be changing gradually in this area, therefore, simple gradient material model was applied to describe this phenomenon. ADM was divided into zones having different values of material properties (stiffness and strength components). Several cases of decomposition of ADM (in the hole vicinity) are presented in Fig. 4. Additionally, the geometrical modifications/ imperfections (e.g. clearance, shape of the hole and lack of holes concentricity in aluminium and composite parts) were taken into account in order to obtain good agreement between the experimental and numerical results.

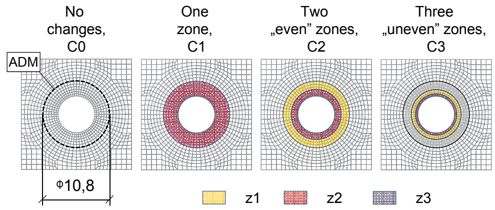


Figure 4: Gradient material models

The results for selected parameters of gradient material models are presented in Fig. 5.

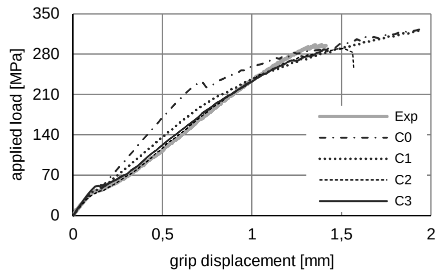


Figure 5: Comparison of experimental and numerical load-displacement curves for various gradient material models

## 5. Conclusions

Analysis of NDT results and global load-displacement curves illustrates that material deterioration of the laminate coupon around the hole, caused by the drilling process, ought to be taken into consideration in FE model in order to obtain satisfactory agreement between numerical and experimental results. A simple gradient material model around the hole has been proposed. The function of gradient material properties is unknown, therefore, it was estimated. Initial numerical delamination between prepreg/lamina layers with no changes of lamina properties does not change the features of the joint in a sufficient manner. Therefore, a gradual change of material properties and several cases of decomposition of ADM were analysed. A gradient material model seems to be of a great value in analysis of mechanical joints of CFRP laminate.

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