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An analytical model for the prediction of load distribution in multi-bolt composite joints including hole-location errors

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ABSTRACT

In the aircraft industry, the method for designing metal-composite joints is mainly based on conservative metallic calculation rules and on applying high safety factors. The reason is that the influence of errors due to manufacturing is not well-known, and few studies deal with this issue. Here, an analytical model is developed to evaluate load distribution in an aluminium-composite double-lap joint, in the presence of clearance and hole-location errors. The model also includes the nonlinear behaviour of the bolt implied by bearing degradation. The analytical model is validated by comparing results obtained by finite element analysis and experiments. Finally, an industrial use of the analytical model is presented.

1. Introduction

The increasing use of composite materials in the aeronautical field leads to metal-composite joints with a large number of fasteners. The choice of joint dimensions, fastener diameter, number of fasteners, spacing between rows of fasteners, is well understood now, thanks to many studies about their influence [1–3]. However, the effect of hole-location errors on the assembly mechanical performance is less well controlled. To reduce location error and thus ensure mechanical performance, fastener holes are made in a single drilling operation which requires a complex flow-process grid. This assembly process is incompatible with cost-efficient interchangeability rules and contributes to the increase in joint manufacturing and maintenance costs.

Few studies have been published dealing with the influence of geometrical errors on the mechanical behaviour of joined structures. This can be explained by the fact that this issue needs an accurate stiffness model for each constituent of the assembly (joined parts, fasteners) which controls load distribution between fasteners. Moreover, even for low hole-location errors or clearance, load distribution between fasteners is controlled by non-linear behaviour of materials, which generates a local softening [4,5]. Another problem, related to experimental validation, is found in introducing a controlled flaw into samples and developing specific instrumentation to analyse the effect of the flaw [4].

The load distribution in bolted joints has mainly been investigated with different levels of complexity. Some studies take the fasteners as rigid bodies and define the material behaviour of structures as elastic linear [6], others integrate nonlinearities due to contact issues (clearance, friction, etc.) and also bolt stiffness [7–10]. These models do not usually include nonlinear behaviour due to material damage in the fastener or around the hole. Some studies take into account material damage [5,11–18]. In [5,11,13,18], 3-D finite element models are used to study the progressive degradation implied by bearing loading. Thus several damage mechanisms are introduced in these models, such as delamination, matrix cracking and fiber compressive failure. However, such complex models cannot be applied to a large structure with multi-bolt joining with a view to study the effect of design parameters. In [12], the most critically loaded fastener is first determined using a linear analysis, and then a specific study including damage mechanisms focuses on this location. Nevertheless, the effect of local softening on load redistribution between fasteners is not represented. In [15,17], a 1-D analytical model is proposed in which each bolt is modelled by a spring with a nonlinear force displacement law in order to represent the local softening due to bearing damage. The evolution of load transfer rate during loading is thus more easily predicted according to joint dimensions and material behaviours. It should be noted that clearance can be included in the spring force displacement law. Gray and McCarthy [16] included nonlinear bolt behaviour previously proposed [15] in a user-defined 10-node super finite element which can be used

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with shell elements to simulate large-scale structures. Results on 20-bolt joints are presented and compared with experimental data in terms of strain distribution. Although good agreement is found, the effect of nonlinear behaviour is not addressed.

The present study focuses on the influence of hole-location error, coupled with the influence of bolt-hole clearance, on multi-bolt aluminium-composite double-lap joints. The defect is introduced by modifying slightly the pitch distances in one substrate, so that once the first bolt is assembled, the holes for the other bolts in composite and aluminium adherents are misaligned. A 1-D analytical model is presented, able to evaluate the preload state implied by the location error, and also to predict the load distribution between bolts when an external load is applied to the joint. The loss of stiffness, implied by bearing damage, is integrated into the whole bolt force displacement law, allowing the description of joint behaviour up to failure. This model is validated by a 3-D finite element model (FEM) produced with Abaqus software, and also by multi-instrumented tests. In the last part of the paper, the model is applied for different location error levels with some discussion of the choice of design tolerance.

2. Analytical model description

2.1. Model formulation

The present study focuses on a multi-bolt metal-composite double-lap joint, as illustrated in Fig. 1 for two bolts. The assembly, with a width w, is made up of a composite plate, with a thickness h_1 and called adherent 1, and two aluminium plates, each one with a thickness h_2 and called adherent 2. A location error δp is introduced by changing the pitch distance on the composite adherent, so that the composite and aluminium holes are no longer aligned. The friction loads between adherents are disregarded since in composite joints the bolt tightening is quite low. The purpose of the analytical model is to evaluate the load transmitted by each fastener.

The model is based on a 1-D model used by several authors [15,17,19–21], representing a multi-bolt joint. For n bolts, each adherent is divided into $n+1$ sections, and each section is considered as a spring, as presented in Fig. 2. Each bolt is also considered as a spring.

As the assembly involves a symmetry plane, only half of the set is modelled. The load F_i, transmitted by the bolt #i, is defined as:

$$F_i = k_i\left(\delta p_i + u_i^{(1)}(d_i) - u_i^{(2)}(d_i)\right) \quad (1)$$

where k_i is the stiffness of the bolt #i, $u_i^{(1)}(d_i)$ and $u_i^{(2)}(d_i)$ are displacements of sections #i of both adherents in $x = d_i$, and δp_i the location error associated to the bolt #i. The joint equilibrium gives the following equation:

$$N_i^{(2)} = F/2 - N_i^{(1)}, \text{ with } \quad i \in [1, n+1] \quad (2)$$

where $N_i^{(1)}$ is half of the tensile load in adherent 1 in section #i, and $N_i^{(2)}$ is the tensile load in adherent 2 in section #i. This is completed by the adherent's equilibrium equation, in $x = d_i$, given by:

$$N_{i+1}^{(1)} - N_i^{(1)} = F_i/2 \text{ with } \quad i \in [1, n] \quad (3)$$

Since substrate sections are considered as linear springs, it can be written:

$$E_1 S_1 \frac{du_i^{(1)}}{dx} = N_i^{(1)} \quad (4)$$

where E_1 is the Young's modulus of adherent 1 and $S_1 = wh_1/2$. The displacement function of section i of adherent 1 vs. x is obtained by integrating Eq. (4):

$$u_i^{(1)}(x) = \frac{N_i^{(1)}}{E_1 S_1}(x - d_i) + u_i^{(1)}(d_i), \text{ with } \quad i \in [1, n+1] \quad (5)$$

In the same way, displacements in adherent 2 are defined as:

$$u_i^{(2)}(x) = \frac{F - N_i^{(1)}}{2E_2 S_2}(x - d_i) + u_i^{(2)}(d_i), \text{ with } \quad i \in [1, n+1] \quad (6)$$

where $S_2 = wh_2$, E_2 is the Young's modulus of adherent 2. The displacement continuity between each section gives:

$$u_{i+1}^{(1)}(d_i) = u_i^{(1)}(d_i), \text{ with } \quad i \in [1, n] \quad (7)$$

Transferring Eq. (7) in Eq. (5), one gets:

$$u_i^{(1)}(d_i) - u_{i+1}^{(1)}(d_{i+1}) + \frac{N_{i+1}^{(1)}}{E_1 S_1}(d_{i+1} - d_i) = 0, \text{ with } \quad i \in [1, n] \quad (8)$$

Similarly, Eqs. (6) and (7) give:

$$u_i^{(2)}(d_i) - u_{i+1}^{(2)}(d_{i+1}) + \frac{F - N_{i+1}^{(1)}}{2E_2 S_2}(d_{i+1} - d_i) = 0, \text{ with } \quad i \in [2, n+1] \quad (9)$$

Combining Eqs. (3) and (1) gives:

$$N_{i+1}^{(1)} - N_i^{(1)} = k_i/2\left(\delta p_i + u_i^{(1)}(d_i) - u_i^{(2)}(d_i)\right), \text{ with } \quad i \in [1, n] \quad (10)$$

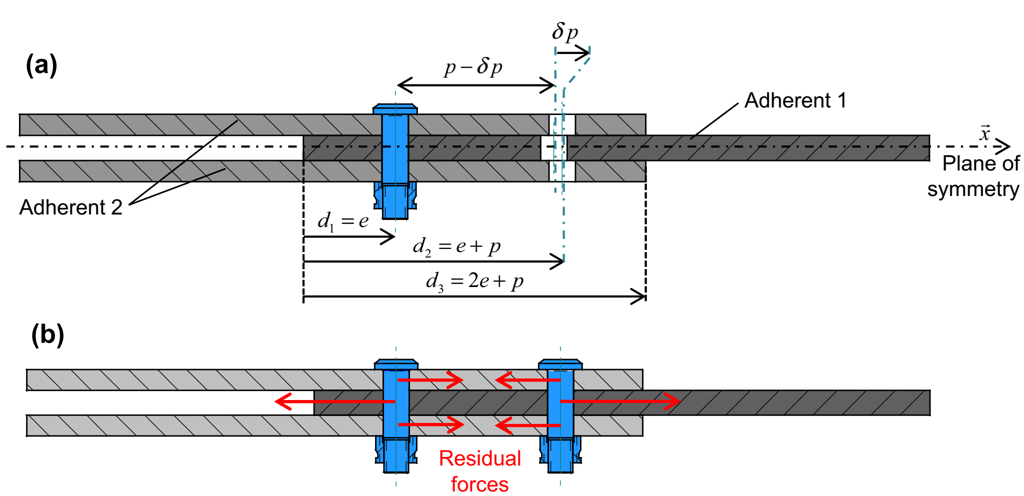

Fig. 1. Double-lap metal-composite joint with location error. (a) Definition of dimension parameters, (b) Illustration of assembly preload due to location error.