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Investigation of the effect of chamfer size on the behaviour of hybrid joints made by adhesive bonding and riveting

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ABSTRACT

The paper reports the results of a numerical study performed on: (a) purely adhesive joints and (b) new hybrid single lap joints with a variable adherend thickness in the lap region. The variable thickness creates chamfer defined by a geometric parameter *ch* which has a very positive influence on the mechanical response of the joint. The novelty in this paper is the investigation of the effect of chamfer size on the behaviour of hybrid joints made by 2 simple techniques: adhesive bonding and riveting. In particular, 10 types of chamfer geometries are considered, each causing a different stiffness of the adherends being joined. As a result, the strength of the connection is increased and its weight reduced, which is of vital importance in aircraft constructions.

The adherends and rivets are assumed to be made of aluminium, i.e., an elastic-plastic material, and subjected to gradual degradation due to tension. The adhesive layer is modelled as a semi-brittle material with progressive degradation using cohesive elements. Following the creation of 3D finite element models, the samples are subjected to quasi-static uniaxial deformation (nonlinear analysis with ABAQUS/Explicit).

The numerical results lead to the conclusion that the variable geometry, i.e., chamfering, has a very positive effect. At the maximum chamfer length equal to 10 mm, the increase in the maximum force was about 32.8% compared to the model without chamfer.

1. Introduction

All connections currently used in the joining of structural elements can be divided into:

- purely mechanical (welding, fastening, riveting, clinching),
- purely adhesive, e.g. [1–5],
- and hybrid joints, e.g. [6–13].

In the design of adhesive joints, one must consider many technological, geometrical or material factors [1–5,14] that exert a major impact on the connection strength. These factors include: (a) shape and dimensions of the laps [15], (b) surface preparation, (c) thickness of the adhesive and adherends [16]. The strength of purely adhesive joints can be increased by means of several techniques, such as the shaping of geometric or material properties of the joint by:

- filleting of the adhesive layers, e.g. [17–22],
- introducing functional gradation of the adhesive properties, e.g. [23],
- varying the adherend shape via filleting or chamfering of the overlap edges of the adherends, e.g. [24–30],
- manufacturing of multistep-lap joints, e.g. [31].

Adhesive filleting [17–22] significantly decreases the maximum shear and peel stresses at the end of overlap edges. For instance in [17] it was noticed that those stresses can be reduced by over 60% using an arc-shaped fillet. The experimental results reported in [18,19] confirm that the strength increases by 11%-25% when the spew fillet is applied. In addition to that, the introduction of a fillet angle of 45^0 leads to a decrease in the peel and shear stresses [20]. To further increase the strength of single lap joints, the spew fillet should also be used at the side edges [22].

The problem of variation of the adherend shape by filleting of the plate edges and chamfering the inner and outer faces of adherends was first discussed for double lap joints in [24]. The best results were obtained by the introduction of an inner tapper in the outer adherends with the application of an adhesive filled alongside the tapper inclined at an angle of 30^0. Similar results leading to the increase in the joint strength were obtained for single lap joints made of aluminium or steel with tapered adherend ends. The authors of [27] analysed different chamfering profiles with respect to improving the joint strength. The

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considered chamfer shapes significantly reduced the peak of the shear stresses in the adhesive layer at the overlap edges. Moreover, they increased load transfer in the central region of the overlap.

The last method for improving the mechanical behaviour of lap joints is to create single-, three- or, in general, multi-step lap joints [31]. Though their manufacturing is more complicated in comparison with the manufacturing process for single lap joints, the load carrying capacity of such joints can be increased up to 60% or more. However, this only applies to thick sheets.

Hybrid joints, e.g. [6–13] as a composition of mechanical fastening and adhesive bonding, have many advantages, such as higher strength and stiffness, higher energy required to failure, and higher fatigue strength [32,33]. However, hybrid joints are more complicated and can be described by other parameters characterising mechanical fasteners such as: (a) their quantity, (b) strength, (c) the use of interference or clearance [34], (d) the use of prestressing [11].

To sum up, there are many parameters that affect the strength of single lap joints. Moreover, the uniaxial stretching of a single lap joint generates rotation in the overlap region, which creates additional eccentricity and bending deformation. However, there is no detailed analysis of methods for improving the hybrid joint strength. To initiate a discussion on this problem, we therefore investigate the effect of chamfer size on the behaviour of a hybrid joint made by 2 simple techniques: adhesive bonding and riveting (Fig. 1b). In order to assess the effectiveness of the outer chamfer of the adherends, the same analysis is performed for a purely adhesive joint. Therefore, the paper presents the results of a numerical study performed on both purely adhesive and hybrid single lap joints with a variable adherend stiffness, subjected to uniaxial stretching.

The objective of this paper is to determine the effect of chamfer size on the strength and strain energy accumulation in both purely adhesive and hybrid joints.

2. Finite Element Models (FEM) of purely adhesive and hybrid joints

Single lap joints were analysed as purely adhesive and hybrid (adhesive + rivets) joints. The assemblies consisted of three elements in the case of the adhesive joints and five elements in the case of the hybrid joints. In the hybrid joint model, two mechanical fasteners were considered (Fig. 2). In the analysis we applied the simplest rivet geometry, without fitting, and with friction set to 0.1.

The parameter which distinguished particular models was a chamfer width c or its non-dimensional version $ch = c/t$. The value of c ranged from 1 mm to 10 mm, with 1 mm of increment for both the hybrid and adhesive joint. If the thickness of the adherend was equal to $t = 2$ mm, then the parameter ch varied from 0.5 to 5 (Fig. 3).

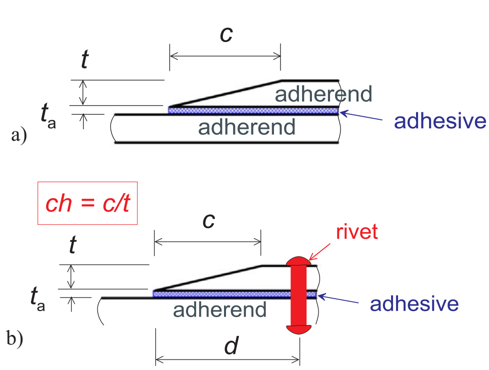

Fig. 1. Chamfer geometry described by geometric parameter "ch" for a) purely adhesive joint, b) hybrid joint produced by adhesive bonding and riveting.

2.1. Ductile damage model (DDM) of the rivet

We assumed that the rivets were made of aluminium, i.e., an elastic-plastic material, and subjected to gradual degradation due to tension.

The basis for this ductile phenomenological model is the observation of initiation, growth and further coalescence of the voids [35,36]. Fig. 4 shows a complete stress-strain diagram obtained for the DDM. The damage process begins at the peak of this constitutive curve and up to this moment the Young modulus of the material remains constant.

(E_0 = const.). The onset of damage in the model takes place for the equivalent plastic strain $\bar{\varepsilon}_{eq}^{\mathrm{pl}} = \bar{\varepsilon}_0^{\mathrm{pl}}$:

$$\bar{\varepsilon}_0^{\mathrm{pl}} = \bar{\varepsilon}_0^{\mathrm{pl}}(\eta, \dot{\bar{\varepsilon}}_0^{\mathrm{pl}}), \tag{1}$$

which is a function of stress triaxiality $\eta = \sigma_m/\sigma_{eq}$ and the equivalent plastic strain rate $\dot{\bar{\varepsilon}}_0^{\mathrm{pl}}$. The damage process starts when the following criterion is satisfied:

$$\omega_D = \int \frac{\mathrm{d}\bar{\varepsilon}^{\mathrm{pl}}}{\bar{\varepsilon}_0^{\mathrm{pl}}(\eta, \dot{\bar{\varepsilon}}_0^{\mathrm{pl}})} = 1, \tag{2}$$

where ω_D is the state variable that increases monotonically with of the plastic deformation. Then, for $\bar{\varepsilon}_{eq}^{\mathrm{pl}} > \bar{\varepsilon}_0^{\mathrm{pl}}$ the damage develops, i.e., the variable D increases from 0 to the final value 1, ($D \in (0 \to 1)$) and the current state of stress is equal to (e.g. [37–43]):

$$\sigma = (1 - D)\bar{\sigma}, \tag{3}$$

where $\bar{\sigma}$ is the effective (undamaged) stress tensor. It can be seen in Fig. 3 that $D\bar{\sigma}$ denotes the loss of loading capacity of the material by the current damage state described by a scalar variable D. One can notice that the damage of the material causes a decrease in the initial value of Young modulus E_0, i.e., the material unloading is described by the current value of elastic unloading modulus:

$$E = (1 - D)E_0. \tag{4}$$

The material loses its load carrying capacity for the equivalent plastic strain $\bar{\varepsilon}_{eq}^{\mathrm{pl}} = \bar{\varepsilon}_f^{\mathrm{pl}}$ when the damage variable reaches the final value $D = 1$.

In order to numerically describe the material's behaviour after damage initiation, the fracture energy approach [35] was applied by the introduction of a material parameter, G_{I}, which can be defined as the energy required to open a unit area of crack surface, triggering a stress-displacement response. The implementation of this concept in the FEM model was necessary to introduce a characteristic length, L, associated with the integration point. Then, the fracture energy is given by:

$$G_I = \int_{\bar{\varepsilon}_0^{\mathrm{pl}}}^{\bar{\varepsilon}_f^{\mathrm{pl}}} L\sigma_y \mathrm{d}\bar{\varepsilon}^{\mathrm{pl}} = \int_0^{\bar{u}_f^{\mathrm{pl}}} \sigma_y \mathrm{d}\bar{u}^{\mathrm{pl}}, \tag{5}$$

where $\bar{u}^{\mathrm{pl}}$ is the equivalent plastic displacement which can be defined as the fracture energy conjugate of the yield stress after damage initiation and is equal to:

$$\dot{\bar{u}}^{\mathrm{pl}} = L\dot{\bar{\varepsilon}}^{\mathrm{pl}}. \tag{6}$$

The damage evolution law can be specified in terms of the equivalent plastic displacement $\bar{u}^{\mathrm{pl}}$ or in terms of the fracture energy dissipation G_I. Both options take into account the characteristic length of the element to alleviate mesh dependency of the results. The damage-governing equation can be expressed as the equivalent plastic displacement $\bar{u}^{\mathrm{pl}}$:

$$D = D(\bar{u}^{\mathrm{pl}}). \tag{7}$$

In general, we obtain a linear, piece-wise linear or exponential form of (7).

2.2. Degradation of the adhesive described by Cohesive Zone Model (CZM)

The adhesive layer has a small thickness t_a = 0.1 mm and was modelled as a semi-brittle material with progressive degradation using